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California Environmental Protection Agency

Air Resources Board

2016 Edition

California's 2000-2014 Greenhouse Gas Emission Inventory

Technical Support Document

Archive

State of California
Air Resources Board
Air Quality Planning and Science Division

September 2016

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INTRODUCTION

The Global Warming Solutions Act of 2006 (AB 32, Núñez, Statutes of 2006, chapter 488) requires that the California Air Resources Board (ARB) to determine the statewide 1990 greenhouse gas (GHG) emissions level and approve a statewide GHG emissions limit, equal to that level, to be achieved by 2020. Assembly Bill 1803, which became law in 2006, made ARB responsible to prepare, adopt, and update California's GHG inventory.

This technical support document presents a comprehensive and detailed discussion of the emissions estimation methods, equations, data sources, and references that ARB staff employed to develop the 2016 edition of California's GHG emission inventory, covering years 2000 to 2014.[1]

The structure of the inventory and this report follow the categorization of GHG emissions contained in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC Guidelines)* (IPCC 2006b). In developing the 2016 California GHG inventory, staff consulted with other State agencies and the U.S. Environmental Protection Agency (USEPA). Some methodologies and data from the *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2014*, published in April 2016 by the USEPA were also incorporated for use in developing California emissions estimates.

The technical background of each category is presented followed by a discussion of the methodology used to estimate GHG emissions , including calculation equations, data sources, tables of intermediary results, etc. For each category, the complete list of activity and parameter values used in the equations is made available in an online documentation annex linked to this report.

In preparation for each new edition of the GHG inventory, recalculations are made to correct errors, incorporate new methodologies or, most commonly, to reflect changes in statistical data supplied by other agencies. Emission estimates are recalculated for all years to maintain a consistent time-series within the inventory. This approach follows the recommendation for developing GHG inventories discussed in Volume 1, Section 5.2 of the IPCC Guidelines (IPCC 2006b). As a consequence, successive editions of the inventory may report a different amount of emissions or removal for a given year than earlier published inventories. Emission inventories are, by nature, the reflection of the best available data and the most applicable methods at the time of their compilation. With each new edition of the California GHG inventory, staff make improvements to methods or data sources. In this technical support document, all changes in methodology and data since the previous edition of the inventory

[1] GHG Emission Inventory data and documentation can be found at www.arb.ca.gov/cc/inventory/data/data.htm

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are described and their impacts on emissions estimates are quantified. An overview of the major updates to the inventory over the years is provided later in this chapter.

International Panel on Climate Change (IPCC) guidelines

The IPCC guidelines are the recognized international standard for calculating national GHG inventories. They were developed through an international process which included work by teams of experts from many countries; technical and regional workshops held in Africa, Asia, Latin America, Central Europe and Western Europe; testing of the methods through the actual development of inventories; and country studies to assess the methods in a variety of national contexts.

The first version of the IPCC Guidelines was published in 1995 and has undergone multiple revisions. The latest *2006 IPCC Guidelines* (IPCC 2006b) include new sources and gases as well as updates to the previously published methods and default emission factors.

The IPCC Guidelines include summaries of the methods' scientific background, estimation equations, default emission factors and other parameters to use in generating the estimates, and sources of activity data. The Guidelines' methods are ranked in three tiers:

- Tier 1 methods are the simplest and use commonly available data sources. Emission estimates are based on activity levels and emission factors and use IPCC default values.
- Tier 2 methods are intermediate in complexity and data requirements. Refinements include disaggregating activity data among contrasting processes, using process- or country-specific emission factors and/or parameter values, etc.
- Tier 3 methods are the most complex. Often based on mathematical models of the processes involved, they typically require having extensive knowledge of management practices and detailed activity data.

Properly implemented, all tiers are intended to provide unbiased estimates, and accuracy and precision should, in general, improve from Tier 1 to Tier 3. The IPPC recommends using Tier 2 or Tier 3 methods for *key categories*. Key categories are defined as are those with a significant influence on a country's total inventory of GHGs in terms of the absolute level, the trend, or the uncertainty in emissions and removals. All categories in the ARB GHG inventory have followed the 2006 IPCC guidelines since the third edition of the inventory (emission years 2000-2008).

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A comprehensive inventory

There are two main types of inventory approaches used to determine GHG emissions from a region: the top-down and bottom-up approach. The California GHG inventory uses both approaches. The top-down approach utilizes nationwide or statewide data from various federal and state government agencies to estimate emissions. The bottom-up approach utilizes data from individual activity units to compute unit level emissions that are then aggregated to the national or state level for a particular source category.

Bottom-up methods use individual facility data collected through the Regulation for the Mandatory Reporting of Greenhouse Gas Emissions (MRR) program (ARB 2015b). MRR data are used in two ways: exclusively in the case of industry sectors that are completely captured by the MRR program (cement plants and refineries), and as a complement to top-down data sources for other sectors not completely captured by MRR (in-state electricity generation and general fuel combustion facilities).

In the absence of a comprehensive GHG emissions reporting system, a top-down approach is usually followed. Aggregate levels of activity are in general robust because they are augmented by, or checked against, other statistics. For instance, survey and census data can be supplemented with sales tax records, or with the balance of national production plus imports and minus exports. However, these national level statistics are not always available at the state level. This is true in particular of import–export records between California and other states, since interstate commerce is under federal jurisdiction. For this reason, state-level inventories are often more difficult to develop than national inventories. In the case of some categories, as state-level data were lacking, staff opted to use national-level aggregate data adjusted pro-rata to the population or to production capacity, to estimate California's emissions.

Overview of Major Inventory Updates

This section describes the major updates made to the inventory since the inception of California's GHG inventory. It is not a comprehensive listing of all updates made to the inventory.

The CEC published the first multi-year inventory of California GHG emissions (CEC 1997), covering years 1990 through 1994. The emission estimates presented in that report were based on methods from USEPA's "States Workbook: Methodologies for Estimating Greenhouse Gas Emissions" (USEPA 1992). In 2000, the California Legislature passed Senate Bill 1771 requiring the CEC, in consultation with other state agencies, to update California's GHG inventory. In 2002, the CEC updated the inventory (CEC 2002) based on the 1996 Revised IPCC Guidelines (IPCC 1997), the 1990-1999 national GHG inventory (USEPA 2001), and USEPA's Emission Inventory Improvement

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Program (USEPA 1999). In 2005, CEC included GHG emissions from out-of-state electricity imported to California and excluded all international fuel uses from the inventory totals, reporting them as separate line items.

In 2006, Assembly Bill 1803 transferred the responsibility to prepare, adopt, and update California's GHG inventory from the CEC to the ARB. The same year, Assembly Bill 32 required that the ARB determine the statewide GHG emissions level in 1990 and approve a statewide GHG emissions limit, equal to that level, to be achieved by 2020.

In developing ARB's first edition of California's GHG inventory, ARB staff consulted with other State agencies, stakeholders and the public through a series of workshops and technical discussions. That public process resulted in major revisions to the inventory, including changes to the classification of emissions and sinks, selected emission estimation methods, GHG emission factors, and other parameters to bring them in accord with the 2006 IPCC guidelines. Subsequent editions of ARB's GHG inventory saw a number of additional changes to the data and methods used for the estimates. Updates to the inventory were described in the online documentation published with these inventories on ARB's website.

In the 2011 edition, data collected under MRR was integrated for the first time including information from cement plants, refineries and hydrogen production, electricity generation and electricity imports (ARB 2007c). Emissions from ethanol fuel were broken out from the generic gasoline category. Nitrogen trifluoride (NF_3) emissions were added to the inventory following an amendment to AB 32.

In the 2014 edition, the Global Warming Potentials (GWPs) values used in the inventory were updated from IPCC's Second Assessment Report (SAR) (IPCC 1996) to Fourth Assessment Report (AR4) (IPCC 2007). All the previous editions of the inventory were based on the GWPs in SAR.

In the 2015 edition, emission estimation methodologies for the oil and gas and natural gas pipeline sectors were updated to capture additional fugitive emissions not captured by MRR. The lead smelting sector became subject to MRR reporting and its emissions were added to the inventory.

In the 2016 edition, CO_2 emissions from combustion of transportation biofuels (ethanol, biodiesel, renewable diesel, and biomethane) were reclassified as "biogenic CO_2" and tracked separately as informational items to align with the existing treatment of stationary biofuel combustion in the inventory, as well as the IPCC guidelines, the USEPA's national GHG inventory, and other nations' inventories submitted to the UNFCCC. Natural petroleum seeps emissions were reclassified as excluded emissions to be consistent with IPCC guidelines and USEPA's national GHG inventory.

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Updates made to the inventory since the previous release of this technical support document are further described in the Summary of Method Updates below.

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SUMMARY OF METHOD UPDATES

Emission inventories are a reflection of the best available data and the most applicable methods at the time of their compilation. As data grow and understanding develops they can be updated and improved. Table 1 summarizes the major updates to methodology or data sources since the previous release of the technical support document in 2014. It is organized by IPCC category, consistent with the organization of this technical support document. Table 1 also shows Scoping Plan category for reader's reference. These method updates are discussed in detail in the *Inventory Updates Since the 2015 Edition of the Inventory* (ARB 2016b) and the *Method Updates Since the 2014 Edition of the Inventory* (ARB 2015a) documents that were released with the 2015 and 2016 editions of annual inventory data. These updates are incorporated into this edition of the technical support document.

Table 1. Summary of methodology changes since the previous release of the technical support document

IPCC Category/Code	***Scoping Plan Sector Category***	***Description of Update***	***Year Updated***
Energy: 1A1a	Electricity	Add a new category for biomethane combustion to distinguish from generic biomass fuel combustion	2016
Energy: 1A1ai	Electricity	Track biogenic CO_2 from imported electricity as part of the "biogenic CO_2 emissions", consistent with the Mandatory GHG Reporting Regulation (MRR) data.	2016
Energy: 1A1cii & 1B2	Industrial	Emissions estimation method for oil and gas production is changed to capture additional fugitive CH_4 emissions that were not captured by MRR	2015
Energy: 1A2m	Industrial	Correct a typo in IPCC code assignment	2016
Energy: 1A3	Transportation	Add new fuel categories for biodiesel, renewable diesel, and biomethane fuel combustion to distinguish from their generic fuel blends	2016
Energy: 1A3	Transportation	Reclassify CO_2 from combustion of biofuels (ethanol, biodiesel, renewable diesel, and biomethane) as "biogenic CO_2"	2016
Energy: 1A3	Transportation	Add new on-road unspecified diesel category	2016
Energy: 1A3b	Transportation	CH_4 and N_2O emissions from combusting gasoline and diesel fuels in on-road transportation sources are now based on the output of the 2014 version of the EMFAC model	2015

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IPCC Category/Code	Scoping Plan Sector Category	Description of Update	Year Updated
Energy: 1A3biii	Transportation	Separate emissions from heavy duty trucks, buses, and motorhomes into three categories to allow independent tracking of each vehicle type	2016
Energy: 1A3d	Transportation	Use interim emission estimation methodology for ocean going vessels due to unavailability of 2014 data	2016
Energy: 1B2	Industrial	Reclassify natural petroleum seeps as "excluded" emissions	2016
Energy: 1B2b	Industrial	Emissions estimation method for natural gas pipelines is changed to capture additional fugitive CH_4 emissions that were not captured by MRR.	2015
Industrial Processes and Product Use: 2C5	Industrial	Process emissions from lead production, a new sector added to MRR program, have been added to the GHG emission inventory	2015
Industrial Processes and Product Use: 2E	High GWP	Update estimation of emissions from semiconductor operations to incorporate revised ARB survey data	2016
Industrial Processes and Product Use: 2F	High-GWP	The "Other Ozone Depleting Substances (ODS) substitutes" category in previous editions of the inventory has been disaggregated into individual compounds to provide details on the emissions	2015
Industrial Processes and Product Use: 2F	High GWP	Update estimation of emissions from ozone depleting substance (ODS) substitutes using new data reported by users of ODS substitutes under the Refrigerant Management Program	2016
Industrial Processes and Product Use: 2G4a	Industrial	Use interim emission estimation methodology for CO_2 consumption due to unavailability of 2014 data	2016
Agriculture, Forestry and Other Land Use: 3A1 & 3A2	Agriculture	Revise cattle population estimates used for manure and enteric fermentation emission estimates	2016
Agriculture, Forestry and Other Land Use: 3A1 & 3A2	Agriculture	Use interim emission estimation methodology for cattle emission factors due to unavailability of 2014 data	2016
Agriculture, Forestry and Other Land Use: 3C4	Commercial and Residential	The use of nitrogen fertilizer on commercial and residential turf grass has been added as a new inventory category	2015

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IPCC Category/Code	***Scoping Plan Sector Category***	***Description of Update***	***Year Updated***
Agriculture, Forestry and Other Land Use: 3C5	Agriculture	Method for estimating N_2O emissions from fertilizer applied to crops is updated based on crop acreage and recommended fertilizer application rate.	2015
Agriculture, Forestry and Other Land Use: 3C4 & 3C5	Agriculture	Disaggregate soil management N_2O emissions from managed and unmanaged manure applied to soils into sub-categories by detailed animal type	2016
Waste: 4A1	Recycling & Waste	Incorporate new CalRecycle 2014 waste characterization into landfill model for years 2012 through 2014	2016
Waste: 4D1	Recycling & Waste	Update emission estimation for domestic wastewater treatment with anaerobic digester using California-specific activity data	2016
Waste: 4D1	Recycling & Waste	Update emission estimation for domestic wastewater effluent using California-specific activity data	2016
Waste: 4D2	Industrial	Methane emissions from wastewater of non-citrus fruit processing plants now exclude apples and wine grapes, which are accounted in a separate category	2015
Waste: 4D2	Recycling & Waste	Update industrial pulp & paper wastewater treatment emissions with California-specific activity data	2016

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I. Energy

A. Electricity and Heat Production – In State (IPCC 1A1a)

1. Background

The sources of energy used for electricity generation are varied in nature and origin: fuel combustion, hydropower, nuclear, solar, wind, and geothermal. The dominant source of energy for electricity and heat production in California is fuel combustion, and GHGs are emitted during this process. With the exception of fugitive emissions of CO_2 released from geologic formations tapped for geothermal energy, other energy sources do not emit GHG in the energy conversion process. Emissions from fuel combustion activities are estimated and tallied under this category (1A1a); CO_2 emissions from geothermal power are included in the inventory and reported under category 1B3 (Other Emissions from Energy Production). Note also that the SF_6 emissions associated with the distribution of electricity through the power grid are reported under IPCC code 2G1b (Use of Electrical Equipment).

The California GHG inventory includes the emissions of CO_2, CH_4 and N_2O resulting from the combustion of fossil fuels, including gaseous fuels (natural gas, refinery gas, etc.), liquid fuels (distillate, residual fuel oil, jet fuel, etc.), and solid fuels (coal, petroleum coke, etc.). Various biomass fuels (wood, agricultural biomass and landfill or digester gas) are also used to produce heat and electricity. The GHG inventory includes only the CH_4 and N_2O emissions resulting from the combustion of biomass fuels since the CO_2 emissions would have occurred eventually as the biomass decayed. These CO_2 emissions, labeled "from biogenic materials", are estimated and tracked, but are not included in California's GHG inventory total.

Within this inventory category (IPCC 1A1a), power plants are classified by fuel, and by type of generation: either electricity generation or combined heat and power (CHP). The CHP process makes use of otherwise wasted exhaust heat, making it a potentially more energy efficient means of generating electricity. Although Combined-Cycle Power Plants that use a combustion turbine (usually burning natural gas) followed by a heat-recovery steam generator to convert waste heat into steam for additional power generation, are a type of CHP, they are not considered CHP in IPCC categorization because they do not produce "useful thermal output" (UTO). For CHP, the GHG emissions associated with UTO are not attributed to the electric power sector; they are reported separately for the sector (industrial or commercial) in which

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the UTO is used. CHP plants are classified by the sector to which they provide their UTO, and thus labeled either as "CHP: Commercial" or "CHP: Industrial". Non-CHP power plants are classified under IPCC code 1A1ai (Electricity Generation), CHP plants are classified under IPCC code 1A1aii (Combined Heat and Power Generation). Geothermal emissions are classified under IPCC code 1B3 (Other Emissions from Energy Production).

Power plants are also classified into two ownership categories: "Utility owned" or "Merchant owned". Utility owned plants are those under direct ownership of a public or investor-owned utility responsible for providing electricity to their customers. Merchant owned plants are under private or corporate ownership, engaging in the buying and selling of electricity in the open market, and eventually selling to utilities that cannot provide all the electricity they need through their own plants.

2. Methodology

2.1 Stationary combustion emissions

The method for estimating stationary combustion emissions follows IPCC 2006 guidelines (IPCC 2006a). California or US-specific emission factors and heat content values are used when available.

Equation 1: Emissions from stationary combustion

$$E_{GHG,\ fuel} = FC_{fuel} \bullet HC_{fuel} \bullet EF_{GHG,\ fuel}$$

Where,

$E_{GHG,\ fuel}$ = Emissions of the given GHG for the type of fuel (g of GHG)

FC_{fuel} = Amount of fuel combusted (in units of tons for solid fuels, gallons for liquid fuels or standard cubic feet for gaseous fuels)

HC_{fuel} = Heat content (higher heating value) of the type of fuel (BTU / unit)

$EF_{GHG,\ fuel}$ = Emission factor of the given GHG by the type of fuel (g GHG / BTU)

With,

GHG = [CO_2, CH_4, N_2O]

Fuel = [associated gas, biomass, coal, crude oil, digester gas, distillate, jet fuel, kerosene, landfill gas, municipal solid waste, natural gas, petroleum coke, propane, refinery gas, residual fuel oil, tires, waste oil]

A variant of this estimation method was used to estimate CO_2 emissions in the case of partially biomass fuels. These fuels are a mix of materials from

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biomass and fossil origins. Municipal solid waste (MSW) and used tires are two such fuels.

Equation 2: Variant for partially renewable fuels

$$E_{GHG,\ fuel,\ origin} = E_{GHG,\ fuel} \bullet P_{fuel,\ origin}$$

Where,

$E_{GHG,\ fuel,\ origin}$ = Emissions of the given GHG for the proportion of materials of given origin for the type of fuel (g of GHG)

$E_{GHG,\ fuel}$ = Emissions of the given GHG for the type of fuel (g of GHG)

$P_{fuel,\ origin}$ = proportion of material of given origin in the type of fuel (fraction)

With,

GHG = [CO_2]

Fuel = [MSW, tires]

Origin = [Fossil, Biomass]

For a list of yearly activity, heat content and emission factor values used in the emission estimation equations, please consult the online documentation annex at: https://www.arb.ca.gov/cc/inventory/doc/methods_00-14/annex_1a_electricity_and_heat_production_in_state.pdf

2.2 Other emissions

Non-combustion emissions from electricity and heat production include CO_2 from acid gas control devices and fugitive emissions of CH_4 from coal storage piles. Information about these sources of emissions first became available through the ARB Mandatory Reporting Regulation (MRR) (ARB 2007c).

To estimate emissions from these sources for years without MRR data, staff assumed that these emissions would scale with the amount of activity associated with each source. For acid gas control, the MRR data showed that only coal, coke, biomass and MSW fuels were associated with this process. Thus, emissions from this source were estimated for years 2000 to 2008 pro rata the total amount of heat (BTU) generated by these fuels in each of these years. A similar method was applied to scale the fugitive methane emissions from coal storage piles for 2000 to 2008 and for 2011 onwards as MRR no longer required these emissions be reported, using only the amount of coal consumed for this purpose. That is:

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Equation 3: Back-scaling of non-combustion emissions

$$E_{GHG,\,source,year} = \frac{E_{GHG,\,source,MRR}}{H_{source,MRR}} \bullet H_{source,\,year}$$

Where,

$E_{GHG,\,source,\,year}$ = Emissions of the given GHG from the particular sources in the given year (g of GHG)

$E_{GHG,\,source,\,MRR}$ = Emissions of the given GHG from the particular source in MRR (g of GHG)

$H_{source,\,year}$ = amount of combustion heat associated with the source in the given year (BTU) for acid gas, or amount of coal consumed (tons) for fugitive methane

$H_{source,\,MRR}$ = amount of combustion heat associated with the source in MRR (BTU) for acid gas, or amount of coal consumed (tons) for fugitive methane

With,

GHG = [CO_2 or CH_4]

Source = [Acid gas control device, Coal pile]

3. Data Sources

Fuel-use data for 2000 was obtained through personal correspondence with the U.S. Energy Information Administration (EIA), the statistical arm of the U.S. Department of Energy (Schnapp 2008). Fuel use data for 2001-2008 was downloaded from EIA databases published online (EIA 2013a). These fuel-use datasets are available online in full detail starting with year 2001, but are not available at the same level of detail for previous years. Detailed data for these years are available from the EIA upon special request.

Heat content data for 2000-2008 also came from the EIA (Schnapp 2008, EIA 2013a). CO_2, CH_4 and N_2O emissions factors come from ARB's Mandatory Reporting Program data (ARB 2015b).

The data source for 2009+ fuel-use, heat content, and emissions are primarily from ARB's Mandatory Reporting Program data (ARB 2015b). The threshold of reporting for power plants excludes plants with emissions less than 2,500 metric tons per year (10,000 metric tons in 2011 onwards), so for these plants (which amount to less than 2 percent of the emissions from in-state electricity generation) EIA data were used (EIA 2013a).

3.1 Mapping EIA codes to ARB categories

Fuel use and heat content data reported by the EIA are grouped as indicated in Table 2 and Table 3. The EIA fuel codes and sector codes provide the

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information necessary to apportion ARB's emissions estimates into the categories presented in the inventory.

Table 2: EIA to ARB fuel mapping

ARB GHG Inventory Fuel	***EIA Fuel Code(s) Included***
Associated Gas	OG (for EIA ID: 56090 only)
Biomass	AB, BLQ, OBL, OBS, ORW, SLW, WDL, WDS, WWW
Coal	BIT, LIG, SUB, SC, WC
Crude Oil	OTH
Digester Gas	OBG
Distillate	DFO
Geothermal	GEO
Jet Fuel	JF
Kerosene	KER
Landfill Gas	LFG, MLG
Municipal Solid Waste (MSW)	MSB, MSN, MSW
Natural Gas	NG
Petroleum Coke	PC
Propane	PG
Refinery Gas	BFG, OG
Residual Fuel Oil	RFO
Tires	TDF
Waste Oil	WO

Table 3: EIA to ARB category mapping

ARB GHG Inventory Category	***EIA Sector Code (EIA #)***
Utility Owned	1
Merchant Owned	2, 4, 6
CHP: Commercial	5
CHP: Industrial	3, 7

3.2 Use of MRR Data in the inventory

Some MRR data are classified differently than IPPC categories used in ARB's emission inventory, requiring data processing. Data for facilities that report to MRR (those with emissions of 10,000 $MTCO_2e$ or greater with one or more electricity generating units or cogeneration units), are used exactly as reported in MRR. The fuel and emissions associated with generation of UTO are separated and reported under the cogeneration (or Combined Heat and Power, CHP) categories according to IPCC categorization. Additional information on the use of MRR data can be found in the *Guidance for Working with the GHG Inventory and MRR Data Using Disaggregated Industrial Cogeneration Data* (ARB 2016c) document available on GHG inventory webpage.

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Some facilities use continuous emission monitoring system (CEMS) to measure total CO_2 emissions. These facilities report measured CO_2 totals, fuel amounts, and calculated CH_4 and N_2O emissions for the fuel amounts they include. The inventory divides up the single CEMS CO_2 value among the reported fuel amounts by a simple allocation procedure which weights each fuel by its reported heat content. First, each reported fuel amount is converted to a default CO_2 emission using the MRR default emission factors for that fuel and the reported amount of heat. The default CO_2 emissions are summed, and compared to the reported CEMS total. The ratio of total CEMS CO_2 to total default CO_2 is used to correct the emissions so that the final corrected values sum to the reported CEMS CO_2 amount.

Emissions from acid gas control are taken directly from reported values of sorbent use in MRR and the CO_2 emissions are inventoried without any changes.

3.3 Combined Heat and Power

CHP plants report separate amounts of fuel and heat for electricity generation and for UTO to the EIA. Staff attributed the amount reported under electricity generation to the electric power sector and the remainder to either the industrial or commercial sector under "useful thermal output" based on the EIA sector code in Table 3. For years 2009+ staff also used data from ARB's Mandatory Reporting Program for CHP facilities reporting therein.

3.4 Partially renewable fuels

Certain fuels, namely, municipal solid waste (MSW) and used tires, are not completely composed of fossil carbon, but contain carbon from renewable sources as well. Staff determined that tires contain approximately 20 percent renewable natural rubber based on data from the Rubber Manufacturers Association (RMA 2007). Staff used source test data provided by Covanta Energy (Hahn 2007) from the three power plants burning MSW in the state to estimate that, on a carbon basis, about 66 percent of the MSW burned in California for energy is from renewable biomass origin. These values serve as defaults when source specific data is not available.

For 2009+, staff used Mandatory Reporting data supplied updated values for these fuels where reported as based on source tests or other measurement methods done by each reporting facility.

4. Changes in Estimates

No changes in methods have occurred in the version of the inventory when compared to the 2000 – 2013 edition of the GHG inventory.

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5. Future Improvements

Staff plans to continue to identify data sets to further refine emissions estimates. For example, ARB's Mandatory Reporting Program includes detailed information related to cogeneration activities (amount of useful thermal output generated and amount of gross generation produced). These data also enable allocating emissions between the electric power and UTO components of cogeneration plants. The data were first available for 2011, but data have not been consistently reported by the facility operators. ARB staff is evaluating the use of these data in future GHG inventory editions.

B. Electricity Production – Imports (IPCC 1A1a)

1. Background

California's highly interconnected electricity system relies on imports as well as on electricity generated in state. The Global Warming Solutions Act of 2006 (AB 32) requires that ARB include estimates of out-of-state GHG emissions from imported electricity in California's GHG inventory. Imported power may come from a variety of energy sources but, while the sources of in-state generation are well known, the origin of imported electricity is often unknown. Emissions from imports that can be directly linked to a known out-of-state power plant are tallied under "specified imports" (I.B.3.1 below); emissions from all other imports are discussed in the "unspecified imports" (I.B.3.2 below).

Specified imports are those with a well-known and documented generation source. In these cases, the specific amount of fuel used to generate the imported power can be obtained and used to determine emissions. The specified imports consist of those listed in Table 4 below.

Two natural gas plants, La Rosita and Termoeléctrica de Mexicali are located in Mexico (MEX) and thus do not report to the EIA (and do not have an EIA ID). Data for these plants comes from the CEC's Quarterly Fuels and Energy Report (QFER) database (Nyberg 2009). The CEC ID of these two facilities is included instead of the EIA ID. The Armstrong Woodwaste Cogeneration Plant and the Prince George Pulp & Paper Plant are biomass plants in Canada (CAN), and do not have EIA IDs; nor do they report to the CEC. The emission factors for these plants were estimated from data obtained through a survey of the two facilities. Bonneville Power Administration (BPA) and Powerex are Asset Controlling Suppliers and have no individual EIA IDs. PacifiCorp is a Multi-Jurisdictional Retail Provider and also has no individual EIA ID. For 2011, BPA used a default assumption of 20 percent of the Unspecified Imports Emission Factor as their own; they were the only one of the three to report in 2011. For 2012 and beyond, all three provided their own emission factors for years in which they

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imported power based on their total system emissions and generation, available through MRR.

Table 4: Specified imports

Plant Name-Primary Fuel (EIA ID)	***State/Country (Import Region)***
Apache Station - Coal (160)	AZ (Pacific Southwest)
Apex Generating Station - Natural Gas (55514)	NV (Pacific Southwest)
Arlington Valley Energy Facility - Natural Gas (55282)	AZ (Pacific Southwest)
Apache Station - Coal (160)	AZ (Pacific Southwest)
Apex Generating Station - Natural Gas (55514)	NV (Pacific Southwest)
Arlington Valley Energy Facility - Natural Gas (55282)	AZ (Pacific Southwest)
Armstrong Woodwaste Cogeneration - Biomass (NA)	AN (Pacifc Northwest)
Blundell - Geothermal (299)	UT (Pacific Southwest)
Boardman - Coal (6106)	OR (Pacifc Northwest)
Bonanza - Coal (7790)	UT (Pacific Southwest)
Bonneville Power Administration - Hydro (Asset-Controlling Supplier 1)	NW (Pacifc Northwest)
Caithness Dixie Valley - Geothermal (52015)	NV (Pacific Southwest)
Chehalis - Natural Gas (55662)	WA (Pacifc Northwest)
Colstrip - Coal (6076)	MT (Pacifc Northwest)
Craig - Coal (6021)	CO (Pacific Southwest)
Currant Creek - Natural Gas (56102)	UT (Pacific Southwest)
Dave Johnston - Coal (4158)	WY (Pacifc Northwest)
Desert View Power - Biomass (10300)	CA (Tribal Lands in CA)
El Dorado Energy - Natural Gas (55077)	NV (Pacific Southwest)
Four Corners - Coal (2442)	NM (Pacific Southwest)
Gadsby - Natural Gas (3648)	UT (Pacific Southwest)
Gila River Power Station - Natural Gas (55306)	AZ (Pacific Southwest)
Grays Harbor Energy Facility - Natural Gas (7999)	WA (Pacifc Northwest)
Griffith Energy - Natural Gas (55124)	AZ (Pacific Southwest)
Hardin Generating Project - Coal (55749)	MT (Pacifc Northwest)
Harquahala Generating Project - Natural Gas (55372)	AZ (Pacific Southwest)
Hermiston Power - Natural Gas (54761, 55328)	OR (Pacifc Northwest)
Hunter - Coal (6165)	UT (Pacific Southwest)
Huntington - Coal (8069)	UT (Pacific Southwest)
Intermountain - Coal (6481)	UT (Pacific Southwest)
Jim Bridger - Coal (8066)	WY (Pacifc Northwest)
Kettle Falls - Biomass (550)	WA (Pacifc Northwest)
Klamath Falls Cogen - Natural Gas (55103)	OR (Pacifc Northwest)
Klamath Peaking - Natural Gas (55544)	OR (Pacifc Northwest)
La Rosita - Natural Gas (G9787)	EX (Pacific Southwest)
Lake Side - Natural Gas (56237)	UT (Pacific Southwest)
Laramie River - Coal (6204)	WY (Pacifc Northwest)
Mesquite Generating Station - Natural Gas (55481)	AZ (Pacific Southwest)
Mohave - Coal (2341)	NV (Pacific Southwest)
Naughton - Coal (4162)	WY (Pacifc Northwest)
Navajo - Coal (4941)	AZ (Pacific Southwest)
Nebo Power Station - Natural Gas (56177)	UT (Pacific Southwest)
Nippon Paper Cogen - Biomass (58352)	WA (Pacifc Northwest)
PacifiCorp - Coal (Multi-Jurisdictional Retail Provider)	NW (Pacifc Northwest)
Powerex - Hydro (Asset-Controlling Supplier 2)	NW (Pacifc Northwest)
Prince George Pulp & Paper - Biomass (NA)	AN (Pacifc Northwest)
Rawhide - Natural Gas (6761)	CO (Pacific Southwest)

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Plant Name-Primary Fuel (EIA ID)	***State/Country (Import Region)***
Red Hawk - Natural Gas (55455)	AZ (Pacific Southwest)
Reid Gardner - Coal (2324)	NV (Pacific Southwest)
River Road - Natural Gas (7605)	WA (Pacifc Northwest)
Roosevelt Biogas - Biomass (7832)	WA (Pacifc Northwest)
San Juan - Coal (2451)	NM (Pacific Southwest)
Seneca Sustainable Energy - Biomass (57457)	OR (Pacifc Northwest)
Sierra Pacific Burlington - Biomass (56406)	WA (Pacifc Northwest)
Simpson - Biomass (57099)	WA (Pacifc Northwest)
Southpoint Energy Center - Natural Gas (55177)	AZ (Pacific Southwest)
Springerville - Coal (8223)	AZ (Pacific Southwest)
Termoelectrica de Mexicali - Natural Gas (G9786)	EX (Pacific Southwest)
Transalta Centralia Generation - Coal (3845)	WA (Pacifc Northwest)
Trans-Jordan Generating Station - Biomass (56853)	UT (Pacific Southwest)
West Valley - Natural Gas (55622)	UT (Pacific Southwest)
Weyerhaeuser Long View - Biomass, Coal and Natural Gas (50187, 54562)	WA (Pacifc Northwest)
Whelan Energy Center - Coal (60)	NE (Pacifc Northwest)
Wyodak - Coal (6101)	WY (Pacifc Northwest)
Yucca/Yuma Axis - Natural Gas (120)	AZ (Pacific Southwest)
Yuma Cogeneration Associates - Natural Gas (54694)	AZ (Pacific Southwest)

Unspecified imports are not assigned an actual fuel value in the inventory because they cannot be linked to a specific plant of origin. For years 2000 to 2008, a composite emission factor was developed, based on data provided by the CEC. For 2009+, staff used an emission factor developed by the Western Climate Initiative (WCI) (WCI 2011). This change of method was motivated by two reasons: (a) the discontinuation in 2009+ of the CEC data reporting (Net System Power) on which the previous emission factors were based; and (b), to maintain consistency with the upcoming cap and trade program, which uses the WCI emission factor. The WCI has estimated unspecified imports emission factors for 2006 to 2008, and staff used the average of these 3 values as the 2009+ emission factor.

As electrical power is transmitted through power lines, losses occur primarily because of resistance. Therefore, more electrical power must be generated than is actually delivered and consumed in California. Staff accounted for these losses and the emissions associated with them in the inventory since they occur as a result of California's demand for imports. In the case of most specified imports, the amount of electricity generated for import into California at the plant of origin was known and thus there was no need for line loss corrections. In some cases (e.g. Colstrip, Bonanza and Hunter in 2000-2008) the amount of electricity produced at the plant of origin was not known: only the amount received by the purchasing agency at the point of reception was available. In those cases, the actual amount of electricity generated at the plant of origin can be estimated by applying a plant specific line loss factor to the amount of electrical power received from the plant. For 2000-2008, staff used line loss factors of 7.5 percent for imports from Colstrip and Hunter, and 3

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percent for imports from Bonanza. This last factor reflects the line loss estimates included in the contract for power purchased from the Bonanza plant by LADWP (Parsons 2009). Line losses from the remaining two specified imports (Colstrip and Hunter) and all unspecified imports were estimated using the CEC suggested loss factor of 7.5 percent. For 2009+, Mandatory Reporting electricity imports data was used, which include line losses (defaulting to 2% if not known), eliminating the need for such a correction.

Statewide electricity imports are typically reported as net imports (gross imports – exports). However, accounting for all emissions resulting from the generation of electrical power for California requires estimating the gross import value. Actual export data was obtained from the California Department of Finance (CDOF) California Statistical Abstract – Table J-11 (CDOF 2010b) for 2001-2008. These export estimates were then added to the net import value to obtain the gross import number. For 2000, the average of the 2002-2004 exports were used as an estimate, and for 2009+, this procedure was no longer necessary as the Mandatory Reporting Program captured gross imports directly.

All imports of electricity are classified under IPCC code 1A1ai (Electricity Generation), while SF_6 emissions from imported power are under IPCC code 2G1b (Use of Electrical Equipment). These SF_6 emissions are attributed to the electric power sector.

2. Data Sources

Imported electric power emissions estimates are based primarily on fuel use, heat and electricity generation data obtained from the EIA. Data for 2000 were obtained through personal correspondence with Robert Schnapp of the EIA (Schnapp 2008). Data for 2001 to 2008 were downloaded from EIA databases published online (EIA 2013a). The Los Angeles Department of Water and Power (LADWP), an importer of out-of-state power, provided fuel use and heat content data for plants (Intermountain, Mohave, and Navajo) for which they have ownership (Parsons 2009). Imported generation contract data was provided by LADWP (Parsons 2009) for the Bonanza and Colstrip plants and by the City of Riverside (Mendez 2009) for the Hunter plant. For 2009+, Mandatory Reporting data (ARB 2015b) was used to determine the amount of electricity (MWh) imported while the emission factors applied to these imports were estimated from EIA data (EIA 2013a), CEC data (Nyberg 2009), or informal surveys of fuel use of facilities that exist outside the USA (e.g. 2 facilities in Canada) for these plants.

Fuel CO_2, CH_4 and N_2O Emissions factors are from ARB's Mandatory Reporting Program data (ARB 2015b).

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Net Imports data for 2000-2008 are from the California Department of Finance's (CDOF) California Statistical Abstract Table J-11 (CDOF 2010a). The CEC provided data on line losses, exports (Alvarado 2007), ownership and entitlement shares (Griffin 2007), and assumptions for the fuel mix of unspecified imports for 2000 and 2001 (CEC 2000) and for 2002 to 2008 (CEC 2011). The emission factor used for 2009+ unspecified imports comes from the Western Climate Initiative (WCI) (WCI 2011), but is contained in ARB's Mandatory Reporting Program data (ARB 2015b).

2.1 Use of MRR Data

Emissions from unspecified imports are reported exactly as they appear in MRR. Emissions from specified imports provided by MRR are adjusted as follows. The imported quantity of MWh is used as reported, but the associated emission factor is obtained from EIA for most facilities. This is because the emission factors used in MRR have a one year lag due to the need to publish emission factors early for reporters to use. For this reason, the overall emissions from specified imports in ARB's GHG inventory will be slightly different than those reported to MRR. The emission factors reported by Bonneville Power Administration, Powerex, and PacifiCorp are used as reported to MRR, and thus will match MRR emissions for this subset of data.

3. Methodology

The steps used to estimate emissions from electricity imports depends upon whether the generation source of the imports is known or not and with the year of the estimate (see Figure 1).

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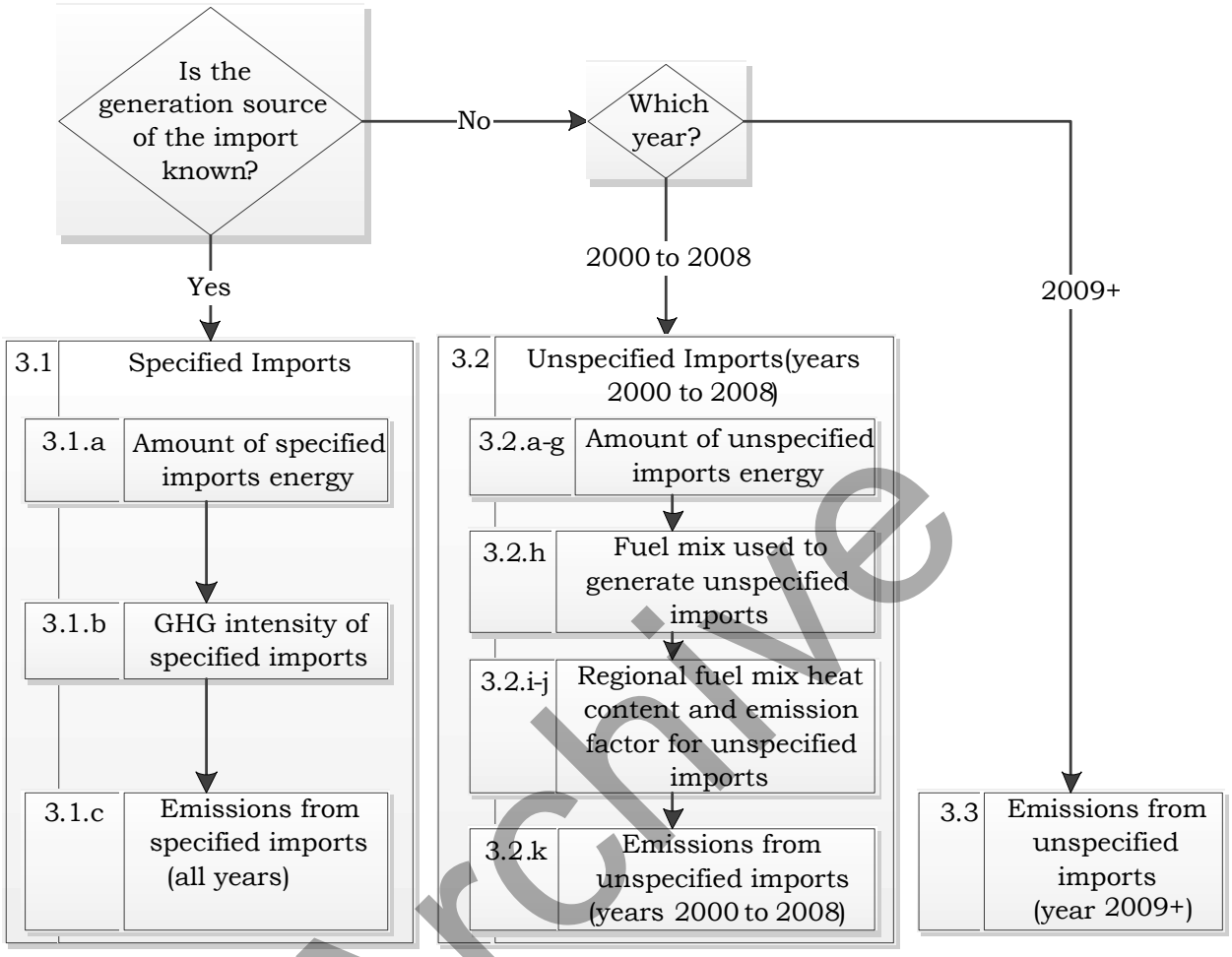
Figure 1: Methodological steps involved in estimating emissions from electricity imports



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3.1 Specified Imports

(a) Amount of specified imports energy

For 2000-2008, ownership, entitlement or contracted import amounts were provided by the CEC except for the Intermountain, Mohave, Navajo, Colstrip, and Bonanza plants, for which data were obtained from the LADWP (Parsons 2009), and for the Hunter plant which information was provided by the City of Riverside (Mendez 2009). For Colstrip, Bonanza and Hunter, the amount of imported power received, rather than generated, was the value documented. Line loss factors were used to adjust these amounts to estimate the actual plant generation required to supply LADWP or the City of Riverside with imported power. For all other specified plants, the ownership share, entitlement share or plant generation share was used, and because these apply

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directly to the plant itself, no line loss adjustment was needed. These data allow one to calculate the percentage of a given plant's electricity generation imported into California that year. A subset of these percentages is shown in Table 5 below. Note that Hoover (hydropower) and Palo Verde (nuclear) are included below even though they are not shown in the inventory itself because they generate no emissions.

Table 5: Percent of plant electricity generation imported by California

Plant Name (State) – Fuel	***2000***	***2001***	***2002***	***2003***	***2004***	***2005***	***2006***	***2007***	***2008***
Boardman (OR) - Coal	27.29	23.50	23.50	23.50	23.50	23.50	23.50	23.50	23.50
Bonanza (UT) - Coal	7.49	5.59	5.24	5.80	5.79	5.76	5.42	5.61	5.61
Caithness Dixie Valley (NV) - Geothermal	97.83	95.10	96.02	96.89	100	98.04	99.44	97.79	99.46
Colstrip (MT) - Coal	0*	0*	0*	0*	0*	0*	0*	0*	0*
Four Corners (NM) - Coal	34.61	36.05	36.05	36.05	36.05	36.05	36.05	36.05	36.05
Hoover (AZ/NV) - Hydro	76.57	76.57	76.57	76.57	76.57	76.57	76.57	76.57	76.57
Hunter (UT) - Coal	2.42	2.78	2.29	2.15	2.28	2.31	2.24	2.09	2.15
Intermountain (UT) - Coal	99.11	96.83	96.38	97.08	93.75	94.76	93.79	89.59	88.57
La Rosita (MEX) - Natural Gas	0*	0*	0*	0*	0*	0*	0*	0*	52.38
Mohave (NV) - Coal	76.02	75.35	66.02	66.12	66.11	66.11	0*	0*	0*
Navajo (AZ) - Coal	21.19	21.18	21.37	21.40	20.74	19.70	20.41	20.83	20.97
Palo Verde (AZ) - Nuclear	27.41	27.41	27.41	27.41	27.41	27.41	27.41	27.41	27.41
Reid Gardner (NV) - Coal	29.22	28.88	28.88	28.88	28.88	28.88	28.88	28.88	28.88
San Juan (NM) - Coal	4.37	24.08	24.08	24.08	24.08	24.08	24.08	24.08	24.08
Termoeléctrica de Mexicali (MEX) - Natural Gas	0*	0*	0*	0*	0*	0*	0*	100	100
Yucca/Yuma Axis (AZ) - Natural Gas	42.61	42.61	42.61	42.61	42.61	42.61	42.61	42.61	42.61

*LADWP imported from Colstrip for years 1990-1999 (about 5.8 percent on average) and from Mohave for years 1990-2005. Termoeléctrica de Mexicali began exporting in 2007 and La Rosita began in 2008.

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For 2009+, the amount of electricity imported into the state from each specified source was queried from ARB's Mandatory Reporting Program's database (ARB 2015b).

(b) GHG intensity of specified imports

Staff used fuel use and heat content data from EIA or CEC, and fuel specific emission factors to estimate the GHG intensity per MWh of electricity from each plant as follows:

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Equation 4: GHG intensity of specified imports

$$I_{GHG,\ plant} = \frac{\sum_{fuel} Q_{fuel,plant} \bullet HC_{fuel,plant} \bullet EF_{GHG,\ fuel,plant}}{TG_{plant}}$$

Where,

$I_{GHG,\ plant}$	= GHG intensity of electricity from the given plant, for the particular GHG (g of GHG per MWh)
$Q_{fuel,\ plant}$	= Amount of fuel combusted at the given plant (in units of tons for solid fuels, gallons for liquid fuels or standard cubic feet for gaseous fuels)
HC_{fuel}	= Heat content of the type of fuel at the given plant (BTU / unit)
$EF_{GHG,\ fuel}$	= Emission factor of the particular GHG by combustion of the given fuel (g GHG / BTU)
TG_{plant}	= Total net generation of electricity at the given plant (MWh)

With,

GHG	= [CO_2, CH_4, N_2O]
Fuel	= [biomass, coal, distillate, natural gas, residual fuel oil]
Plant	= [the specified plant]

Some of the specified imports came from geothermal plants (e.g. Caithness Dixie Valley). GHG intensity was estimated by calculating emissions from those plants with the method described in section I.G below and dividing by the total net amount of electricity produced.

(c) Emissions from specified imports

Emissions from specified imports are then estimated using the following equation:

Equation 5: Emissions from specified imports

$$E_{GHG,\ plant} = I_{GHG,plant} \bullet IG_{plant}$$

Where,

$E_{GHG,\ plant}$	= Emissions of the particular GHG from the specified imports from the given plant (g)
$I_{GHG,\ plant}$	= GHG intensity of electricity from the given plant, for the particular GHG (g of GHG per MWh)
IG_{plant}	= Imported amount of the net electricity generated by the given plant (MWh)

With,

GHG	= [CO_2, CH_4, N_2O]

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Plant = [the specified plant]

Values for the EIA or plant specific heat inputs and emission factors are available upon request. For a list of yearly activity and GHG intensities used in the emission estimation equation, please consult the online documentation annex at: https://www.arb.ca.gov/cc/inventory/doc/methods_00-14/annex_1b_electricity_production_imports.pdf

3.2 Unspecified Imports (years 2000 to 2008)

For years 2000 and 2001, the fuel mix used for unspecified imports and the resulting GHG emissions are based on CEC's *1999 Net System Power Calculation* (CEC 2000), and on CEC's *Net System Power Reports* for years 2002 to 2008 (CEC 2011). ARB staff relies on the expertise of CEC staff in this matter. Any future updates on these fuels used in the production of unspecified power will involve collaboration between staff of ARB and CEC. Detailed data used for all calculations are available upon request.

Electricity imported into California originates from two regions: the Pacific Northwest (PNW) and Pacific Southwest (PSW).

(a) Net electricity imports

Net imports data come from the California Department of Finance (CDOF) California Statistical Abstract – Table J-11 (CDOF 2010a). Table J-11 is based on data supplied to CDOF by the CEC.

Table 6: Net imports (GWh)

Region	2000	2001	2002	2003	2004	2005	2006	2007	2008
PNW	18,777	6,826	27,186	22,303	20,831	20,286	19,803	24,669	23,959
PSW	7,997	58,107	60,408	63,097	70,458	66,795	59,911	67,547	74,113

(b) Electricity exports – years with data

Known exports data for years 2001 to 2008 were also taken from CDOF's table J-11, values for year 2000 are not available:

Table 7: California exports (GWh)

Region	2000	2001	2002	2003	2004	2005	2006	2007	2008
PNW	Unknown	5,846	1,020	1,471	1,532	2,061	2,518	2,620	2,242
PSW	Unknown	9,007	5,514	4,555	3,292	3,623	2,539	2,966	2,822

(c) Electricity exports – estimation for years without data

First, staff used years 2002 to 2004 of data from Table 6 and Table 7 to determine the average ratio of exports to net imports in gigawatt-hours (GWh) for each region as follows:

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Equation 6: Average ratio of exports to net imports of electricity

$$Ratio = \frac{\sum_{year=2002}^{2008} Exports_{year}}{\sum_{year=2002}^{2008} Net_imports_{year}}$$

Note that there was an electricity supply crisis in California in 2001, and for that reason export and import data for that year were not used in the ratio determination. The average export-to-import ratios were 6 percent (0.06) for the PNW and 7 percent (0.07) for the PSW.

These export-to-import ratios were then applied to the net imports for year 2000 from each of these regions to estimate the exports for that year.

Table 8: Estimate of California exports (GWh)

Region	2000	2001-2008
PNW	1,074	See Table 7
PSW	3,418	See Table 7

(d) Gross imports

Gross imports are equal to net imports (Table 6) plus exports (Table 7 or Table 8)

Table 9: Gross imports (GWh)

Region	2000	2001	2002	2003	2004	2005	2006	2007	2008
PNW	19,851	12,672	28,206	23,774	22,363	22,347	22,321	27,289	26,201
PSW	11,415	67,114	65,922	67,652	73,750	70,418	62,450	70,513	76,935

(e) Amount of generation related to gross imports

Gross generation for imports, the actual power generated by out-of-state sources for California's electricity imports, is estimated by adding an assumed 7.5 percent line loss to the gross import number. This was done by dividing the values of Table 9 by 0.925 (i.e., 1 – 0.075):

Table 10: Gross generation for imports (GWh)

Region	2000	2001	2002	2003	2004	2005	2006	2007	2008
PNW	21,461	13,699	30,493	25,702	24,176	24,159	24,131	29,502	28,325
PSW	12,341	72,556	71,267	73,137	79,730	76,128	67,514	76,230	83,173

(f) Amount of specified imports included in net imports data

To avoid double counting emissions, specified imports (see section 3.1 above) were removed from the amount listed in CDOF's table J-11. Per CEC staff,

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import data in CDOF's table J-11 did not include ownership share or entitlement generation prior to 2001. On the basis of this information, ARB staff determined that, before 2001, only contracted imports were included in table J-11 and needed to be removed. These include three plants: Bonanza, Colstrip and Hunter.

For 2000, only Bonanza, Colstrip and Hunter were removed. For years 2001 to 2008, all the specified imports were removed:

Table 11: Specified imports included in CDOF table J-11 (GWh)

Region	2000	2001	2002	2003	2004	2005	2006	2007	2008
PNW	0	1,040	887	1,011	832	814	558	1,023	951
PSW	451	46,505	45,425	44,513	45,397	43,992	37,671	40,164	43,918

(g) Amount of unspecified imports energy

Unspecified imports were calculated by subtracting Table 11 from Table 10 values, which gives:

Table 12: Unspecified imports (GWh)

Region	2000	2001	2002	2003	2004	2005	2006	2007	2008
PNW	21,461	12,659	29,606	24,691	23,344	23,345	23,573	28,478	27,374
PSW	11,890	26,051	25,842	28,624	34,333	32,135	29,842	36,066	39,255

(h) Fuel Mix used to generate unspecified imports

The fuel mix of unspecified imports was based directly on the CEC's *1999 Net System Power Calculation* (CEC 2000) for years 2000 and 2001 and through a reconciliation methodology with their *Net System Power Reports* (NSP) for years 2002 to 2008 (CEC 2011). NSP was not used for 2001 due to the potential for aberrant values resulting from the California energy market crisis.

The methodology for determining the unspecified imports fuel mix for 2002-2008 using the NSP data is described briefly here.

First, the total gigawatt-hours (GWh) of imports by fuel type (Coal, Natural Gas, and Non-Emitting) and by region were compiled from the NSP reports for 2002-2008:

Table 13: Net System Power (GWh by fuel type and region)

Region	Fuel	2002	2003	2004	2005	2006	2007	2008
PNW	Coal	5,283	7,488	5,154	4,926	5,467	6,546	8,581
	Natural Gas	1,717	1,911	1,926	1,786	2,051	1,837	2,939
	Non-Emitting	20,186	12,904	10,346	13,574	12,286	16,286	12,425
PSW	Coal	21,582	24,306	20,760	24,796	23,195	39,275	43,271
	Natural Gas	6,865	7,738	8,400	10,812	13,207	16,363	15,060
	Non-Emitting	7,226	7,464	5,912	6,562	8,557	11,909	15,782

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Second, these values, which represent the amount of electricity measured at the California border (and thus is missing the line losses), were increased to estimate the amount of electricity generated at the plant of origin, so a full reckoning (including line losses) could be developed. The values in Table 13 were divided by 0.925 to account for line losses using the CEC suggested line loss value of 7.5 percent (Alvarado 2007).

Additionally, the amount of generation from two plants (Intermountain and Mohave) was added to the NSP report values for years 2002 to 2006 to stay consistent with CDOF's table J-11. This table includes all imports, whereas the NSP reports for 2002 to 2006 exclude the generation from those two plants, considering them as utility owned rather than imports. The NSP reports for 2007 and 2008 do include these two plants into the totals and future reports will continue to do so. Thus this adjustment is needed only for years 2002 to 2006. Table 14 below incorporates both the line loss adjustment and the addition of the two missing specified imports from Intermountain and Mohave:

Table 14: Net System Power (adjusted to account for missing specified imports & line losses)

Region	Fuel	2002	2003	2004	2005	2006	2007	2008
PNW	Coal	5,926	8,629	6,062	5,866	6,662	7,828	10,145
	Natural Gas	1,926	2,202	2,265	2,127	2,499	2,197	3,475
	Non-Emitting	22,641	14,870	12,168	16,165	14,971	19,476	14,690
PSW	Coal	46,598	48,915	44,852	49,023	40,046	44,324	48,561
	Natural Gas	8,569	9,330	9,933	12,693	15,084	18,466	16,901
	Non-Emitting	9,019	9,000	6,991	7,704	9,773	13,440	17,711

Third, the Specified Imports by fuel type for years 2002 to 2008 were determined. The values in Table 15 below match those of Table 11, except that the Table 15 values are shown in greater detail:

Table 15: Specified imports by fuel type and region (GWh)

Region	Fuel	2002	2003	2004	2005	2006	2007	2008
PNW	Coal	887	1,011	832	814	558	1,023	951
	Natural Gas	0	0	0	0	0	0	0
	Non-Emitting	0	0	0	0	0	0	0
PSW	Coal	32,782	33,125	34,121	33,586	27,460	26,057	25,769
	Natural Gas	171	99	109	105	126	3,417	6,881
	Non-Emitting	12,472	11,289	11,167	10,302	10,086	10,691	11,268

Fourth, Specified Imports (Table 15) were deducted from total imports (Table 14) to obtain the values of Unspecified Imports:

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Table 16: Unspecified imports by fuel type and region (GWh)

Region	Fuel	2002	2003	2004	2005	2006	2007	2008
PNW	Coal	5,039	7,618	5,229	5,052	6,104	6,805	9,194
	Natural Gas	1,926	2,202	2,265	2,127	2,499	2,197	3,475
	Non-Emitting	22,641	14,870	12,168	16,165	14,971	19,476	14,690
	Total	29,606	24,691	19,663	23,345	23,574	28,478	27,359
PSW	Coal	13,816	15,790	10,731	15,437	12,586	18,267	22,792
	Natural Gas	8,398	9,231	9,824	12,588	14,958	15,050	10,020
	Non-Emitting	0	0	0	0	161	2,749	6,443
	Total	**22,214**	**25,021**	**20,555**	**28,025**	**27,705**	**36,066**	**39,255**

Finally, taking the fuel and region specific values in Table 16 and dividing each by the total for that region produced the percentages in Table 17, which were used to calculate the emissions from Unspecified Imports for 2002 to 2008. The values for 2000 and 2001 were taken directly from the CEC's 1999 Net System Power Calculation (CEC 2000) and required no additional calculations:

Table 17: Fuel-mix of unspecified imports (percentage)

Region	Fuel	2000	2001	2002	2003	2004	2005	2006	2007	2008
PNW	Coal	20%	20%	17%	31%	27%	22%	26%	24%	34%
	Natural Gas	0%	0%	7%	9%	12%	9%	11%	8%	13%
	Non-Emitting	80%	80%	76%	60%	62%	69%	64%	68%	54%
PSW	Coal	74%	74%	62%	63%	52%	55%	45%	51%	58%
	Natural Gas	26%	26%	38%	37%	48%	45%	54%	42%	26%
	Non-Emitting	0%	0%	0%	0%	0%	0%	1%	8%	16%

(i) Average heat content and emission factors for unspecified imports

(i.i) Weighted average heat content

Weighted average heat contents (in BTU per MWh) were calculated by region by year for coal and natural gas. Staff obtained plant specific data for amounts of fuel combusted, heat content values and generated power from the EIA. Data from Oregon, Washington, Idaho and Montana were included in calculations for the PNW region; and data from Arizona, Colorado, New Mexico, Nevada and Utah for the PSW region. The weighted average heat contents were calculated as follows:

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Equation 7: Weighted average heat contents of fuels

$$WHC_{fuel} = \frac{\sum_{type,plant}(Q_{fuel,type,plant} \bullet HC_{fuel,type,plant})}{\sum_{type,plant} G_{fuel,type,plant}}$$

Where,

WHC_{fuel} = Weighted average heat content for the given fuel (btu per MWh)

$Q_{fuel, type, plant}$ = Quantity of the given fuel of the particular type combusted by the given plant (tons for coal, scf for natural gas)

$HC_{fuel, type, plant}$ = Heat content of the given fuel of the particular type combusted by the given plant (btu / ton for coal, btu / scf for natural gas)

$G_{fuel, type, plant}$ = Power generated with given fuel of the particular type by the given plant (MWh)

With,

fuel = [coal, natural gas]

type = [bituminous, lignite, etc.], applies only to coal

plant: power plants in either Pacific Northwest or Pacific Southwest region

(i.ii) Weighted average emission factor

Weighted average emission factors (in grams per BTU) were calculated by region and by year for coal and natural gas. Staff obtained fuel specific emission factor values from the EIA for CO_2 and from the IPCC guidelines for CH_4 and N_2O. Emission factors for non-emitting sources of electrical power were assumed to be zero. Staff included data from Oregon, Washington, Idaho and Montana in calculations for the PNW region; and from Arizona, Colorado, New Mexico, Nevada and Utah for the PSW region. The weighted average emissions factors were calculated as follows:

Equation 8: Weighted average fuel emission factors of unspecified imports

$$WEF_{GHG,fuel} = \frac{\sum_{plant}(Q_{fuel,plant} \bullet HC_{fuel,plant} \bullet EF_{GHG,fuel,plant})}{\sum_{plant}(Q_{fuel,plant} \bullet HC_{fuel,plant})}$$

Where,

$WEF_{GHG, fuel}$ = Weighted average emission factor for one of the given GHG, for a given fuel (grams per btu)

$Q_{fuel, plant}$ = Amount of the given fuel combusted by the particular plant (tons for coal, scf for natural gas)

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$HC_{fuel, plant}$ = Heat content of the given fuel combusted by the particular plant (btu / ton for coal, btu / scf for natural gas)

$EF_{GHG, fuel, plant}$ = Emission factor of a given GHG from the given fuel combusted by the particular plant (g of GHG per btu)

With,

fuel = [coal, natural gas]

GHG = [CO_2, CH_4, N_2O]

plant: power plants in either Pacific Northwest or Pacific Southwest region

(i.iii) Combined GHG emission factors

Combined-GHG emission factors (in lbs of CO_2 equivalent per MWh) may be computed from the GHG-specific factors above for the purpose of comparison with other such published factors. For each year and each region, they are the result of:

Equation 9: Combined-GHG emission factors of unspecified imports

$$CEF_{fuel} = \frac{\sum_{GHG} (WHC_{fuel} \bullet WEF_{GHG,fuel} \bullet GWP_{GHG})}{453.6}$$

Where,

CEF_{fuel} = Combined-GHG emission factor of the given fuel (lbs CO_2e per MWh)

WHC_{fuel} = Weighted average heat content for the given fuel (btu per MWh)

$WEF_{GHG, fuel}$ = Weighted average emission factor for the given GHG, for a given fuel (grams per btu)

GWP_{GHG} = Global Warming Potential of a given GHG (unitless)

453.6 = number of grams in a pound

With,

fuel = [coal, natural gas, non-emitting]

GHG = [CO_2, CH_4, N_2O]

The combined-GHG emission factors are listed below, in units of pounds of CO_2 equivalents (lbs CO_2e) per MWh:

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Table 18: Fuel-specific combined-GHG emission factors for Unspecified Imports (lbs CO_2e / MWh)

Region	Fuel	2000	2001	2002	2003	2004	2005	2006	2007	2008
PNW	Coal	2,169	2,268	2,339	2,301	2,316	2,310	2,344	2,316	2,301
	Natural Gas	1,024	1,014	947	923	838	838	852	857	835
	Non-Emitting	0	0	0	0	0	0	0	0	0
PSW	Coal	2,116	2,201	2,208	2,207	2,195	2,210	2,218	2,223	2,209
	Natural Gas	1,141	1,162	1,049	1,062	1,009	943	939	923	916
	Non-Emitting	0	0	0	0	0	0	0	0	0

(j) Regional fuel-mix heat content and emission factors for unspecified imports

Regional fuel-mix heat contents for the Pacific Northwest and Pacific Southwest regions can be estimated by multiplying the weighted average heat contents computed in Section I.B.3.2(i.i) above by the regional fuel mix values of Table 17.

Equation 10: Regional fuel-mix heat contents for unspecified imports

$$RHC_{region} = \sum_{fuel} WHC_{fuel} \bullet P_{fuel,region}$$

Where,

RHC_{region} = Regional fuel-mix heat content for the particular region (btu per MWh)

WHC_{fuel} = Weighted average heat content for the given fuel (btu per MWh)

$P_{fuel,\ region}$ = Proportion of power generated in a particular region using the given fuel (percent)

With,

fuel = [coal, natural gas]

region = [PNW, PSW]

Regional fuel-mix emission factors for the Pacific Northwest and Pacific Southwest regions may be estimated by multiplying the weighted average emission factors computed in Section I.B.3.2(i.ii) above by the regional fuel mix values of Table 17.

Equation 11: Regional fuel-mix emission factors for unspecified imports

$$REF_{GHG,region} = \sum_{fuel} WEF_{GHG,fuel} \bullet P_{fuel,region}$$

Where,

$REF_{GHG,\ region}$ = Regional fuel-mix emission factor for the given GHG in the particular region (g GHG / btu)

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$WEF_{GHG, fuel}$ = Weighted average emission factor for the given GHG for the given fuel (g GHG / btu)

$P_{fuel, region}$ = Proportion of power generated in a particular region using the given fuel (percent)

With,

fuel = [coal, natural gas, non-emitting]

GHG = [CO_2, CH_4, N_2O]

region = [PNW, PSW]

Regional combined-GHG emission factors for unspecified import (in lbs of CO_2 equivalent per MWh) may be computed for the purpose of comparison with other such published factors. These factors are the result of multiplying the fuel-mix percentages (Table 17) by the corresponding combined-GHG fuel-specific emissions factors (Table 18) and summing to arrive at a single factor for each region for each year. The Total Imports row in Table 19 shows the yearly system-wide average emission factors for California's unspecified imports.

Table 19: Regional emission factors for Unspecified Imports (lb CO_2e / MWh)

Region	2000	2001	2002	2003	2004	2005	2006	2007	2008
PNW	434	454	460	792	713	576	697	620	879
PSW	1,862	1,931	1,770	1,785	1,628	1,641	1,514	1,511	1,517
Total Imports	**943**	**1,448**	**1,070**	**1,325**	**1,258**	**1,193**	**1,154**	**1,118**	**1,255**

(k) Emissions from unspecified imports

Emissions from unspecified imports were estimated by multiplying the amount of unspecified import power (Table 12) by the regional fuel-mix heat content and the corresponding regional fuel-mix emission factors:

Equation 12: Emissions from unspecified imports

$$E_{GHG,region} = UI_{region} \bullet RHC_{region} \bullet REF_{GHG,region}$$

Where,

$E_{GHG, region}$ = Emissions of the given GHG for unspecified imports from the particular region (g of GHG)

UI_{region} = Amount of unspecified power imported from the particular region (MWh)

RHC_r = Regional fuel-mix heat content for the particular region (btu per MWh)

$REF_{g,r}$ = Regional fuel-mix emission factor for the given GHG in the particular region (g / btu)

With,

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GHG = [CO_2, CH_4, N_2O]
region = [PNW, PSW]

3.3 Emissions from unspecified imports (year 2009+)

The above detailed method (used for 2000 to 2008) cannot be used 2009 and future years because the CEC no longer generates the Net System Power report required to use the previous methodology.

For 2009+, Mandatory Reporting data was used to determine the total amount of unspecified electricity imported into the state. These unspecified imports were converted into emissions using the unspecified emission factor originating from the Western Climate Initiative (WCI) (WCI 2011), and now contained in ARB's Mandatory Reporting Program data (ARB 2015b).

For a list of yearly activity, heat content and emission factor values used in the inventory estimates, please consult the online documentation annex at: https://www.arb.ca.gov/cc/inventory/doc/methods_00-14/annex_1b_electricity_production_imports.pdf

4. Changes in Estimates

There are no changes in the current estimates of imported electricity emissions when compared with those made for the 2015 edition of the GHG Inventory.

5. Future Improvements

Future improvements may include the use of Open Access Technology International, Inc. (OATI) data. OATI collects data on E-Tags and how much power is imported into each state. This secondary source of data will help insure that all importers are reporting to the ARB's Mandatory Reporting Program, and doing so correctly.

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C. Fuel Combustion in Industrial, Commercial, Residential, Agricultural and Other Sectors (IPCC 1A1b, 1A2, 1A4 & 1A5)

1. Background

Fuel combustion is used as a source of energy to power machinery and heat buildings throughout California. In this section we discuss the emissions from fuel combustion by petroleum refineries (IPCC 1A1b); manufacturing industries and construction (IPCC category 1A2); in agriculture, commercial and institutional settings and residential dwellings (category 1A4); and other non-identified activities (category 1A5). Emissions from fuel combustion for transportation (category 1A3) are discussed in section I.D below.

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Petroleum refineries use catalyst coke, distillate, ethanol, gasoline, LPG, natural gas, petroleum coke, refinery gas and residual fuel oil. Fuels used by manufacturing industries and construction include: biomass & fossil waste fuel, coal, distillate, ethanol, gasoline, kerosene, LPG, natural gas, petroleum & catalyst coke, residual fuel oil, tires, and wood. Fuels used in commercial, institutional and residential settings are: coal, distillate, ethanol, gasoline, kerosene, LPG, natural gas, propane, residual fuel oil, and wood.

The inventory includes the emissions of CO_2, CH_4 and N_2O resulting from the combustion of fossil fuels. Some biomass fuels (biomass waste fuel, wood) are also used as a source of energy. The GHG inventory includes only the CH_4 and N_2O emissions resulting from the combustion of biomass fuels since the CO_2 emissions would have occurred eventually as the biomass decayed. These CO_2 emissions, labeled "from biogenic materials", are estimated and tracked, but are not included in California's GHG inventory total. Other combustibles used as fuels, such as used tires, are made in part from biomass materials (e.g., natural rubber). In this case, two values for CO_2 emissions are estimated in proportion to the biomass and fossil components. Only the CO_2 from the fossil component is included in the inventory total.

2. Methodology

(a) Emission Estimates

The method for estimating emissions follows IPCC 2006 guidelines for stationary combustion (IPCC 2006a). California or US-specific emission factors and heat content values were used when available.

Equation 13: Emissions from stationary combustion

$$E_{GHG,\ fuel} = Q_{fuel} \bullet HC_{fuel} \bullet EF_{GHG,\ fuel}$$

Where,

$E_{GHG,\ fuel}$ = Emissions of the given GHG for the type of fuel (g of GHG)

Q_{fuel} = Quantity of the type of fuel combusted (in units of tons for solid fuels, gallons for liquid fuels or standard cubic feet for gaseous fuels)

HC_{fuel} = Heat content of the type of fuel (BTU / unit)

$EF_{GHG,\ fuel}$ = Emission factor of the given GHG by the type of fuel (g GHG / BTU)

With,

GHG = [CO_2, CH_4, N_2O]

Fuel = [biomass waste fuel, catalyst coke, coal, distillate, ethanol, gasoline, jet fuel, kerosene, LPG, natural gas, petroleum &

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catalyst coke, refinery gas, process gas, residual fuel oil, and wood]

A variant of this estimation method was used to estimate CO_2 emissions in the case of partially renewable fuels. These fuels are a mix of materials from biomass and fossil origins. Used tires are such a fuel.

Equation 14: Variant for partially renewable fuels

$$E_{GHG,\ fuel,\ origin} = E_{GHG,\ fuel} \bullet P_{fuel,\ origin}$$

Where,

$E_{GHG,\ fuel,\ origin}$ = Emissions of the given GHG for proportion of materials of given origin for the type of fuel (g of GHG)

$E_{GHG,\ fuel}$ = Emissions of the given GHG for the type of fuel (g of GHG)

$P_{fuel,\ origin}$ = proportion of material of given origin in the type of fuel (fraction)

With,

GHG = [CO_2]

Fuel = [tires]

Origin = [Fossil, Biomass]

3. Data Sources

The data sources for estimating emissions include CEC's Quarterly Fuels and Energy Report (QFER), CEC's Petroleum Industry Information Reporting Act (PIIRA), the Energy Information Administration State Energy Data System (EIA SEDS), the US Environmental Protection Agency, the Intergovernmental Panel on Climate Change (IPCC), ARB's Mandatory Reporting Program, and selected industry associations.

Fuel use data are primarily from the EIA and CEC. Data on fuel use by petroleum refineries were summarized from the PIIRA database (Schremp 2008, O'Brien 2010) for 2000-2008, and from ARB's Mandatory Reporting Program (ARB 2015b) for 2009+. Natural gas use data were summarized from the QFER database (Gough 2015), except for natural gas use by natural gas pipeline compressor stations, which came from the EIA SEDS (EIA 2013c).

Data for natural gas use by petroleum refineries, taken from PIIRA for 2000-2008, were adjusted to avoid double counting of the amounts that went to cogeneration and hydrogen production by refineries, as they are accounted for in other sections of this inventory. These adjustments were made by calculating the ratio of the amount of natural gas used for these purposes, as reported for 2009 in the Mandatory Reporting database by refineries, to the

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amount reported to PIIRA in 2009. That ratio was then used to adjust the natural gas use data from PIIRA for 2000 to 2008. Data on fuel use by California's cement plants were supplied by the Portland Cement Association (O'Hare 2007) for years 2000 and 2005, and by an ARB survey (ARB 2008) for year 2006. Data reported by cement plants to ARB Mandatory Reporting Program were used for 2008+, and fuel consumption for other years (2001-2004, and 2007) was interpolated between these data values. Distillate, kerosene and residual fuel oil amounts are taken from EIA adjusted Sales values (EIA 2013b). Gasoline and ethanol amounts are detailed later in this section. All other fuel use came from the EIA SEDS (EIA 2013c).

MRR data from refineries that report fuel use and emissions without a CEMS are used as reported in MRR (both heat content and physical quantity). If applicable, the fuel and emissions associated with cogeneration (or Combined Heat and Power, CHP) are taken from this category and recorded in the industrial CHP category, but the total fuel and emissions from both the cogeneration and refinery/hydrogen production add up to the totals reported in MRR.

Facilities that use CEMS report fuel amounts, CH_4 and N_2O emissions based on these fuel amounts and the total measured CEMS CO_2 emissions. The single CEMS CO_2 value is divided among the reported fuels by a simple, three-step, allocation procedure that weights the heat content of each fuel. First each reported fuel amount (both heat and quantity are given in most cases, but in all cases heat is given) is converted into a default CO_2 emissions using the MRR default emission factors for that fuel and the amount of heat reported for that fuel. This assigns each reported fuel an initial, "default" CO_2 emission. The second step then adds up the total of all the "default" CO_2 values calculated in the first step, and compares it to the reported CEMS CO_2 value for that unit. A ratio is then calculated using CEMS CO_2 to total "default" CO_2. The third and final step then takes this ratio and multiplies it across all the default fuel CO_2 values, correcting each one so that the final corrected values now sum to the same CO_2 value reported by the CEMS.

For facilities producing hydrogen, the emissions associated with the hydrogen production is calculated from the reported metric tons of hydrogen produced multiplied by the ratio of CO_2/H_2 which can be determined from the data on carbon and hydrogen content reported by the hydrogen producers in MRR. These process emissions and associated fuel amounts are then deducted from the total reported emissions and fuel amounts for hydrogen production each facility must provide. The remaining fuels and emissions are then added to the fuel emissions category for this sector, as these represent the left over amounts not converted into hydrogen and thus burned as fuel. For hydrogen facilities using CEMS CO2 measurements, emissions are divided using the methodology

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in the previous paragraph. The total hydrogen production process emissions and combustion emissions always add up to the total reported in MRR.

Fugitive emissions reported in MRR (subpart Y) for refineries are used directly as reported.

Table 20: Proportion of ethanol in California's gasoline-ethanol blend

Year	Percent denatured ethanol in the blend	Percent ethanol in denatured ethanol	Percent pure ethanol in blend
2000	0.41%	92.10%	0.38%
2001	0.55%	92.10%	0.51%
2002	0.64%	92.10%	0.59%
2003	3.75%	92.10%	3.46%
2004	5.65%	92.10%	5.21%
2005	6.00%	92.10%	5.53%
2006	6.01%	92.10%	5.54%
2007	6.02%	92.10%	5.55%
2008	6.63%	92.10%	6.11%
2009	6.57%	94.60%	6.21%
2010	10.05%	94.60%	9.50%
2011	10.90%	94.60%	10.31%
2012	10.13%	94.60%	9.58%
2013	10.57%	94.60%	10.00%
2014	11.33%	94.60%	10.72%

Data for 2000 – 2010 on the total use of gasoline-ethanol blend came from the California State Board of Equalization (BOE 2015). The BOE reports the total on-road gasoline blend use and the Federal Highway Administration (FWHA) reports non-road gasoline blend use. Together they make up the total gasoline and ethanol use in the state. The CEC (O'Brien 2010) provided the percent of ethanol in the blend for 2000-2010, while data on amounts of ethanol and gasoline for 2011+ come from ARB's Mandatory Reporting Program (ARB 2015b). The ethanol used in gasoline blends is actually a denatured ethanol which includes up to 5 percent of denaturant (natural gasoline, gasoline components or unleaded gasoline) which renders it undrinkable, in order to avoid alcohol taxes. Thus the percentages of denatured ethanol provided by the CEC or ARB's Mandatory Reporting Program were adjusted to calculate the pure ethanol in California's gasoline blend. This adjustment was based on ASTM D4806 Standard Specification for denatured fuel ethanol for blending with gasoline for use as automotive spark-ignition engine fuel. For 2000 to 2008 the minimum percent volume of pure ethanol in the denatured

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ethanol had to be 92.1 percent, allowing for up to 5 percent denaturant, 1 percent water, 0.5 percent methanol and 1.4 percent other. In 2009+ the percent denaturant was reduced to 2.5 percent, resulting in 94.6 percent pure ethanol in denatured ethanol.

The BOE and FWHA "gasoline" consumption data include the blended ethanol, so the pure ethanol amounts were subtracted from "gasoline" volumes to obtain the pure gasoline consumed in the state. Staff assumed that all inventory categories using "gasoline" used a mix of gasoline and ethanol blended in the same proportions. Staff assumed that the small amount of methanol, water and other substances contained in the denaturant-ethanol blend were grouped as gasoline. These substances amount to around 0.1% of the total fuel volumes, which is much less than the error associated with the emission factor and heat content estimates.

For 2011+, MRR provides an estimate of total gasoline used in California, but does not break down gasoline into on-road and off-road use. Staff distributes MRR total gasoline use into on-road and off-road sectors to allow emission calculations for each sector. Off-road gasoline is calculated by subtracting the BOE on-road gasoline estimates from the total gasoline reported to MRR. Off-road gasoline use is then distributed among equipment types using the relative proportion of gasoline reported by the FHWA. This method ensures that the transportation gasoline use in the ARB GHG emission inventory is equivalent to that reported to MRR.

Also for 2011+, ethanol is broken out from gasoline using MRR ethanol reports. Ethanol reported to MRR includes denaturant which is primarily comprised of gasoline. To estimate the total amount of pure ethanol used in California, the amount of denaturant in the ethanol is estimated, removed from the ethanol totals and added to the gasoline totals. The fraction of reported ethanol that is denaturant is calculated assuming the maximum percentage denaturant allowed. The ratio of total pure ethanol to total gasoline reported to MRR is then used to split gasoline and ethanol for all transportation inventory sectors that burn gasoline (see Table 20 above). Thus the total gallons of gasoline and ethanol in the inventory will match the totals of these fuels reported to MRR.

Heat content values for natural gas are from EIA SEDS (EIA 2013c) when available. Heat content for the various other fuels, except fossil waste fuel, is from ARB's Mandatory Reporting Program (ARB 2015b). Natural gas heat content in the Mandatory Reporting Program is a default value, the same for all sources, while the EIA SEDS is year specific, so for years when natural gas use is not yet available in the EIA SEDS, the Mandatory Reporting Program default is used.

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Unable to locate an authoritative reference for the heat content of the fossil waste fuel used by the cement manufacturing sector, staff assumed that the heat content of an equal mixture of solid biomass and solid fossil fuels would be the best approximation. Thus the heat content for fossil waste fuel is simply the average of those of wood and petroleum coke.

CO_2, CH_4, and N_2O emission factors for fossil waste fuel burned in cement plants are from ARB's Mandatory reporting program (ARB 2015b) if available, otherwise are from the U.S. Environmental Protection Agency GHG Reporting Program (GHGRP) data (USEPA 2012b).

For a list of individual activity and parameter values used in the equations, please consult the online documentation annex at: https://www.arb.ca.gov/cc/inventory/doc/methods_00-14/annex_1c_fuel_combustion_in_industrial_commercial_residential_agricultural_and_other_sectors.pdf

4. Changes in Estimates

No method changes were instituted in this version of the GHG inventory. The methods are the same as that in the previous edition of ARB's GHG inventory.

5. Future Improvements

Staff plans to continue to identify data sets to further refine emissions estimates.

D. Transport (IPCC 1A3)

1. Background

Emissions from the transportation sector include emissions from civil aviation (IPCC category 1A3a); road transportation, also referred to as "on-road" or "highway" vehicles (category 1A3b); railways (category 1A3c); and water-borne navigation (category 1A3d).

The IPCC guidelines recommends separating international from domestic aviation emissions. In the case of a state-level rather than a national inventory, this raises the question of how to treat emissions from interstate flights. Based upon jurisdictional interpretation of IPCC protocols, ARB staff opted to estimate, but not include, the emissions resulting from aviation fuel purchased in California but used for interstate flights. Intrastate aviation was defined as those flights with both origin and destination in California. The aviation fuel purchased in California was apportioned to intrastate and interstate aviation according to miles flown and typical aircraft fuel consumption. Emissions resulting from international flights were also excluded in accordance with

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international convention, and appear as an "excluded line item" in the inventory.

The railways portion of the inventory quantifies emissions based exclusively on fuel purchased in California.

Emissions from on-road vehicles include emissions from passenger cars; light duty trucks (pick-ups, SUVs, and medium-duty vehicles with a gross weight of 8500 lbs or less); heavy-duty trucks over 8500 lbs., buses, motor-homes and motorcycles. The State of California defines vehicle classes by type and/or weight during the vehicle certification process. Emissions from each category were based upon total fuel sales (mostly gasoline blends and diesel blends as sold at the pump reported by BOE) and apportioned based on vehicle fuel consumption from the 2014 version of ARB's EMission FACtors (EMFAC) model. Note that diesel is a common term for on-road distillate and will be used throughout the on-road transportation discussion instead of distillate.

California's water-borne navigation sector includes emissions from shipping activities in California or within 24 nautical miles of the coast (harbor craft, in-port, and transit emissions). All emissions from shipping activities occurring further than 24 nautical miles from California's coast are excluded regardless of trip origin or destination (in accordance with ARB's pre-existing regulatory purview for criteria pollutants). The amount of international bunker fuels used for navigation that were purchased in California in excess of the amount that was combusted within 24 nautical miles from the coast were accounted separately as an informational item. Emissions from these fuels were estimated but excluded from the inventory in accordance with international convention.

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2. Methodology

Staff used two different methodologies to estimate transport emissions. The first is based on the amount of fuel reported and emission factors (consistent with the tier 2 IPCC methodology), and the second is based on emissions/activity modeling (consistent with the tier 3 IPCC methodology). Emissions from on-road vehicles predominantly using gasoline and diesel fuel were based on fuel sales and distributed by vehicle type according to modeling, while water-borne navigation fuel use was modeled then emission factors were applied. Other on-road fuel categories (i.e. fossil natural gas and biomethane) and other transportation categories used IPCC tier 2 methodology based on fuel reported and default emission factors.

2.1 On-road Gasoline & Diesel Vehicles (based on EMFAC model)

The updated 2014 edition of the EMFAC model is used for on-road gasoline and diesel vehicle emissions (ARB 2015d). The 2014 version of EMFAC

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incorporates updated vehicle population and age, based on make, model, and year-specific vehicle population data from the California Department of Motor Vehicles. ARB staff chose to use EMFAC in part because it allows for apportioning fuel sales data (for gasoline and diesel) among different categories of vehicles, and thus for calculating emissions for each of the classes of vehicles. Also, EMFAC has a rigorous scientific foundation (e.g., tailpipe measurements) and multiple versions have been vetted through various stakeholder reviews. Furthermore, the ARB State Implementation Plan (SIP) relies on EMFAC outputs for determining transportation emissions and helping to develop mitigation strategies for criteria pollutants. For the GHG inventory, staff used EMFAC modeled outputs for the amount of fuel combusted, and CH_4 and NO_x emissions (N_2O emissions were derived from NOx emissions). EMFAC outputs were scaled to fuel sales numbers obtained from the BOE.

The EMFAC model is a transportation emission model developed by the ARB to quantify on-road vehicle emissions (THC, CH_4, CO, NO_x, particulate matter, lead, SO_x, etc.). The two primary information sources that feed into the EMFAC model are: 1) activity data (e.g., vehicle miles traveled - VMT) from local and regional transportation surveys and models, and 2) tailpipe emissions tests data from representative vehicle types. EMFAC reports emissions by: a) vehicle type (as listed in Section I.D.1 above), and b) fuel-specific emission control technology. For example, EMFAC has outputs for non-catalyzed gasoline passenger cars and catalyzed gasoline passenger cars.

EMFAC uses a bottom-up approach (local-level data aggregated to the state level) and, therefore, the total fuel consumption computed by EMFAC differs somewhat from the values in top-down fuel inventories based on reported fuel sales. As mentioned above, staff decided to scale EMFAC outputs to match the fuel sales numbers reported by the BOE (and CEC) to maintain a consistent state-level energy balance. This was done by scaling EMFAC model outputs using the ratio of the reported fuel sales over the modeled EMFAC fuel consumption. That way, emission estimates remain consistent with EMFAC outputs (in terms of emissions per gallon combusted for each vehicle type) but the total emissions match the amount of fuel reported by BOE.

In both EMFAC fuel consumption data and BOE fuel sales data, “gasoline” is a blend of gasoline and ethanol. The proportions of ethanol and pure gasoline in this blend have changed from year to year. To allow separate emission estimates for gasoline and ethanol, staff used data from the CEC and MRR (as described in Section I.C.3 Data Sources for Fuel Combustion) to compute the proportion of ethanol in the blend for each year. Since EMFAC does not model the two components of the gasoline-ethanol separately, staff opted to use the emission factors approach to estimate CO_2 emissions. The derivation of the pure gasoline heat content and the choice of appropriate emission factors are discussed in Section I.C.3 above.

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CH_4 emissions are now derived directly from EMFAC 2014 outputs. EMFAC outputs are still scaled to fuel sales, as in previous GHG inventories.

Estimation of the on-road gasoline and diesel vehicle emissions are as follows:

(a) Converting EMFAC outputs per weekday to outputs per year

EMFAC emission outputs are in short tons per weekday (note that some raw EMFAC outputs are in thousand units, such as gallons, and VMT). In order to convert from EMFAC's average weekday outputs (i.e., an average of the five days of the week, excluding Saturday and Sunday) to a full year, staff multiplied EMFAC outputs by annual conversion factors based on differences between weekday and weekend activity levels for each vehicle category (Table 2).

Equation 15: Conversion of emissions per weekday to emissions per year

$$Y = W \bullet C \bullet 0.90718474$$

Where,

Y = Emission value in tonnes per year

W = Emission value in short tons per average weekday

C = Annual conversion factor to convert from average weekday value to annual total for a given vehicle category (from Table 21)

0.90718474 = factor to convert short tons to metric tonnes

Table 21: Factors to convert each vehicle category's activity (weekday to annual)

Vehicle & Technology	***Annual Conversion Factor***	***Mapping to GHG Inventory Vehicle Categories***
All Other Buses - DSL	292	heavy duty
LDA - DSL	347	light duty vehicle- passenger car
LDA - GAS	347	light duty vehicle- passenger car
LDT1 - DSL	347	light duty vehicle- light duty (aka passenger) trucks/SUVs
LDT1 - GAS	347	light duty vehicle- light duty (aka passenger) trucks/SUVs
LDT2 - DSL	347	light duty vehicle- light duty (aka passenger) trucks/SUVs
LDT2 - GAS	347	light duty vehicle- light duty (aka passenger) trucks/SUVs
LHD1 - DSL	327	heavy duty
LHD1 - GAS	327	heavy duty
LHD2 - DSL	327	heavy duty
LHD2 - GAS	327	heavy duty
MCY - GAS	347	light duty vehicle- motorcycle
MDV - DSL	347	light duty vehicle- light duty (aka

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Vehicle & Technology	***Annual Conversion Factor***	***Mapping to GHG Inventory Vehicle Categories***
		passenger) trucks/SUVs
MDV - GAS	347	light duty vehicle- light duty (aka passenger) trucks/SUVs
MH - DSL	327	heavy duty
MH - GAS	327	heavy duty
Motor Coach - DSL	292	heavy duty
OBUS - GAS	327	heavy duty
PTO - DSL	312	heavy duty
SBUS - DSL	327	heavy duty
SBUS - GAS	327	heavy duty
T6 Ag - DSL	312	heavy duty
T6 CAIRP heavy - DSL	312	heavy duty
T6 CAIRP small - DSL	312	heavy duty
T6 instate construction heavy - DSL	312	heavy duty
T6 instate construction small - DSL	312	heavy duty
T6 instate heavy - DSL	312	heavy duty
T6 instate small - DSL	312	heavy duty
T6 OOS heavy - DSL	312	heavy duty
T6 OOS small - DSL	312	heavy duty
T6 Public - DSL	312	heavy duty
T6 utility - DSL	312	heavy duty
T6TS - GAS	327	heavy duty
T7 Ag - DSL	312	heavy duty
T7 CAIRP - DSL	312	heavy duty
T7 CAIRP construction - DSL	312	heavy duty
T7 NNOOS - DSL	312	heavy duty
T7 NOOS - DSL	312	heavy duty
T7 other port - DSL	312	heavy duty
T7 POAK - DSL	312	heavy duty
T7 POLA - DSL	312	heavy duty
T7 Public - DSL	312	heavy duty
T7 Single - DSL	312	heavy duty
T7 single construction - DSL	312	heavy duty
T7 SWCV - DSL	312	heavy duty
T7 tractor - DSL	312	heavy duty
T7 tractor construction - DSL	312	heavy duty
T7 utility - DSL	312	heavy duty
T7IS - GAS	327	heavy duty
UBUS - DSL	327	heavy duty
UBUS - GAS	327	heavy duty

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(b) Scaling EMFAC outputs to match reported fuel sales

Staff accounted for differences between EMFAC fuel consumption and reported fuel sales values by calculating fuel-specific ratios for each year of the inventory, as follows:

Equation 16: Ratio of EMFAC fuel combustion to reported fuel sales

$$R_{fuel,\,year} = \frac{S_{fuel,\,year}}{M_{fuel,\,year}}$$

Where,

$R_{fuel,\,year}$ = Ratio of reported fuel sales to EMFAC modeled fuel combustion for a given fuel in a given year

$S_{fuel,\,year}$ = reported fuel sales of the given fuel in the given year (gallons)

$M_{fuel,\,year}$ = modeled fuel consumption of the given fuel in the given year (gallons)

With,

Fuel = [gasoline-ethanol blend, diesel blend]

Year = [2000 – 2014]

Table 22: Ratio of EMFAC modeled fuel combustion to reported fuel sales

Year	Fuel	Source	Reported (gal)	EMFAC (gal)	Ratio
2000	Gasoline-ethanol blend	BOE	14,760,642,277	14,854,521,063	0.993680120
2001	Gasoline-ethanol blend	BOE	14,873,287,328	14,974,619,512	0.993233071
2002	Gasoline-ethanol blend	BOE	15,497,850,137	15,623,665,999	0.991947097
2003	Gasoline-ethanol blend	BOE	15,660,106,873	15,849,299,959	0.988063000
2004	Gasoline-ethanol blend	BOE	15,882,228,670	16,172,230,459	0.982067916
2005	Gasoline-ethanol blend	BOE	15,912,767,049	16,189,185,002	0.982925765
2006	Gasoline-ethanol blend	BOE	15,802,491,301	16,143,192,555	0.978895051
2007	Gasoline-ethanol blend	BOE	15,644,532,462	15,977,349,137	0.979169468
2008	Gasoline-ethanol blend	BOE	15,007,122,838	15,311,004,402	0.980152735
2009	Gasoline-ethanol blend	BOE	14,791,632,891	15,189,522,999	0.973804964
2010	Gasoline-ethanol blend	BOE	14,851,505,738	15,184,580,322	0.978064946
2011	Gasoline-ethanol blend	BOE	14,583,411,578	14,885,198,863	0.979725680
2012	Gasoline-ethanol blend	BOE	14,487,897,816	14,593,712,753	0.992749279
2013	Gasoline-ethanol blend	BOE	14,516,519,877	14,374,193,920	1.009901491
2014	Gasoline-ethanol blend	BOE	14,686,723,856	14,440,544,810	1.017047767
2000	Diesel blend	BOE	2,632,760,095	2,660,379,546	0.989618229
2001	Diesel blend	BOE	2,627,365,783	2,666,890,335	0.985179536
2002	Diesel blend	BOE	2,700,122,539	2,757,421,172	0.979220210
2003	Diesel blend	BOE	2,667,933,637	2,781,714,949	0.959096703

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Year	Fuel	Source	Reported (gal)	EMFAC (gal)	Ratio
2004	Diesel blend	BOE	2,842,332,046	2,952,751,396	0.962604590
2005	Diesel blend	BOE	2,963,733,672	3,071,891,727	0.964791059
2006	Diesel blend	BOE	2,994,049,134	3,141,453,525	0.953077647
2007	Diesel blend	BOE	3,082,740,281	3,191,774,423	0.965839020
2008	Diesel blend	BOE	2,827,526,205	2,922,281,862	0.967574772
2009	Diesel blend	BOE	2,580,139,949	2,682,967,285	0.961674025
2010	Diesel blend	BOE	2,590,655,088	2,703,263,445	0.958343551
2011	Diesel blend	BOE	2,622,534,125	2,724,183,652	0.962686243
2012	Diesel blend	BOE	2,603,545,631	2,725,962,176	0.955092354
2013	Diesel blend	BOE	2,740,305,658	2,771,644,965	0.988692885
2014	Diesel blend	BOE	2,776,180,358	2,825,543,622	0.982529640

EMFAC outputs can then be scaled to the reported fuel sales by using the ratios from Table 22 and the following equation:

Equation 17: Scaling of EMFAC outputs to reported fuel sales

$$Z_{type,fuel,year} = Y_{\text{type, fuel, year}} \bullet R_{fuel,year}$$

Where,

$Z_{\text{type, fuel, year}}$ = Scaled EMFAC output value for a particular vehicle type using a given fuel in a given year

$Y_{\text{type, fuel, year}}$ = Modeled output value for a particular vehicle type using a given fuel in a given year

$R_{\text{fuel, year}}$ = Ratio of reported fuel sales to EMFAC modeled fuel combustion for a given fuel in a given year

With,

Type = [passenger cars, light duty trucks, heavy-duty trucks, buses, motorhomes, motorcycles]

Fuel = [gasoline-ethanol blend, diesel blend]

Year = [2000 – 2014]

(c) Proportions of gasoline versus ethanol, and fossil diesel versus biodiesel and renewable diesel, in the fuel blends sold at the pump

Both the EMFAC modeled fuel use and the BOE reported fuel sales data are in fact amounts of an unspecified fuel blend which includes non-fossil fuel components. To allow for the separate analysis of pure fossil fuel (gasoline and diesel) versus pure biofuels (ethanol, biodiesel, and renewable diesel), staff calculated the yearly proportions of pure biofuel in the blend and the proportion of fossil fuel by difference.

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Equation 18: Proportion of fossil fuel in the blend

$$P_{FossilFuel,\,year} = 1 - P_{Biofuel,\,year}$$

Where,

$P_{Fossil\ fuel,\ year}$ = Proportion of fossil fuel in the blend for a given fuel in a given year

$P_{Biofuel,\ year}$ = Proportion of biofuel in the blend for a given fuel in a given year.

With,

Year = [2000 – 2014]

Gasoline-ethanol annual proportions are assumed to be constant across all sectors (industrial, transportation, etc.) and are calculated in section I.C above (see Table 20). The biofuels components of on-road transportation diesel are reported by BOE (Covert 2013, BOE 2015). The biodiesel and renewable diesel totals are subtracted from the total on-road diesel blend volume, and the remainder is considered fossil diesel. A summary of fossil diesel, biodiesel and renewable diesel fuel used for on-road transportation are reported in Table 23.

Table 23. Fossil diesel, biodiesel, and renewable diesel consumed by on-road transportation.

Year	***Fossil Diesel (gallons)***	***Biodiesel (gallons)***	***Renewable Diesel (gallons)***
2000	2,630,760,095	2,000,000	0
2001	2,624,865,783	2,500,000	0
2002	2,696,122,539	4,000,000	0
2003	2,667,033,637	900,000	0
2004	2,840,932,046	1,400,000	0
2005	2,961,163,237	2,570,435	0
2006	2,974,438,787	19,610,347	0
2007	3,065,281,223	17,459,058	0
2008	2,815,824,095	11,702,110	0
2009	2,573,218,825	6,921,124	0
2010	2,583,286,837	5,398,081	1,970,170
2011	2,602,519,606	18,211,031	1,803,488
2012	2,573,961,746	20,477,781	9,106,104
2013	2,555,554,814	48,969,002	135,781,842
2014	2,614,724,120	56,908,662	104,547,576

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The fossil and biofuel contributions to emissions of fuel blends can be calculated in their pure form using their respective proportions in the blend.

Equation 19: Calculating pure fuel quantities from scaled EMFAC output values to each component of a fuel blend

$$U_{type,fuel,year} = Z_{type,blend,year} \bullet P_{fuel,year}$$

Where,

$U_{fuel,year}$ = Pure fuel value for a particular vehicle type using the given fuel in a given year

$Z_{type,blend,year}$ = Scaled EMFAC output value for a particular vehicle type using gasoline-ethanol blend or diesel blend in a given year (from Equation 17)

$P_{fuel,year}$ = Proportion of fuel in the blend (from Table 20 and Equation 18)

With,

Type = [passenger cars, light duty trucks, heavy-duty trucks, buses, motorhomes, motorcycles]

Blend = [Gasoline-ethanol or Diesel blend]

Fuel = [Gasoline, Ethanol, Diesel, Biodiesel, Renewable Diesel]

Year = [2000 – 2014]

(d) Calculating CO_2 emissions

Emissions of CO_2 are estimated with the emissions factors method. Vehicles combusting a blend of fossil fuel and biofuel(s) involves factors to separate the emissions of each of the fuel components in a blend.

Equation 20: CO_2 emissions from on road transport (gasoline-ethanol and diesel vehicles)

$$E_{type,fuel,year} = (V_{type,blend,year} \bullet R_{blend,year}) \bullet P_{fuel,year} \bullet HC_{fuel} \bullet EF_{CO2,fuel}$$

Where,

$E_{type,fuel,year}$ = CO_2 emissions of a particular vehicle type using the given fuel in the given year (g of CO_2)

$V_{type,blend,year}$ = Amount of gasoline-ethanol blend or diesel blend combusted by the particular type of vehicle in a given year (gallons) as modeled with EMFAC

$R_{blend,year}$ = Scaling factor for the blend in the given year (from Table 22)

$P_{fuel,year}$ = Proportion of the given fuel in the blend (from Table 20 and Equation 18)

HC_{fuel} = Heat content of the given fuel (BTU / unit)

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$EF_{CO_2, fuel}$ = CO_2 emission factor for given fuel (g CO_2 / BTU)

With,

Type = [passenger cars, light duty trucks, heavy-duty trucks, buses, motorhomes,, motorcycles]

Blend = [gasoline-ethanol blend, diesel blend]

Fuel = [ethanol, gasoline, diesel, biodiesel, renewable diesel]

Year = [2000 – 2014]

(e) Calculating CH_4 emissions

CH_4 emissions are from EMFAC 2014 scaled to the reported fuel sales with Equation 17. In the case of gasoline-ethanol powered vehicles, the yearly proportions of gasoline and ethanol in the gasoline-ethanol blend are then used to separate the respective share of emissions from gasoline and ethanol (using Equation 19).

(f) Calculating N_2O emissions

We calculated N_2O emissions from gasoline vehicles by establishing a correlation between ARB tailpipe test measurements of NO_x and N_2O emissions. For every gram of NO_x emitted from gasoline vehicles, an average of 0.0416 grams of N_2O is emitted. That is:

Equation 21: Correlating N_2O emissions to NO_x emissions (gasoline vehicles)

$$E_{N_2O} = 0.0416 \bullet O_{NOx}$$

Where,

E_{N_2O} = N_2O emissions of gasoline vehicles (grams)

0.0416 = emission of N_2O for every unit of NO_x emitted

O_{NO_x} = scaled EMFAC output for NO_x emitted by that category of vehicles (grams)

Equation 21 was used for each vehicle type and year and results were adjusted using the ratio of reported fuel sales from Equation 17. Then the respective share of N_2O emissions of gasoline and ethanol were estimated using Equation 19.

Based on ongoing ARB-supervised diesel tailpipe research, staff determined that the N_2O emission factor for diesel vehicles was 0.3316 grams of N_2O per gallon. Diesel vehicle N_2O emissions are computed by multiplying this emission factor by BOE diesel fuel sales, for each category of vehicles:

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Equation 22: Transportation - on road N_2O emissions (diesel vehicles)

$$E_{N_2O} = V \bullet EF_{N_2O}$$

Where,

E_{N_2O}	= N_2O emissions of a type of diesel vehicles (grams)
V	= Fuel consumption of that type of diesel vehicles (gallons) scaled to reported fuel sales with Equation 17
EF_{N_2O}	= Emission factor for diesel vehicles (0.3316 grams per gallon)

Methodologies for on-road vehicles running on fossil natural gas and biomethane, airplanes, trains, and ships are similar, and are discussed in the next section.

2.2 On-road natural gas vehicles, airplanes, trains, ships

Staff used the amount of fuel combusted along with emission factors to estimate emissions from on-road fossil natural gas and biomethane-fueled vehicles, airplanes, trains, ships, and from a few unspecified uses of fuel combustion for transportation; consistent with IPCC tier 2 methodology. IPCC assumes 100 percent combustion efficiency, as reflected in the following equations. Staff did not estimate indirect emissions resulting from the energy consumed by electric vehicles in the transportation sector because those emissions occur upstream (during electricity generation) and are discussed under Section I.A above.

(a) Apportionment of aviation fuel data

For the reasons discussed in section I.D.1 above, staff apportioned aviation fuel use among intrastate, interstate and international flights. Statistics from the US Department of Transportation (USDOT) are available for all commercial airlines' flights taking off and/or landing in California which allows for distinguishing intrastate flights from interstate and international ones. Such statistics were not available for military flights and general aviation flights. General aviation flights are private and commercial flights other than military, scheduled airline or regular cargo flights. This led staff to focus on the apportionment of jet fuel used by scheduled airlines which, as estimated in section I.D.2.2(a.i) below, constitutes approximately 90 percent of the jet fuel sold in California.

ARB staff retrieved data for total jet fuel sold within California from the Energy Information Administration (EIA 2013b) typically, aircrafts do not carry significant extra fuel, or fuel for a continuing flight, since that would add to the weight being transported, and thus to the fuel consumed and the costs incurred. Thus, the amount of aviation fuel sold within California should

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approximate the amount of fuel consumed on all flights originating in California.

(a.i) Commercial airlines versus general aviation and military aircrafts

The first step was to distribute the jet fuel sold in California between general aviation, military activity, and scheduled commercial flights. California's taxable general aviation jet fuel is reported by BOE. CEC only reports military jet fuel from 2004 onward so historical data was estimated by assuming that the amount of fuel obtained for 2004-2010 (O'Brien 2010) fluctuated in proportion with the amount of fuel consumed by military aviation nationwide (i.e. USA military jet fuel Tbtu for each calendar year 2000-2003 was multiplied by scaling factor 1,298,720 to estimate the *scaled fuel). The amount of fuel used nationwide for military activity is reported in the USEPA annual GHG inventory (USEPA 2015g). Staff then assigned the remainder of the aviation fuel to commercial airlines activity (Table 24).

Table 24: Estimation of California commercial jet fuel use (gallons)

Year	Total CA Jet Fuel (from EIA)	CA General Aviation	USA Military Jet Fuel (Tbtu)	CA Military jet fuel (*scaled)	CA commercial airlines jet fuel (by difference)
2000	4,326,042,000	121,428,020	292.5	*379,856,351	3,824,757,629
2001	4,083,072,000	128,008,285	318.5	*413,660,159	3,541,403,556
2002	4,315,752,000	125,254,189	284.9	*370,044,631	3,820,453,180
2003	4,188,282,000	126,076,880	286.6	*372,181,710	3,690,023,410
2004	4,427,136,000	141,395,642	294.8	339,343,349	3,946,397,009
2005	4,393,704,000	148,400,808	251.0	336,774,630	3,908,528,562
2006	4,468,926,000	147,011,420	226.2	305,384,496	4,016,530,084
2007	4,653,348,000	155,414,192	223.3	285,390,657	4,212,543,151
2008	4,235,112,000	141,712,863	224.7	272,713,681	3,820,685,456
2009	4,115,370,000	106,573,334	195.5	260,519,367	3,748,277,299
2010	4,031,496,000	119,296,386	173.0	262,755,664	3,649,443,950
2011	4,071,984,000	121,155,444	.	234,600,600	3,716,227,956
2012	3,967,908,000	128,434,645	.	292,165,000	3,547,308,355
2013	4,170,852,000	134,789,361	.	241,822,523	3,794,240,116
2014	4,409,454,000	127,685,818	.	241,822,523	4,039,945,659

(a.ii) Intrastate versus Interstate and International

In a second step, commercial airlines fuel consumption was subdivided among intrastate, interstate, and international flights. First, staff downloaded data regarding flight activity from the USDOT's Air Carrier Statistics database

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of T-100 flight segments (USDOT 2013). Based on the airports of departure and arrival, these flights were subdivided into three categories:

1. Flights originating and ending in California (intrastate)
2. Flights originating in California but ending in another state (interstate from CA)
3. Flights originating in California but ending in another country (international from CA)

These flight categories should all consume fuel purchased in CA — thus contributing to the amounts in the last column of Table 24. For example, in 2007, the database indicated that 402,758 intrastate flights occurred in California; 583,247 interstate flights originated in California; and 88,510 international flights originated in CA.

For each flight, the USDOT Air Carrier Statistics database also provides information on the type of aircraft and the length of the flight in miles. In the 2000-2004 edition of ARB's GHG Inventory staff had used distance to apportion fuel use into interstate, intrastate and international amounts. However, this approach introduces a bias because it does not account for the impact of the size of the airplane on fuel consumption and, since smaller airplanes are used on shorter distances, they are used for a higher proportion of intrastate flights than of interstate or international ones. In 2007, eighty five different types of airplanes were used by airlines operating in California with a wide range of maximum takeoff weight: from the 3.3 tonnes of the Cessna 208 Caravan to the 365 tonnes of the Airbus A340-600 and 405 tonnes of the Antonov 124 (a cargo plane).

For each of these aircrafts, ARB staff estimated a fuel consumption factor that could be applied to each flight as a function of distance. These fuel consumption factors were based on data from the European Environment Agency (EEA) 2007 EMEP/CORINAIR Air Pollutant Emissions Inventory Guidebook (EEA 2007). The Guidebook contains fuel consumption, as a function of flight distance, for 26 main aircraft types. For each aircraft type, the fuel consumption is subdivided into the fuel associated with the landing/takeoff phase of the flight and the fuel consumed during the other phases (Figure 2). An example of the data from the Guidebook is shown in Table 25.

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Figure 2: Standard flying cycles (from EMEP/CORINAIR Guidebook)

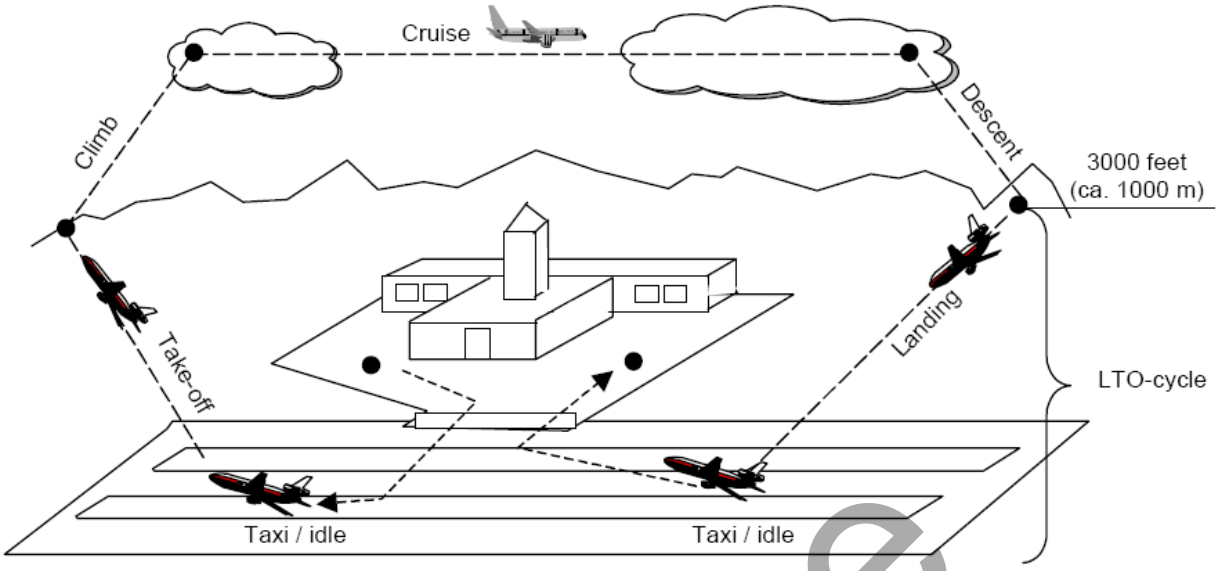

Table 25: Example of typical fuel consumption (from EMEP/CORINAIR Guidebook)

Aircraft Type: Boeing 737-400							
Standard flight distances (nautical miles) [1 nautical mile = 1.15078 statute mile]							
Climb / Cruise / Descent	125	250	500	750	1000	1500	2000
Corresponding fuel use (kilograms)							
Landing & Take Off (LTO)	825.4	825.4	825.4	825.4	825.4	825.4	825.4
Climb / Cruise / Descent	777.7	1442.6	2787.4	4134.9	5477.2	8362.3	11342.2
Flight total	**1603.1**	**2268**	**3612.8**	**4960.3**	**6302.6**	**9187.7**	**12167.6**

ARB staff used the EMEP/CORINAIR fuel consumption data to construct a linear formula that would estimate fuel consumption as a function of distance for each of the 26 aircraft. The coefficients for the resultant formulae are shown in Table 26.

Table 26: Fuel consumption factors estimated for aircraft listed in the EMEP EEA Inventory.

Aircraft IATA code	***Aircraft***	***Engine type***	***LTO Fuel (kg)***	***Cruise Fuel (kg/mi)***	***Max Takeoff Weight (kg)***
405	Beech 1900 A/B/C/D	Turboprop	59.9	0.78	7,688
416	Cessna 208 Caravan	Turboprop	28.8	0.49	3,310
442	Aerospatiale/Aeritalia Atr-72	Turboprop	135.9	1.49	22,000
449	Dornier 328	Turboprop	123.9	1.20	13,990
450	Fokker Friendship F-27/Fairchild F-	Turboprop	158.2	1.58	20,410

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Aircraft IATA code	Aircraft	Engine type	LTO Fuel (kg)	Cruise Fuel (kg/mi)	Max Takeoff Weight (kg)
	27/A/B/F/J				
456	Saab-Fairchild 340/B	Turboprop	74.9	1.19	13,155
482	Dehavilland Dhc8-400 Dash-8	Turboprop	180.9	2.64	27,330
556	Lockheed L100-30/L-382e	Turboprop	272.0	5.96	70,310
602	Fokker F28-4000/6000 Fellowship	Turbofan	666.1	3.89	33,110
603	Fokker 100	Turbofan	744.4	4.12	43,090
617	Boeing 737-400	Turbofan	825.4	4.87	62,820
620	Boeing 737-100/200	Turbofan	919.7	4.58	52,390
622	Boeing 757-200	Turbofan	1,253.0	6.19	108,860
626	Boeing 767-300/300er	Turbofan	1,617.1	8.49	181,890
627	Boeing 777-200/200lr/233lr	Turbofan	2,562.8	12.30	286,897
640	Mcdonnell Douglas Dc-9-30	Turbofan	876.1	4.95	64,885
656	Mcdonnell Douglas Md-90	Turbofan	1,003.1	5.59	67,800
692	Airbus Industrie A310-200c/F	Turbofan	1,540.5	7.81	150,000
694	Airbus Industrie A320-100/200	Turbofan	802.3	4.42	77,000
696	Airbus Industrie A330-200	Turbofan	2,231.5	10.43	230,000
715	Boeing 727-200/231a	Turbofan	1,412.8	7.17	95,030
730	Mcdonnell Douglas Dc-10-10	Turbofan	2,381.2	14.48	263,085
816	Boeing 747-100	Turbofan	3,413.9	19.20	340,195
819	Boeing 747-400	Turbofan	3,402.2	17.51	362,875
867	British Aerospace Bae-146-200	Turbofan	569.5	4.44	42,185
873	Airbus Industrie A340-200	Turbofan	2,019.9	11.34	260,000

For each aircraft, the fuel consumption is subdivided into the fuel associated with the landing/takeoff (LTO) of the aircraft and the fuel consumed during the climb, cruise and descent ("cruise") phase. The fuel consumed during the landing and takeoff is assumed independent of the flight distance for all aircrafts. In EMEP/CORINAIR tables, the fuel consumed during the landing and takeoff of smaller aircraft is somewhat affected by flight distance – presumably because smaller aircraft travel at different elevations and project from the ground at different angles depending on flight distance. This factor was considered negligible in the context of the overall inventory and ignored for simplification sake. The EMEP/CORINAIR fuel consumptions associated with the cruise phase were linear for most aircraft and thus assumed linear for all aircrafts for estimation purposes.

For example, using Table 26, the fuel consumed during a 2,850 mile flight by a Boeing 737-400 would be approximated as 825 kg of fuel during the landing/takeoff phase and 4.87 kg of fuel for each mile flown between takeoff and landing (i.e. 825 + 4.87*2850) for a total of 14,704 kg of fuel. A 600-mile flight of a de Havilland Dhc8-400 Dash-8 would consume approximately (181 + 2.64*600 =) 1,765 kg of fuel.

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In addition to the 26 aircraft types listed in the EMEP/CORINAIR guidebook, the flight activity originating in California between 2000 and 2008 comported approximately 80 other aircraft types. To estimate the fuel consumption associated with these aircraft, staff assumed that the fuel consumed by an aircraft during its flight cycle is largely proportional to its size. Because the exact size of an aircraft can vary between flights due to its payload, staff used the aircraft's maximum takeoff weight as representative of its size.

The equations to estimate fuel consumption of aircrafts based on their takeoff weight were fitted by least-square regression using the maximum takeoff weight values for each of the 26 EMEP aircraft types (shown in Table 26). Staff separated the aircrafts in 2 groups based on engine type (turboprop vs. turbofan) because doing so yielded better fitting equations. The equations are as follow:

Equation 23: Fuel consumption regressions for turboprop aircrafts

$$F_{LTO} = 0.58 + 0.0082 \bullet W - 6.2 \bullet 10^{-8} \bullet W^2)$$
$$F_{Cruise} = 0.064 + 8.325 \bullet 10^{-5} \bullet W$$

Where,

F_{LTO} = Amount of fuel consumed in the Landing and Take-off phase of the flight (kg)

F_{Cruise} = Amount of fuel consumed during the climb/cruise/descent phase of the flight (kg/mile)

W = Maximum takeoff weight (kg)

Equation 24: Fuel consumption regressions for turbofan aircrafts

$$F_{LTO} = 546.49 + 0.0047 \bullet W - 8.86 \bullet 10^{-9} \bullet W^2)$$
$$F_{Cruise} = 3.61 + 1.6 \bullet 10^{-5} \bullet W + 6.94 \bullet 10^{-11} \bullet W^2$$

Where,

F_{LTO} = Amount of fuel consumed in the Landing and Take-off phase of the flight (kg)

F_{Cruise} = Amount of fuel consumed during the climb/cruise/descent phase of the flight (kg/mile)

W = Maximum takeoff weight (kg)

The fuel consumption factors estimated with the regression model are shown in Table 27.

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Table 27: Fuel consumption factors estimated for aircraft not listed in the EMEP EEA Inventory.

Aircraft Type	Aircraft	LTO Fuel (kg)	Cruise fuel (kg/mile)	Max Takeoff Weight (kg)
79	Piper Pa-32 (Cherokee 6)	13.86	0.20	1,633
110	Beechcraft Beech 18 C-185	36.29	0.44	4,490
430	Convair Cv-580	174.42	2.26	26,371
441	Aerospatiale/Aeritalia Atr-42	126.50	1.53	17,650
448	Dornier 228	52.02	0.61	6,575
461	Embraer Emb-120 Brasilia	87.02	1.02	11,500
464	Embraer Emb-110 Bandeirante	46.23	0.55	5,800
467	Swearingen Metro Iii	54.42	0.64	6,900
469	British Aerospace Jetstream 31	54.79	0.64	6,950
470	Gulfstream I	117.00	1.40	16,100
471	British Aerospace Jetstream 41	82.92	0.97	10,900
479	Pilatus Pc-12	38.20	0.46	4,740
483	Dehavilland Dhc8-100 Dash-8	114.18	1.37	15,650
484	Dehavilland Dhc8-300 Dash 8	137.46	1.69	19,500
485	Dehavilland Twin Otter Dhc-6	38.38	0.46	4,763
489	Shorts 360	90.24	1.06	11,975
491	Dehavilland Dhc8-200q Dash-8	119.26	1.43	16,465
507	Antonov 12	271.36	5.14	61,000
520	Canadair Cl-44d	220.55	7.99	95,250
550	Lockheed L-188a/C Electra	261.65	4.45	52,664
552	Lockheed L-382b	271.99	5.92	70,300
555	Lockheed L100-20 Hercules	271.99	5.92	70,310
560	Shorts Belfast Freighter-Sh5	208.59	2.89	34,000
601	Fokker F28-1000 Fellowship	691.31	4.13	29,000
604	Fokker 70	739.29	4.32	38,000
608	Boeing 717-200	818.97	4.64	52,390
609	Bombardier Bd-100-1a10 Challenger 300	632.60	3.91	17,600
612	Boeing 737-700/700lr	864.51	4.83	60,330
614	Boeing 737-800	924.68	5.08	70,535
616	Boeing 737-500	818.97	4.64	52,390
619	Boeing 737-300	843.78	4.74	56,740
621	Boeing 737-200c	818.97	4.64	52,390
623	Boeing 757-300	1259.47	6.61	122,470
624	Boeing 767-400/Er	1882.42	9.77	204,120
625	Boeing 767-200/Er/Em	1650.94	8.56	175,540
628	Canadair Rj-100/Rj-100er	652.55	3.99	21,523
629	Canadair Rj-200er /Rj-440	665.49	4.03	24,040
630	Mcdonnell Douglas Dc-9-10	756.14	4.38	41,100
631	Canadair Rj-700	711.84	4.21	32,885
632	Dornier 328-300	622.84	3.88	15,660

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Aircraft Type	Aircraft	LTO Fuel (kg)	Cruise fuel (kg/mile)	Max Takeoff Weight (kg)
633	Boeing 737-600	840.94	4.73	56,245
634	Boeing 737-900	950.61	5.20	74,840
635	Mcdonnell Douglas Dc-9-15f	811.11	4.61	51,000
636	Cessna Citation Ii/ Bravo	579.35	3.72	6,850
637	Boeing 777-300/300er/333er	2405.68	12.62	263,080
638	Canadair Crj 900	731.27	4.29	36,514
639	Cessna Citationjet/Cj1/Cj2/Cj3	569.49	3.69	4,812
641	Gulfstream Aerospace G-Iii/G-Iv	713.52	4.22	33,200
642	Raytheon Beechcraft Hawker 400xp	581.54	3.73	7,300
643	1124a Westwind Ii	597.99	3.79	10,660
644	Airbus Industrie A-318	909.56	5.02	68,000
645	Mcdonnell Douglas Dc-9-40	833.16	4.70	54,885
646	Cessna Citation X Model 650/550b/550xl	626.43	3.89	16,375
647	Cessna Citation X Model Ce750 X	626.43	3.89	16,375
648	Gulfstream G200	624.95	3.89	16,080
650	Mcdonnell Douglas Dc-9-50	833.16	4.70	54,885
651	Gulfstream G150	603.82	3.81	11,840
652	Canadair CL-600 Challenger	642.48	3.95	19,550
654	Mcdonnell Douglas Dc9 Super 87	883.03	4.91	63,505
655	Mcdonnell Douglas Dc9 Super 80/Md81/82/83/88	883.03	4.91	63,505
657	Bombardier Crj 705	731.21	4.29	36,504
658	Bombardier Bd-700 Global Express	767.06	4.43	43,091
665	Hawker Siddeley 125	599.67	3.79	11,000
667	Gulfstream Iii/V/ G-V Exec/ G-5/550	752.16	4.37	40,370
668	Canadair (Bombardier) Challlenger 601	642.74	3.95	19,600
669	Bombardier Challenger 604/605	654.30	3.99	21,865
671	Gulfstream G450	715.23	4.22	33,520
673	Embraer ERJ-175	743.56	4.33	38,790
674	Embraer-135	639.69	3.94	19,000
675	Embraer-145	647.83	3.97	20,600
676	Embraer-140	650.38	3.98	21,100
677	Embraer 170	725.55	4.26	35,450
678	Embraer 190	788.64	4.51	46,990
679	Grumman G-1159 Gulfstream Ii/Iii	700.05	4.17	30,660
681	Dassault-Breguet Mystere-Falcon	588.64	3.76	8,755
682	Dassault Falcon 2000ex	637.66	3.93	18,600
683	Boeing B777-F	3265.37	17.57	347,800
684	Raytheon Beechcraft Hawker 800xp	608.08	3.82	12,700
686	Learjet45	590.62	3.76	9,160
687	Airbus A330-300	2148.80	11.20	235,000
689	Airbus Industrie A330-600st (Beluga)	1493.51	7.76	155,000
690	Airbus Industrie A300b/C/F-100/200	1018.81	5.50	85,910

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Aircraft Type	Aircraft	LTO Fuel (kg)	Cruise fuel (kg/mile)	Max Takeoff Weight (kg)
691	Airbus Industrie A300-600/R/Cf/Rcf	1611.61	8.35	170,500
693	Airbus Industrie A310-300	1456.32	7.57	150,000
695	Airbus Industrie A300-B2	1397.73	7.28	142,000
697	Airbus Industrie A340	2518.95	13.26	275,000
698	Airbus Industrie A319	885.94	4.92	64,000
699	Airbus Industrie A321	1038.24	5.58	89,000
710	Boeing 727-100	936.90	5.14	72,570
711	Boeing 727-100c/Qc	936.90	5.14	72,570
732	Mcdonnell Douglas Dc-10-30	2405.73	12.62	263,085
733	Mcdonnell Douglas Dc-10-40	2371.69	12.43	259,450
735	Mcdonnell Douglas Dc-10-30cf	2405.73	12.62	263,085
740	Mcdonnell Douglas Md-11	2502.78	13.17	273,314
760	Lockheed L-1011-1/100/200	1943.48	10.09	211,375
765	Lockheed L-1011-500 Tristar	2116.25	11.02	231,330
770	Dassault Falcon 900	648.03	3.97	20,640
771	Dassault Falcon 50	632.60	3.91	17,600
775	Dassault Falcon 7x	703.57	4.18	31,325
780	Tupolev Tu-154	1115.27	5.93	101,000
800	Boeing 707-100	1219.24	6.42	116,600
806	Boeing 707-300	1465.94	7.62	151,300
808	Boeing 707-300b	1465.94	7.62	151,300
809	Boeing 707-300c	1465.94	7.62	151,300
817	Boeing 747-200/300	3306.19	17.81	351,535
818	Boeing 747c	3431.66	18.56	362,875
820	Boeing 747-400f	3431.66	18.56	362,875
822	Boeing 747sp	2943.45	15.69	317,515
840	Mcdonnell Douglas Dc-8-10	1268.67	6.65	123,800
848	Mcdonnell Douglas Dc-8-50	1354.54	7.07	136,000
850	Mcdonnell Douglas Dc-8-50f	1419.57	7.39	145,000
851	Mcdonnell Douglas Dc-8-61	1437.26	7.48	147,415
852	Mcdonnell Douglas Dc-8-63f	1521.77	7.90	158,760
854	Mcdonnell Douglas Dc-8-62	1470.77	7.64	151,950
856	Mcdonnell Douglas Dc-8-63	1521.77	7.90	158,760
860	Mcdonnell Douglas Dc-8-71	1546.51	8.02	162,025
862	McDonnell Douglas DC-8-72	1546.51	8.02	162,025
864	Mcdonnell Douglas Dc-8-73	1546.51	8.02	162,025
865	Mcdonnell Douglas Dc-8-73f	1546.51	8.02	162,025
866	British Aerospace Bae-146-100/Rj70	761.07	4.40	42,000
868	British Aerospace Bae-146-300	773.31	4.45	44,225
870	Lockheed Jetstar	643.98	3.95	19,844

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Aircraft Type	Aircraft	LTO Fuel (kg)	Cruise fuel (kg/mile)	Max Takeoff Weight (kg)
871	Airbus Industrie A340-300	2376.82	12.46	260,000
872	Airbus Industrie A340-500	3455.43	18.70	365,000
874	Airbus Industrie A340-600	3455.43	18.70	365,000
876	Ilyushin 62	1569.22	8.14	165,000
877	Ilyushin 76/Td	1607.74	8.34	170,000
879	Ilyushin 96	2284.28	11.95	250,000
880	Antonov 124	3917.69	21.48	405,000
882	Airbus Industrai A380-800	5976.67	34.34	560,000
890	Antonov 225 (6 Engine)	7205.87	42.29	640,000

Staff then multiplied these aircraft-specific fuel consumption factors by the total number of flights and the total flight distance travelled by each aircraft type in each of the three categories of flights originating in California (intrastate, interstate, international) to estimate the total fuel consumed for flights originating in California. Table 28 shows examples of these estimates for three common aircraft types.

Table 28: Fuel consumption in flights originating in California for three common aircrafts in 2007

Aircraft Type	Aircraft	Flight Category	Number of flights originating in CA	Total Distance Travelled (miles)	LTO Fuel (kg)	Cruise Fuel (kg)
612	Boeing 737-700/700lr	International	4,680	5,918,964	4,045,971	28,595,314
612	Boeing 737-700/700lr	Interstate	81,757	75,399,452	70,680,869	364,264,933
612	Boeing 737-700/700lr	Intrastate	71,646	26,739,509	61,939,670	129,182,178
819	Boeing 747-400	International	18,573	115,324,611	63,188,306	2,019,197,081
819	Boeing 747-400	Interstate	1,453	4,817,124	4,943,338	84,342,125
819	Boeing 747-400	Intrastate	677	228,003	2,303,262	3,992,062
627	Boeing 777-200/200lr/233lr	International	7,301	42,494,441	18,711,295	522,883,132
627	Boeing 777-200/200lr/233lr	Interstate	3,322	6,417,767	8,513,754	78,968,967
627	Boeing 777-200/200lr/233lr	Intrastate	3	1,011	7,689	12,440

The share of total jet fuel consumption of each flight category within each calendar year is shown in Table 29.

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Table 29: Share of total jet fuel consumption of each flight category.

Year	International	Interstate	Intrastate	Grand Total
2000	44.6%	48.8%	6.6%	100%
2001	43.6%	49.8%	6.5%	100%
2002	41.8%	51.7%	6.5%	100%
2003	40.1%	53.0%	6.9%	100%
2004	40.7%	52.5%	6.8%	100%
2005	42.1%	51.1%	6.8%	100%
2006	42.6%	50.5%	6.9%	100%
2007	42.3%	50.4%	7.2%	100%
2008	44.2%	48.6%	7.2%	100%
2009	44.7%	48.1%	7.2%	100%
2010	45.1%	48.2%	6.7%	100%
2011	47.0%	46.7%	6.3%	100%
2012	47.1%	46.6%	6.3%	100%
2013	48.2%	45.6%	6.2%	100%
2014	49.6%	44.5%	5.9%	100%

Note: Staff assumed that the share of each category in 2009 remained the same as in 2008.

Staff then applied the distribution of estimated fuel consumption in Table 29 to the estimated jet fuel sales to commercial airlines in California (last column of Table 24) to allocate California jet fuel sales to each of the three flight categories (Table 30).

Table 30: Apportionment of California's commercial aviation fuel sales (gallons)

Year	Intrastate	Interstate	International	Total
2000	254,262,902	1,866,203,760	1,704,290,967	3,946,185,649
2001	231,835,074	1,764,858,780	1,544,709,702	3,669,411,841
2002	247,604,073	1,976,547,037	1,596,302,070	3,945,707,369
2003	253,668,618	1,956,618,733	1,479,736,059	3,816,100,290
2004	268,561,848	2,073,606,111	1,604,229,050	4,087,792,651
2005	265,084,350	1,997,757,794	1,645,686,418	4,056,929,370
2006	276,467,791	2,029,035,215	1,711,027,078	4,163,541,504
2007	303,938,534	2,124,757,324	1,783,847,294	4,367,957,343
2008	275,544,797	1,855,484,120	1,689,656,539	3,962,398,319
2009	271,165,111	1,802,896,430	1,674,215,759	3,854,850,633
2010	243,554,343	1,758,550,879	1,647,338,727	3,768,740,336
2011	233,414,014	1,736,253,832	1,746,560,110	3,837,383,400
2012	223,007,900	1,652,392,718	1,671,907,737	3,675,743,000
2013	234,695,450	1,729,957,485	1,829,587,182	3,929,029,477
2014	236,564,783	1,798,002,815	2,005,378,061	4,167,631,477

In the final inventory allocation, staff assumed that all of California's general aviation jet fuel was consumed in the state and added it to the intrastate commercial jet fuel. Thus, the results from Table 24 and Table 30 can be

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combined to calculate the final apportionment of total jet fuel sales for California. Table 31 presents these results.

Table 31: Apportionment of California's jet fuel sales (gallons)

Year	Intrastate (commercial + general aviation flights)	Interstate commercial flights	International commercial flights	CA Military flights	Total CA fuel sales (from EIA SEDS)
2000	375,690,922	1,866,203,760	1,704,290,967	379,856,351	4,326,042,000
2001	359,843,359	1,764,858,780	1,544,709,702	413,660,159	4,083,072,000
2002	372,858,262	1,976,547,037	1,596,302,070	370,044,631	4,315,752,000
2003	379,745,498	1,956,618,733	1,479,736,059	372,181,710	4,188,282,000
2004	409,957,490	2,073,606,111	1,604,229,050	339,343,349	4,427,136,000
2005	413,485,158	1,997,757,794	1,645,686,418	336,774,630	4,393,704,000
2006	423,479,211	2,029,035,215	1,711,027,078	305,384,496	4,468,926,000
2007	459,352,726	2,124,757,324	1,783,847,294	285,390,657	4,653,348,000
2008	417,257,660	1,855,484,120	1,689,656,539	272,713,681	4,235,112,000
2009	377,738,445	1,802,896,430	1,674,215,759	260,519,367	4,115,370,000
2010	362,850,729	1,758,550,879	1,647,338,727	262,755,664	4,031,496,000
2011	354,569,458	1,736,253,832	1,746,560,110	234,600,600	4,071,984,000
2012	351,442,545	1,652,392,718	1,671,907,737	292,165,000	3,967,908,000
2013	369,484,811	1,729,957,485	1,829,587,182	241,822,523	4,170,852,000
2014	364,250,601	1,798,002,815	2,005,378,061	241,822,523	4,409,454,000

(b) Apportionment of marine vessel fuel

Staff apportioned diesel and residual fuel oil used by marine vessels for port activities, harbor craft, transit (within 24 nautical miles from California's coast) and travel outside of California waters among intrastate, interstate and international activities using an ARB model based on geographically specific shipping activity data which was developed for the Goods Movement Plan (ARB 2010b, ARB 2011b). At the time of GHG inventory compilation, the ocean going vessels (OGV) model was in the process of being updated and 2014 activity was not yet available; therefore, staff used an interim emission quantification methodology to estimate 2014 emissions. A growth factor surrogate was calculated from the twenty-foot equivalent unit (TEU) container activities at the three largest ports in California. TEU activities for the ports of Oakland (PO 2016), Los Angeles (PLA 2015), and Long Beach (PLB 2015) were compiled for 2013 and 2014. The relative change in activity for 2013 and 2014 was used as a growth surrogate for 2014 emissions, calculated based on 2013 emissions.

(c) Rail distillate

Sales of rail distillate gallons in California were reported by EIA (EIA 2015). Staff used those numbers without adulteration, so CO_2 calculations simply

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follow the methodology for calculating emissions from any source of distillate combustion.

(d) Off-Road mobile sources

Fuel use estimates of distillate (in gallons) from Off-Road mobile sources (airport ground support equipment, construction and mining equipment, industrial equipment, and oil drilling equipment) operated in California were obtained from ARB's Off-Road Model (ARB 2011a). Staff used those numbers without adulteration, so CO_2 calculations simply follow the methodology for calculating emissions from any source of distillate combustion.

Distillate fuel use for unspecified transportation sources comes from a report from BOE (Singh 2015) on non-taxable uses of diesel fuel. This is fuel not captured by other data sources, representing refunds to end users who used the fuel in a manner exempting them from on-road taxes. All other fuels in the unspecified transportation category come from EIA SEDS (EIA 2013c).

(e) Emission calculations

All CO_2 emissions (as well as the CH_4 and N_2O emissions from LPG, and fossil natural gas, and biomethane) were estimated using the fuel combustion equation based on heat content:

Equation 25: Emissions from mobile source combustion (case 1)

$$E_{GHG,\ fuel} = Q_{fuel} \bullet HC_{fuel} \bullet EF_{GHG,\ fuel}$$

Where,

$E_{GHG,\ fuel}$ = Emissions of the given GHG for the type of fuel (g of GHG)

Q_{fuel} = Amount of fuel combusted (in units of gallons for liquid fuels or standard cubic feet for gaseous fuels)

HC_{fuel} = Heat content of the type of fuel (BTU / unit)

$EF_{GHG,\ fuel}$ = Emission factor of the given GHG by the type of fuel (g GHG / BTU)

With,

(1) GHG = [CO_2] and Fuel = [aviation gasoline, distillate, jet fuel, LPG, fossil natural gas, biomethane, residual fuel oil]

(2) GHG = [CH_4, N_2O] and Fuel = [LPG, Fossil Natural Gas, Biomethane]

A slightly different equation was used for estimating CH_4 and N_2O emissions from aviation gasoline, distillate, jet fuel and residual fuel oil, because the country specific emissions factors available were expressed by mass of fuel rather than by volume.

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Equation 26: Emissions from mobile source combustion (case 2)

$$E_{GHG,\ fuel} = Q_{fuel} \bullet D_{fuel} \bullet EF_{GHG,\ fuel}$$

Where,

$E_{GHG,\ fuel}$ = Emissions of the given GHG for the type of fuel (g of GHG)

Q_{fuel} = Amount of fuel combusted (in units of gallons for liquid fuels or standard cubic feet for gaseous fuels)

D_{fuel} = Density of the type of fuel (kg / unit)

$EF_{GHG,\ fuel}$ = Emission factor of the given GHG by the type of fuel (g GHG / kg fuel)

With,

GHG = [CH_4, N_2O]

Fuel = [aviation gasoline, distillate, jet fuel, residual fuel oil]

3. Data Sources

On-road gasoline blended fuel, on-road diesel blended fuel, and aviation gasoline fuel sales numbers are from the BOE (Covert 2013, BOE 2015). Data for jet fuel and on-road natural gas sold within California came from the EIA (EIA 2013b). Data regarding distillate fuel use for railroad activity (locomotives) were obtained from the EIA (EIA 2015, Walzer 2011). On-road fossil natural gas came from EIA (EIA 2013c) and heavy-duty truck biomethane came from the ARB Low Carbon Fuel Standard (LCFS) (ARB 2016a).

Heat content values for all fuels are from ARB's Mandatory Reporting Program (ARB 2015b) which references the USEPA GHG Reporting Program (GHGRP) (USEPA 2012b).

CO_2 emission factor values for gasoline-ethanol blend and diesel blend are discussed in Section I.C.3. Other CO_2 emission factors for fossil natural gas, biomethane, aviation gasoline, and distillate and residual fuel oil used in international shipping were from USEPA (USEPA 2012b). CH_4 and N_2O emission factors values are from GHGRP (USEPA 2012b).

For a list of individual activity and parameter values used in the equations, please consult the online documentation annex at:
https://www.arb.ca.gov/cc/inventory/doc/methods_00-14/annex_1d_transport.pdf

4. Changes in Estimates

4.1 Biofuel CO_2 Reclassification and Disaggregation of Biofuels

In previous editions of the GHG inventory, the biofuel components of diesel and natural gas used for transportation fuels were not explicitly broken out from the fossil diesel and natural gas fuel categories; and the ethanol

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component of gasoline blend was broken out but not classified as a biogenic source of emissions. Therefore, the biofuel components of fuel combustion CO_2 emissions were included as fossil fuel emissions. In this version of the inventory, biofuels were broken out from fossil fuels for all transportation categories, and the CO_2 emissions from biofuels was reclassified as a biogenic source of emissions. CH_4 and N_2O emissions from combustion of biofuels are still included in California's GHG inventory. This methodology aligns with the existing treatment of stationary biofuel combustion in the inventory, as well as IPCC Guidelines (IPCC 2006a) for GHG inventory development, the USEPA national GHG inventory, and other nations' inventories submitted to the United Nations Framework Convention on Climate Change (UNFCCC). Following the IPCC Guidelines ensures consistency and comparability with other subnational and national inventories.

Three new biogenic fuels, biodiesel, renewable diesel, and biomethane, are now reported as separate line items. CO_2 emissions from these biofuels are considered biogenic, and are not included in California's GHG inventory. Emission calculations follow methodology for the corresponding fossil fuel, with adjusted heat contents where appropriate.

4.2 Disaggregation of heavy duty vehicles

In previous editions of the GHG inventory, the on-road heavy duty vehicle category was a combination of trucks, buses, and motorhomes grouped into one inventory category. To better support program data needs, the 2016 edition of the GHG inventory disaggregates the previous heavy duty vehicle category into the three vehicle subcategories so that they can be tracked and analyzed separately.

4.3 New on-road distillate unspecified category

The BOE tracks diesel fuel sold to on-road transportation in California. Other agencies (such as the EIA) track distillate fuel used in non-road applications. A portion of diesel fuel purchased from on-road fuel suppliers is initially reported to BOE as on-road end use, but is then later excluded from BOE totals because the end user reports its use as non-road. This fuel is purchased in California, but has been excluded from the on-road totals published by BOE and is not included in the non-road totals published by other agencies. BOE tracks this fuel volume but does not typically publish the data annually. For the 2016 edition of the inventory, ARB obtained the unpublished data from BOE and added the volumes back into the GHG inventory, but placed in a new unspecified diesel category.

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5. Future Improvements

Staff plans to incorporate refined modeled output from EMFAC to further improve emissions estimates in the inventory.

E. Oil and Gas Production (IPCC 1A1cii)

1. Background

This section discusses combustion emissions arising from the energy-producing industries own (on-site) energy use for oil and gas extraction, the processing and upgrading of natural gas, and the transport in pipelines. The fuels used for these processes may be produced on site (crude oil, associated gas, natural gas) or may have gone through a refinery (distillate, residual fuel oil). Crude oil combustion occurred in California in the early 1990's but has since been discontinued.

When crude oil is first brought to the surface, it may contain a mixture of associated gas, produced fluids such as salt water, and both dissolved and suspended solids. Water (which can constitute more than 90 percent of the fluid extracted in older wells) is separated out, as are solids and any associated gas. The crude oil is then prepared for shipment to storage facilities and ultimately to refineries. The separated associated gas consists predominantly of methane and carbon dioxide, but ethane, propane, and butane are also significant components. The heavier components, including propane and butane, liquefy when cooled and compressed; these are often separated and processed as natural gas liquids. Associated gas is typically consumed on site as an energy source for steam generation. When consumed in this way, this gas is also called lease fuel.

Natural gas is produced from dry gas wells that produce no oil, and is typically sent to natural gas processing plants for distribution and sale through natural gas pipelines. Natural gas is composed of methane, ethane and other combustible hydrocarbons, but it may also contain water vapor, hydrogen sulfide, carbon dioxide, nitrogen, and helium. During processing, many of these components are removed to improve the quality of the natural gas or to make it easier to move the gas over great distances through pipelines. The resulting processed natural gas contains mostly methane and ethane, although there is no such thing as a "typical" natural gas. Emissions from fuel combusted in pipelines compressor stations are included in this section, but the fugitive emissions from pipelines are reported in section I.F.

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2. Methodology

The method for estimating emissions follows IPCC 2006 guidelines for stationary combustion (IPCC 2006a). California or US-specific emission factors and heat content values were used when available.

Equation 27: Emissions from oil and gas production

$$E_{GHG,\,fuel} = Q_{fuel} \bullet HC_{fuel} \bullet EF_{GHG,\,fuel}$$

Where,

$E_{GHG,\,fuel}$	= Emissions of the given GHG for the type of fuel (g of GHG)
Q_{fuel}	= Amount of fuel combusted (in units of gallons for liquid fuels or standard cubic feet for gaseous fuels)
HC_{fuel}	= Heat content of the type of fuel (BTU / unit)
$EF_{GHG,\,fuel}$	= Emission factor of the given GHG by the type of fuel (g GHG / BTU)

With,

GHG	= [CO_2, CH_4, N_2O]
Fuel	= [Associated gas, Distillate, Natural Gas, Residual fuel oil]

3. Data Sources

The data sources for estimating emissions include the CEC's Quarterly Fuels and Energy Report (QFER), the CA Department of Conservation Division of Oil, Gas & Geothermal Resources (DOGGR), the Energy Information Administration (EIA), the US Environmental Protection Agency (USEPA), the Intergovernmental Panel on Climate Change (IPCC), and the Western States Petroleum Association (WSPA).

Distillate and residual fuel oil use are from EIA (EIA 2013d). The QFER (Gough 2015) provided natural fuel use. The DOGGR (Winkler 2013) provided data on associated gas fuel use.

Natural gas heat content values are from EIA SEDS (EIA 2013c), associated gas values from WSPA (Wang 2007) and other heat content values from ARB's Mandatory Reporting Program (ARB 2015b).

Emission factor values for CO_2 are from WSPA (Wang 2007) for associated gas and from ARB's Mandatory Reporting Program (ARB 2015b) for other fuels. Emissions factor values for CH_4 and N_2O are from ARB's Mandatory Reporting Program (ARB 2015b).

For a list of individual activity and parameter values used in the equations, please consult the online documentation annex at: https://www.arb.ca.gov/cc/inventory/doc/methods_00-14/annex_1e_oil_and_gas_production.pdf

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4. Changes in Estimates

No changes were made for the categories included in this section when compared with the estimates in the previous edition of ARB's GHG inventory.

5. Future Improvements

Staff plans to continue to identify data sets to further refine emissions estimates.

F. Fugitive Emissions from Fuels and Energy Production (IPCC 1B1, 1B2, and 1B4)

1. Background

This section discusses various emissions associated with fuels and energy production, other than combustion emissions, in several industrial sectors.

Methane emissions occur due to leaks arising from the pumping and pressurization of pipelines used to transport crude oil, refined petroleum products, natural gas liquids and natural or associated gases, and with their storage in tanks. These emissions are associated with oil and gas extraction, petroleum refining and marketing activities; and a variety of manufacturing activities such as construction, chemicals, plastics and rubber, electric and electronic equipment, food products, etc. Fugitive emissions of methane also occur from the natural off-gassing of methane from petroleum gas seeps and coal storage piles.

Carbon dioxide emissions are generated by some processes used to control and eliminate acid gases in the exhaust of power plants. For example, limestone or lime is injected to react with acid gases and result in the release of CO_2 as a byproduct of the reaction.

Emissions of both CH_4 and CO_2 arise from certain processes occurring in petroleum refineries. These emissions result from the purposeful venting of exhaust gases, rather than an unintended leakage from pipes or tanks. Sources of these process emissions include: asphalt blowing, coke drum vents, and sulfur recovery units.

Flaring at petroleum refineries is a process that burns various waste products for which a more useful purpose cannot be found. The composition of these waste streams can vary greatly and are usually not monitored in such a way as to allow a breakdown into their component parts. They are grouped here with the fugitive and process emissions even though they are a type of combustion emission. Flaring produces the usual gases associated with combustion: CO_2, $CH_4$and N_2O.

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2. Methodology

2.1 Pipeline Methane Fugitives

Methane emissions occur due to leaks arising from the pumping and pressurization of pipelines. Previous versions of the inventory used data from the MRR. Because MRR does not capture all the emitting activities in the natural gas pipelines category, staff scaled up the emissions captured by MRR using the ratio of natural gas production reported to MRR and to the DOGGR (DOGGR 2015). The emissions were extended back to 2000-2010 using the trends in ARB's California Emission Inventory Development and Reporting System (CEIDARS) (ARB 2015c).

The 2007 SSD Survey (ARB 2007a) captured additional fugitive emissions from natural gas distribution system that were not captured by either CEIDARS or MRR (for 2011-2014). The data from the 2007 SSD Survey is used as the basis for year 2007 emissions. This single year of data is then scaled forward and backward to span all other inventory years using the PHMSA Pipeline Mileage data (PHMSA 2010) to capture the impact of pipeline leakage, combined with data on number of residential housing units (DOF 2015) to capture the impact of customer meter leaks. Both surrogates are given equal weight in the scaling.

Equation 28: CH_4 emissions from PHMSA pipeline mileage

$$P_{20xx} = \sum Mi_{20xx} \bullet EF_i$$

Where,

P_{20xx} = Estimate of emissions derived from PHMSA pipeline mileage for year 20xx (g)

Mi_{20xx} = Pipeline mileage of material type i (e.g. steel, plastic, iron) in year 20xx (miles)

EF_i = Default MRR emission factor for material type i in year 20xx (g/mile)

Equation 29: CH_4 emissions from pipeline leaks

$$E_{20xx} = \frac{E_{2007} \bullet \left(\frac{P_{20xx}}{P_{2007}} + \frac{R_{20xx}}{R_{2007}}\right)}{2}$$

Where,

E_{20xx} = Emissions from Pipeline leaks in year 20xx (g)

E_{2007} = Emissions from Pipeline leaks in year 2007 (g)

P_{20xx} = PHMSA pipeline mileage emissions estimate in year 20xx (g)

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P_{2007} = PHMSA pipeline mileage emissions estimate in year 2007 (g)
R_{20xx} = Residential Housing units in year 20xx (g)
R_{2007} = Residential Housing units in year 2007 (g)

2.2 Oil & Gas CH4 Fugitives

This version of the GHG inventory uses the 2007 Oil & Gas survey conducted by ARB's Stationary Source Division (SSD) (ARB 2007a), which captured additional fugitive emissions from the oil & gas sector that were not captured by either the CEIDARS or MRR, which had been used in previous inventory versions. The 2007 SSD Survey is considered the most comprehensive data source for this sector and is used as the basis for year 2007 emissions. This single year of data is then scaled forward and backward to span all other inventory years using the emissions for the *Production Field Operations (Potential)* category in the USEPA National GHG Inventory (USEPA 2015g). Using emissions data from CEIDARS can introduce additional uncertainties; therefore, the National GHG Inventory trend will be used as the scaling surrogate until a better surrogate becomes available.

Equation 30: *CH_4 emissions from oil & gas production*

$$E_{20xx} = E_{2007} \bullet \frac{EPA_{20xx}}{EPA_{2007}}$$

Where,

E_{20xx} = Emissions from oil and gas production in year 20xx (g)
E_{2007} = Emissions from oil and gas production in year 2007, based on the 2007 SSD Survey (g)
EPA_{20xx} = EPA National Inventory methane emissions estimate for *Production Field Operations (Potential)* in year 20xx (g)
EPA_{2007} = EPA National Inventory methane emissions estimate for *Production Field Operations (Potential)* in year 2007 (g)

2.3 Fugitive emissions from other sectors

For some of the categories, staff queried ARB's CEIDARS database for total organic gases (TOG) emissions and then speciated the results to estimate fugitive emissions of CH_4. In the CEIDARS database, total organic gases include emissions of compounds of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and ammonium carbonate. The ARB maintains and updates estimates of the chemical composition and size fractions of particulate matter (PM) and the chemical composition and reactive fractions of TOG in CEIDARS, for a variety of emission source categories. These speciation profiles provide estimates of the chemical composition of the emissions, and are used in the emission inventory

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and air quality models. For more information see: http://arb.ca.gov/ei/speciate/speciate.htm

Year 2009+ data from MRR were used for some categories. Estimates for fugitive emissions from flaring in refineries (CO_2, CH_4 and N_2O); acid gas control devices (CO_2); refinery process such as asphalt blowing, coke drum vents, and sulfur recovery units (CO_2, CH_4); and fugitives from coal storage piles (CH_4) are based on data from ARB's MRR. For MRR categories without any previous data source, MRR emissions for 2009 were obtained from the MRR database, and then scaled back in time —proportionally to the relevant level of activity— to estimate values for 2000-2008.

Equation 31: Scaling of some fugitive emissions back in time

$$E_{year} = \frac{E_{2009}}{H_{2009}} \bullet H_{year}$$

Where,

E_{year}	= GHG emission estimate for a given economic subsector in a particular year (g of GHG)
E_{2009}	= GHG emission reported by the given economic subsector in 2009 (g of GHG)
H_{2009}	= Total amount of heat or fuel used by the facilities in the given subsector in 2009 (btu or tons)
H_{year}	= Total amount of heat or fuel used by the facilities in the given subsector in the particular year (btu or tons)

With

Year	= [2000 to 2008]

The scaling used CEC's Petroleum Industry Information Reporting Act (PIIRA) data on the total heat used by refineries to scale emissions from flaring, refinery process emissions and the refinery portion of acid gas control. Total fuel use for coal was used to scale methane emissions from coal storage piles not already addressed in the electricity sector.

3. Data Sources

Pipeline fugitive methane emissions are calculated from the ARB Pipeline Survey (ARB 2007b), PHMSA Pipeline Data (PHMSA 2010), and Residential Units Data (DOF 2015). The default emission factor for each pipeline material type came from MRR (ARB 2015b).

Oil & gas fugitive methane emissions are calculated from the ARB Oil & Gas Production Survey (ARB 2007a), and the USEPA National GHG Inventory (USEPA 2015g).

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Fugitive emissions from other sectors are from ARB's Mandatory Reporting Program (ARB 2015b) or CEIDARS data (ARB 2015c) for 2009+. Data from the PIIRA database (O'Brien 2010) and from EIA SEDS databases published online (EIA 2013c) were used to scale 2009 emissions found only in the Mandatory Reporting database back in time to cover 2000-2008 (e.g. emissions from coal piles, flaring, or acid gas control devices).

4. Changes in Estimates

No methodology changes were made in this version of the GHG inventory, the methods are the same as those used in the previous edition of ARB's GHG inventory.

5. Future Improvements

Staff plans to continue to identify data sets to further refine emissions estimates. For example, new data from recent ARB-funded contract may provide California-specific emission factor for pipeline emissions, and data collected under Senate Bill 1371 can provide information on leaks and mitigation.

G. Carbon Dioxide from Geothermal Energy Production (IPCC 1B3)

1. Background

Geothermal power plants use high-pressure hot water and steam from deep inside the earth crust to turn turbine generators to produce electricity. The geothermal wells and gathering systems collect and convey the deep geothermal fluid to the power plants. Geothermal fluids contain minerals leached from the reservoir rock and variable quantities of gas, mainly carbon dioxide and a smaller amount of hydrogen sulfide (H_2S). The quantity and composition of dissolved gases depend on the local geological conditions. When the steam cools it turns back into water and is re-injected back into the reservoir, with most of its mineral content and some of the gases. Most of the non-condensable gases are released to the environment. Some plants remove the H_2S in a gas treatment process before releasing the CO_2 to the environment.

Certain facilities use a closed loop system (utilizing binary turbines) that keeps the fluids from direct contact with the environment, exchanging heat by means of a heat exchanger. These systems eliminate the emissions of CO_2 altogether.

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2. Methodology

2.1 Years 2000 to 2008

To estimate the CO_2 emissions resulting from the exploitation of geothermal power, staff obtained data from the EIA for the amount of geothermal heat used by power plants and applied the CO_2 emission factor obtain by averaging the emission factors used by geothermal plants reporting to ARB's Mandatory Reporting Program. The emission factor is 0 for geothermal resources using Binary Turbines to generate electricity, as they prevent any escape of CO_2.

Equation 32: CO_2 emissions from geothermal power

$$E = GH \bullet EF$$

Where,

E	= CO_2 emissions by geothermal plants (g of CO_2)
GH	= Amount of geothermal heat used by the plants (btu)
EF	= CO_2 emission factor (g of CO_2 per btu)

2.2 Year 2009+

Emissions data reported by individual power plants under ARB's MRR were used for 2009+. However, small plants emitting less than the Mandatory Reporting threshold of 2,500 metric tons of CO_2 (10,000 metric tons for 2011 onwards) do not report their emissions. For those plants staff used the same methodology as for years 2000 to 2008, see Equation 32 above.

3. Data Sources

Geothermal heat data was obtained from the EIA. Data for 2000 was obtained through personal correspondence with Robert Schnapp of the EIA (Schnapp 2008). Data for 2001-2008 data was downloaded from EIA databases published online (EIA 2013a). The emission factor for 2000-2008 is an average of those used by geothermal plants reporting to the ARB's MRR (ARB 2015b), while actual reporting data was used for 2009+ for plants reporting to ARB.

For a list of individual activity and parameter values used in the equations, please consult the online documentation annex at:
https://www.arb.ca.gov/cc/inventory/doc/methods_00-14/annex_1g_carbon_dioxide_from_geothermal_power.pdf

4. Changes in Estimates

No changes were made for the categories included in this section when compared with the estimates in the previous edition of ARB's GHG inventory.

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5. Future Improvements

ARB's GHG Mandatory Reporting data for geothermal plants will continue to be included in future editions of the GHG inventory.

II. Industrial Processes and Product Use

A. Cement Production (IPCC 2A1)

1. Background

In cement manufacturing, CO_2 emissions occur during the production of clinker, an intermediate product that is the main component of hydraulic (usually portland) cements.

To produce clinker, limestone (predominantly calcium carbonate $CaCO_3$) is heated at high temperature in a kiln to produce lime (CaO), and CO_2. This process is called calcination. The CaO then reacts with silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3) in the raw materials to make the clinker minerals (chiefly calcium silicates). During the making of clinker some cement kiln dust (CKD) may leave the kiln system. Since that CKD is made up of partially calcined carbonates, cement manufacture emission estimates should also account for the CO_2 emissions associated with the CKD.

Masonry cement is produced by adding lime or ground limestone to portland cement. Since the emissions associated with the lime is already accounted for under the lime production section of the ARB statewide GHG inventory, the production of masonry cement does not lead to additional emissions in this section. Similarly, the emissions resulting from the combustion of fuels to heat the kiln are accounted for in another section of the inventory, as described in section 1.C of the TSD.

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2. Methodology

Clinker production is calculated using a Tier 1 approach for years 2000 to 2007 and 2010 to 2014, and a Tier 3 approach — based on facility level measurements — for years 2008 and 2009.

2.1 Methodology for years 2000 through 2007 and 2010 through 2014

Staff estimated the cement manufacture CO_2 emissions using Tier 1 methodology from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006c).

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Equation 33: CO_2 emissions from cement production (equation 2.2 of the guidelines)

$$E_K = M_{cl} \bullet EF_{cl} \bullet CF_{ckd}$$

Where,

E_K	= emissions of CO_2 from cement production in the clinker process (tonnes)
M_{cl}	= weight (mass) of clinker produced (tonnes) [2000 through 2007 data from USGS] [2010 through 2014 data from ARB's Mandatory Reporting]
EF_{cl}	= emission factor for clinker (tonnes CO_2/tonne clinker). This clinker emission factor (EF_{cl}) is not corrected for CKD.
CF_{ckd}	= emissions correction factor for CKD, (dimensionless)

The emission factor for clinker is based on the average fraction of lime used in cement clinker and a constant reflecting the mass of CO_2 released per unit of lime (IPCC 2006c). The CKD emissions are estimated as two percent of the CO_2 emissions from clinker production (IPCC 2006c).

2.2 Methodology for years 2008 and 2009

Years 2008 and 2009 CO_2 emissions were quantified by each cement manufacturing plant in California using the calculation methodology specified by the ARB's MRR (ARB 2007c). This is a clinker-based method using the volume and composition of clinker produced and the amount of CKD discarded. A plant-specific clinker CO_2 emission factor and a CKD emission factor for CO_2 were also determined. The clinker emission factor is based on the actual percentage of lime (CaO) and magnesium oxide (MgO) content of the clinker. For any CKD which is not recycled back into the kiln, a plant-specific CKD calcination rate was determined. Further, each cement plant calculates the process-related emissions resulting from the total organic carbon (TOC) content of the raw materials such as limestone, shale, or fly ash.

The plant-specific clinker emission factor is determined using the following equation:

Equation 34: Clinker emission factor

$$EF_{cl} = (F_{CaO} \bullet 0.785) + (F_{MgO} \bullet 1.092)$$

Where,

EF_{cl}	= emission factor for clinker (tonnes CO_2/tonne clinker). This clinker emission factor is not corrected for CKD.
F_{CaO}	= fraction content of CaO in the clinker by weight minus non-carbonate CaO in the clinker by weight (fraction)

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0.785	= molecular weight ratio of CO_2/CaO (44g/56g), (dimensionless)
F_{MgO}	= fraction content of MgO in the clinker by weight minus non-carbonate MgO in the clinker by weight (fraction)
1.092	= molecular weight ratio of CO_2/MgO (44g/40g), (dimensionless)

The plant-specific CKD emission factor is quantified for cement plants that generate CKD which is not recycled back to the kiln as follows:

Equation 35: Clinker kiln dust emission factor

$$EF_{CKD} = \frac{\frac{EF_{cl}}{1+EF_{cl}} \bullet d}{1 - \frac{EF_{cl}}{1+EF_{cl}} \bullet d}$$

Where,

EF_{CKD}	= emission factor for CKD (tonnes CO_2/tonne CKD)
EF_{cl}	= emission factor for clinker (tonnes CO_2/tonne clinker). This clinker emission factor is not corrected for CKD.
d	= plant-specific CKD calcination rate (dimensionless, see Equation 36)

Equation 36: Plant specific clinker kiln dust calcination rate

$$d = 1 - \frac{C_d \bullet (1 - C_{RM})}{(1 - C_d) \bullet C_{RM}}$$

Where,

d	= plant-specific CKD calcination rate (dimensionless)
C_d	= fraction of original carbonate in the CKD (fraction)
C_{RM}	= fraction of original carbonate in the raw material (fraction)

The CO_2 emissions from the clinker process for each cement plant are calculated using the following equation:

Equation 37: CO_2 emissions from clinker production

$$E_{cl} = (M_{cl} \bullet EF_{cl}) + (M_{CKD} \bullet EF_{CKD})$$

Where,

E_{cl}	= emissions of CO_2 from clinker calcination process (tonnes)
M_{cl}	= amount of clinker produced (tonnes)
EF_{cl}	= emission factor for clinker (tonnes CO_2/tonne clinker).

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M_{CKD} = amount of CKD not recycled to the kiln (tonnes)
EF_{CKD} = emission factor for CKD (tonnes CO_2/tonne CKD)

The estimation of CO_2 emissions from the combustion of the total organic carbon (TOC) in raw materials is calculated as follows (with a default value of 0.2 percent organic carbon):

Equation 38: CO_2 emissions from combustion of organic carbon in raw materials

$$E_{TOC} = TOC \bullet C_{RM} \bullet 3.664$$

Where,

E_{TOC} = emissions of CO_2 from the combustion of organic carbon (TOC) content in raw materials (tonnes)
TOC = total organic carbon content of raw material, default value = 0.002 (fraction)
C_{RM} = fraction of original carbonate in the raw material (fraction)
3.664 = molecular weight ratio of CO_2/C (44g/12g), (dimensionless)

The total CO_2 emissions from the calcination process for each plant are finally determined using the next equation; by summing the emissions from the clinker process and the emissions from the combustion of organic carbon in raw materials described above.

Equation 39: Total CO_2 emissions from cement production process

$$E_{total} = E_{cl} + E_{TOC}$$

Where,

E_{total} = total process emissions of CO_2 from cement production (tonnes)
E_{cl} = emissions of CO_2 from the clinker calcination process (tonnes)
E_{TOC} = emissions of CO_2 from the combustion of organic carbon in raw materials (tonnes)

Note that to satisfy the ARB GHG Mandatory Reporting regulation, cement plant operators also have the option to determine CO_2 emissions from installed Continuous Emission Monitoring Systems (CEMS) which comply with federal performance standards. The cement sector total in California is obtained by summation of all cement plants' emissions.

2.3 Use of MRR Data in Cement Emissions for 2010-2014

MRR regulation went under major revisions, which resulted in a change of the data that cement plants report, starting with emissions reported for 2010. For those plants that report the fuel use and emissions without a CEMS, the

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emissions and fuel amounts (both heat content and physical quantity) are used exactly as reported in MRR. If applicable, the cement plant fuel and emissions associated with cogeneration are recorded under the cogeneration categories. Emissions from clinker production are then derived from the total reported in MRR minus the cogeneration emissions.

Facilities using CEMS report fuel consumption by fuel type, associated CH_4 and N_2O combustion emissions, and the total CEMS CO_2 emissions. The total CEMS CO_2 emissions include both process (clinker) and fuel combustion emissions, which were separated during post-processing of the data to allow more detailed inventory reporting. CO_2 from clinker production was determined from reported clinker production and using a 2 percent adjustment factor for emissions associated with CKD, as described in the previous section. The remaining CEMS CO_2 emissions were attributed to fuel combustion, and were additionally subdivided into fuel type for inventory reporting. To calculate fuel-specific CO_2 emissions, reported fuel consumption (both heat and quantity are given in most cases, but in all cases heat is given) were converted into "default" CO_2 emissions using the MRR default emission factors and the amount of heat reported for that fuel. This "default" CO_2 emission result was corrected using the ratio of CEMS CO_2 to the total "default" CO_2. Each fuel-specific "default" CO_2 emission was multiplied by this ratio to calculate the final emissions. This assures that the reported CEMS CO_2 emissions equals the sum of the clinker CO_2 plus the fuel-specific fuel combustion CO_2 reported in the inventory.

3. Data Sources

Clinker production for 2000 through 2007 is from the United States Geological Survey (USGS) crushed stone report (USGS Various Years-a). Data for 2008 through 2014 is from both iterations of ARB's MRR (ARB 2007c, ARB 2015b), due to the revisions that resulted in a change of data reported to MRR. Default emission factors and CKD correction factors were from the 2006 IPCC guidelines (IPCC 2006c). For a list of individual activity and parameter values used in the equations, please consult the online documentation annex at: https://www.arb.ca.gov/cc/inventory/doc/methods_00-14/annex_2a_cement_production.pdf

4. Changes in Estimates

For consistency, emissions from 2000 to 2007 were updated to use the same methodology as 2010 through 2014. This update resulted in minimal emission estimate changes, averaging +1.6% for 2000 through 2007. Emissions for other years did not change from the previous inventory.

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5. Future Improvements

Staff plans to continue to identify data sets to further refine emissions estimates.

B. Lime Production (IPCC 2A2)

1. Background

Lime production involves three key stages: stone preparation, calcination, and hydration. This section focuses on the CO_2 emitted during the calcination process, when limestone (mostly $CaCO_3$) or dolomitic limestone (higher Mg concentration) is heated in a kiln to produce lime (CaO), CO_2 emissions and lime kiln dust (LKD) as a by-product.

Equation 40: Calcination processes

$$\boxed{\begin{aligned} CaCO_3 + Heat &\rightarrow CaO + CO_2 \\ MgCO_3 + Heat &\rightarrow MgO + CO_2 \end{aligned}}$$

Lime is used in a variety of industrial applications, such as in steelmaking, water and sewage treatment, sugar refining and paper manufacturing.

2. Methodology

There are two types of lime material: high-calcium lime and dolomitic lime. Quicklime is the product which results from the calcination of limestone material. High-calcium quicklime is derived from limestone material containing less than 5 percent magnesium carbonate ($MgCO_3$). Dolomitic quicklime is produced from limestone material containing 35 to 46 percent $MgCO_3$. For years 2000 through 2010, CO_2 emissions were provided by the National Lime Association, using a plant-specific CO_2 emission factor developed through laboratory analysis of the percent CaO and percent magnesium oxide (MgO) in the input limestone material. The quantity of lime produced annually at a plant was multiplied by the derived CO_2 emission factor to provide annual CO_2 emissions. This methodology is consistent with emission estimation methodology used by the USEPA Emission Inventory Improvement Program guidance (USEPA 2004), and with the Tier 3 method of the 2006 IPCC guidelines (IPCC 2006c).

Equation 41: CO_2 emissions from lime calcination

$$\boxed{E_l = W_l \bullet (P_{CaO,l} \bullet 0.7848 + P_{MgO,l} \bullet 1.0918)}$$

Where,

E_1 = CO_2 emissions from lime calcination process (tonnes)

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W_l	= Weight (mass) of lime produced (tonnes)
$P_{CaO, l}$	= Proportion of CaO in lime (fraction)
0.7848	= Molecular weight ratio of CO_2 to CaO (44g/56g), (dimensionless)
$P_{MgO, l}$	= Proportion of MgO in lime (fraction)
1.0918	= Molecular weight ratio of CO_2 to MgO (44g/40g), (dimensionless)

Equation 42: CO_2 emissions from LKD by-product

$$E_{LKD} = W_{LKD} \bullet (P_{CaO, LKD} \bullet 0.7848 + P_{MgO, LKD} \bullet 1.0918)$$

Where,

E_{LKD}	= CO_2 emissions from LKD calcined by-product generation (tonnes)
W_{LKD}	= Weight (mass) of LKD generated (tonnes)
$P_{CaO, LKD}$	= Proportion of CaO in LKD (fraction)
0.7848	= Molecular weight ratio of CO_2 to CaO (44g/56g), (dimensionless)
$P_{MgO, LKD}$	= Proportion of MgO in LKD (fraction)
1.0918	= Molecular weight ratio of CO_2 to MgO (44g/40g), (dimensionless)

Equation 43: Total CO_2 emissions from lime production

$$E_{total} = E_l + E_{LKD}$$

Where,

E_{total}	= total process emissions of CO_2 from lime production (tonnes)
E_l	= CO_2 emissions from lime production (tonnes)
E_{LKD}	= CO_2 emissions from LKD calcined by-product generation (tonnes)

Emissions for years 2011 through 2014 were quantified using data reported under the ARB's MRR (ARB 2015b). Reported facility process emissions were adjusted to account for the reported annual amount of CO_2 captured on-site. The CO_2 captured on-site is recovered by facilities for use in sugar refining and precipitated calcium carbonite production.

3. Data Sources

The National Lime Association (NLA) provided CO_2 emission estimates from lime production operations in California for years 2000 through 2010 using

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plant-specific CO_2 emission factors and material throughput for both limestone calcination and LKD by-product generation (Lime-Producers 2011). The limestone material is generally mined on-site and mineral characteristics for CaO and MgO concentrations are determined monthly by laboratory analysis. The molecular weight ratio of CO_2 to CaO (0.7848) and CO_2 to MgO (1.0918) are derived from molecular weight data published by the International Union of Pure and Applied Chemistry (Wieser 2006). Facility-specific process emissions and on site CO_2 capture for 2011 through 2014 were from MRR (ARB 2015b).

For a list of individual activity and parameter values used in the equations, please consult the online documentation annex at: https://www.arb.ca.gov/cc/inventory/doc/methods_00-14/annex_2b_lime_production.pdf

4. Changes in Estimates

There were no methodology changes to the sector.

C. Non-energy Uses of Fossil Fuels (IPCC 2B, 2D)

1. Background

Some fossil fuels are also consumed for non-energy uses. These non-energy uses include use as feedstock for the chemical industry (IPCC category 2B) for the manufacture of plastics, rubber, synthetic fibers and other materials. Other consumptive uses of fossil fuels involve non-energy products such as lubricants, waxes, asphalt, and the evaporation of solvents (category 2D). The fuels used for these purposes include natural gas, liquefied petroleum gases (LPG), asphalt, naphtha, petroleum coke and other petroleum products.

Non-energy uses of fossil fuels often do generate some CO_2 emissions. Emissions may occur during the manufacture of various products from fuel-derived feedstock or they may occur during the product's lifetime, for instance some of the lubricant in motors will end up being burned and evaporated solvents are eventually oxidized in the atmosphere. However, emissions from lubricants, solvents and materials made from fossil fuels that are combusted after the end of the useful life are not accounted in this section but under the appropriate fuel combustion category in Section I above.

In California, the only known activities of this kind are the consumption of lubricants and evaporation of solvents. Hydrogen production which also consumes fuels, is discussed in a later section (IPCC 2H3)

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2. Methodology

2.1 Consumption of lubricants

Staff used a simple methodology consistent with that used by USEPA for the national GHG inventory (USEPA 2012a). The proportion of the carbon that is stored in the derived product and thus not oxidized is used to modify the carbon oxidation formula used for fuel combustion. The proportion of carbon stored can vary from 1 (all of the fuel's carbon is stored) as in the case of asphalt used for pavement, to 0 (none of the carbon is stored) as in the case of natural gas or refinery gas used for hydrogen production.

Staff determined that, in the case of California, only lubricants consumed incidentally in internal combustion engines make up this category, as no data could be found for consumptive use of other fossil fuels resulting in their partial oxidation.

Equation 44: CO_2 emissions from non-energy uses of fossil fuels

$$E_{fuel} = Q_{fuel} \bullet HC_{fuel} \bullet EF_{fuel} \bullet (1 - CS_{fuel})$$

Where,

E_{fuel}	= CO_2 emissions for the particular fuel used as feedstock or other non-energy use (g)
Q_{fuel}	= Amount of fuel used as feedstock or other non-energy use (in units of gallons for liquid fuels or standard cubic feet for gaseous fuels)
HC_{fuel}	= Heat content of the type of fuel (BTU / unit)
EF_{fuel}	= CO_2 emission factor for the type of fuel (g / BTU)
CS_{fuel}	= Proportion of carbon that is stored in the derived product (unitless)

With,

fuel	= [lubricants]

2.2 Solvent evaporation

Solvent evaporation data was retrieved from ARB's CEIDARS database. Emissions of Reactive Organic Compounds (ROG), which do not include methane, are converted into the amount of CO_2 that would result from the oxidation of all carbon atoms in the ROG compounds into CO_2. To do that, staff assumed that each ROG compound can be approximated as a hydrocarbon, where each carbon is bonded to 2 other carbon atoms and to 2 hydrogen atoms.

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Equation 45: Assumed oxidation of reactive organic compounds

$$C_nH_{2n} + nO_2 \rightarrow nCO_2 + nH_2O$$

Thus each CH_2 chain in the ROG molecules is converted into a molecule of CO_2. CH_2 has an approximate molar mass of 14 grams/mole, while CO_2 has a molar mass of approximately 44 grams/mole. Thus, multiplying by 44/14 converts the amount of evaporated ROG the resulting amount of CO_2 emissions.

3. Data sources

Lubricant consumption data came from EIA SEDS (EIA 2013c). The proportion of carbon stored came from USEPA inventory annex 2 (USEPA 2012c). The heat content and emission factor for CO_2 are from ARB's MRR (ARB 2015b). Solvent evaporation data comes from the CEIDARS database (ARB 2015c).

For a list of individual activity and parameter values used in the equations, please consult the online documentation annex at: https://www.arb.ca.gov/cc/inventory/doc/methods_00-14/annex_2c_non-energy_uses_of_fossil_fuels.pdf

4. Changes in Estimates

No changes were made from the previous methodology for the categories included in this section.

5. Future Improvements

ARB staff will seek to obtain more detailed data about the non-energy use of fuel in California, to determine if any other fuel use as feedstock should be included in this section.

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D. Nitric Acid Production (IPCC 2B2)

1. Background

The main use of nitric acid (HNO_3) is for the manufacture of nitrogen fertilizer. It is also used in the production of adipic acid and explosives (e.g., dynamite), for metal etching and in the processing of ferrous metals. During the production of nitric acid, N_2O is generated as an unintended by-product of the high temperature catalytic oxidation of ammonia (NH_3), and is released into the atmosphere. The amount of N_2O formed varies with the process conditions (pressure, temperature), catalyst composition and age, etc. Nitric acid is manufactured by the catalytic oxidation of ammonia. California nitric acid

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manufacturing plants have emissions control devices that reduce the amount of N_2O released to the atmosphere.

2. Methodology

2000 through 2010 nitric acid emissions were calculated from national data (USEPA 2015g) using a California-specific scaling factor. The scaling factor was calculated from the ratio of 2013 US nitric acid N_2O emission to 2013 California nitric acid N_2O emissions reported under the MRR (ARB 2015b). 2011 through 2014 annual N_2O nitric acid emissions were used as reported under the MRR (ARB 2015b). This methodology is consistent with the Tier 3 method of the 2006 IPCC guidelines (IPCC 2006b).

3. Data sources

National N_2O emission from nitric acid are from the USEPA Greenhouse Gas Emission Inventory (USEPA 2015g) and California N_2O emissions for 2011 through 2014 were from the ARB MRR (ARB 2015b).

4. Changes in Estimates

The previous inventory used a single value for N_2O emissions from nitric acid plants for 2000 through 2010. This methodology has been updated to use national N_2O emissions from USEPA scaled to California to better quantify year to year variations in emissions. This method update resulted in a small increase in emissions from this sector, +10.6% on average for 2000 through 2010.

E. Semiconductor Manufacturing (IPCC 2E)

1. Background

Manufacturers of semiconductors use fluorinated GHGs in plasma etching and plasma enhanced chemical vapor deposition processes. Plasma etching of dielectric films creates the pattern of pathways connecting individual circuit components in semiconductors. Vapor deposition chambers are used for depositing the dielectric films, and are cleaned periodically using fluorinated gases. Fluorinated gases are converted to fluorine atoms in plasma, which etches away dielectric material or cleans the chamber walls and hardware. Un-dissociated fluorinated gases and other products end up in the waste streams and, unless captured by abatement systems, into the atmosphere. Some fluorinated compounds can also be transformed in the plasma processes into other compounds (e.g., CF_4 generated from C_2F_6). If they are not captured by

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emission control systems, then the process-generated gases will also be released into the atmosphere.

2. Methodology

ARB conducted a survey of 2006 emissions from California semiconductor manufacturing businesses (ARB 2009). To calculate emissions for other years, the ratio of California's 2006 survey emissions to U.S. 2006 emissions from USEPA was multiplied by annual U.S. emissions. This methodology assumes that emissions of individual fluorinated gas from semiconductor manufacturing facilities in California are proportional to emissions at the national level from 2000 through 2014. 2006 emissions estimates use Tier 3 methodology (IPCC 2006b).

National semiconductor emissions are informed by reports to the U.S. Environmental Protection Agency GHG Reporting Program (GHGRP), participants in its PFC Reduction/Climate Partnership for the Semiconductor Industry, and USEPA's PFC Vintage Model. USEPA GHG inventory reports seven fluorinated gases: CF_4, C_2F_6, C_3F_8, C_4F_8, HFC-23 (CHF_3), SF_6, and NF_3.

Equation 46: Emissions from semiconductor operations

$$E_{CA,\,GHG} = E_{US,\,GHG} \bullet \left(\frac{S_{CA,2006}}{E_{US,2006}} \right)$$

Where,

$E_{CA,\,GHG}$	= Emissions of a particular fluorinated gas from semiconductor operations in California (g)
$E_{US,\,GHG}$	= Emissions of the particular fluorinated gas from semiconductor manufacturing in the entire US (g)
$S_{CA,2006}$	= 2006 survey of emissions of a particular fluorinated gas from semiconductor operations in California (g)
$E_{US,2006}$	= 2006 emissions of the particular fluorinated gas from semiconductor manufacturing in the entire US (g)
GHG	= [CF_4, C_2F_6, C_3F_8, C_4F_8, HFC-23 (CHF_3), SF_6, NF_3]

3. Data Sources

Data sources include the ARB 2006 survey information (ARB 2009), a ratio of 2006 California emissions to 2006 national emissions for each compound, and USEPA emissions estimates (USEPA 2015g).

For a list of parameter values used in the equations, please consult the online documentation annex at: https://www.arb.ca.gov/cc/inventory/doc/methods_00-14/annex_2e_semiconductor_manufacturing.pdf

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4. Changes in Estimates

There were no changes to methodology for this sector compared to the last version of the inventory. However, for the 2016 edition of the inventory, ARB staff revised the 2006 emission data to reflect a clarification in the IPCC Tier 2b methodology in calculating emissions and by-product emissions (IPCC 2006b).

5. Future Improvements

ARB enacted a 2010 Semiconductor Manufacturing Regulation to reduce GHG emissions from this sector. This rule includes annual GHG emission reporting for each company to the air districts. ARB staff is investigating the possibility of acquiring these data for a complete year to inform future emission estimates.

F. Use of ODS Substitutes (IPCC 2F)

1. Background

Ozone-depleting substances (ODS) (chlorofluorocarbons (CFCs), halons, carbon tetrachloride, hydrochlorofluorocarbons (HCFCs), and methyl chloroform) are being phased out under the terms of the Montreal Protocol, and the Clean Air Act Amendments of 1990. ODS were used in refrigeration and air conditioning equipment, solvent cleaning, foam production, sterilization, fire extinguishing, and consumer products. Replacements, knowns as ODS substitutes, are also GHGs and include hydrofluorocarbons (HFC) and perfluorocarbons (PFC). Emissions of ODS substitutes are increasing as they are phased in to replace ODS.

Emissions of ODS substitutes occur when they are released into the atmosphere (e.g., from fire extinguishers or aerosol cans) or when they leak out of equipment such as refrigerators and air conditioning units. Estimating these emissions is difficult because the sources are diffuse and the emissions occur over the equipment lifetime.

2. Methodology

ARB staff have implemented a detailed ODS substitutes emissions model based on California-specific research, as well as regulatory data reported under the refrigerant management program (RMP). This model is consistent with IPCC Tier 2 methodology (IPCC 2006b). Due to the high level of detail inherent in the ODS substitutes model, the ARB has published a separate technical support document containing methodology for this sector (ARB 2016d). A brief overview is presented here.

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The model includes estimates for 11 individual f-gases (CF4, HFC-125, HFC-134a, HFC-143a, HFC-152a, HFC-227ea, HFC-236fa, HFC-245fa, HFC-32, HFC-365mfc, HCF-43-10mee) and one group (other PFC and PFE). The other PFC and PFE category represents a mixture of compounds employed for solvent applications. Emissions of these compounds are estimated for the following emission categories:

- Refrigeration and Air Conditioning
- Aerosol Propellants
- Insulating Foams
- Solvents
- Fire Protection

And are further subdivided into the following economic sectors:

- Commercial
- Industrial
- Residential
- Transportation

The general methodology to estimate emissions follows two steps: First, the total ODS substitutes used in California are calculated using detailed inventory of equipment type and age or external models. Second, emissions of ODS substitutes are calculated using either emission factors that reflect the unique emission characteristics of the equipment and process, or a mass balance approach is used based on new and retiring equipment information.

Calculation of emissions using the known charge amounts of each GHG compound and average loss rate for equipment reaching end-of-life is used for sources such as Refrigeration and Air Conditioning equipment with known refrigerant charge and leak rates (ARB 2014c).

Equation 47: Emissions of ODS substitutes using Simple Calculation Inputs

$$E_{CA,GHG,EQUIPMENT} = [N_{units} \bullet C_{unit} \bullet L_{rate}] + [N_{EOL} \bullet C_{EOL} \bullet L_{EOL}]$$

Where,

$E_{CA, GHG, EQUIPMENT}$ = Estimate of the given GHG (ODS substitute) emissions in California for each Equipment Type or Emissions sub-sector (g)

N_{units} = Number of units (equipment) in use (dimensionless)

C_{unit} = Average chemical charge rate per unit (g/unit)

L_{rate} = Average annual leak or loss rate (dimensionless)

N_{EOL} = Number of units reaching end-of-life (dimensionless)

C_{EOL} = Average chemical charge at end-of-life (g/unit)

L_{EOL} = Average loss rate at end-of-life (dimensionless)

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With,

GHG = [CF_4, HFC-125, HFC-134a, HFC-143a, HFC-152a, HFC-227ea, HFC-236fa, HFC-245fa, HFC-32, HFC-365mfc, HFC-43-10mee, Other PFC and PFE]

Note: Other PFC/PFE includes various PFCs and perfluoropolyethers (PFEs) employed for solvent applications. The GWP for C_6F_{14} is used for these emissions.

Mass emissions for more complex equipment varieties employed several calculation sources such as vehicle emissions models or information obtained from ARB research projects. The more complex emission profiles included the following categories: Mobile Vehicle Air Conditioning (ARB 2015d); Marine Vessel Ships; Aircraft Air Conditioning; Metered Dose Inhaler Aerosol Propellant; Aerosol Propellants from products (consumer, commercial, and industrial); Fire Suppressants; Insulating Foam; Solvents; and Medical Sanitizers.

3. Data Sources

The ARB ODS substitutes model relies on a variety of input data sources. These include internal ARB research, ARB-funded consultant surveys, models, and regulatory data reported under the RMP. A full description of the model inputs and data sources can be found in (ARB 2014c) and in the external documentation technical support document (ARB 2016d).

4. Changes in Estimates

The ARB ODS substitutes model has been updated to include new data reported under the RMP. This data was used to update emission factors, improve equipment population and size estimates, and update assumptions about the type of f-gases commonly used. In addition, parameters used to estimate emissions from residential refrigerator-freezers, consumer aerosol propellants, and medical dose inhaler (MDI) propellants were revised to reflect lower usage based on information from the Department of Energy data (DOE 1997), data provided by the ARB consumer products survey (ARB 2006), and from data reported by the United Nations Environment Programme (UNEP) for MDI propellants (UNEP, 2010; UNEP, 2011; 2012; 2013.) These updates resulted in a reduction in estimated ODS substitutes emissions of 24 percent on average across all years. The general trend in emissions remains the same.

5. Future Improvements

ARB staff will continue to track further updates of information sources to periodically revise the emission time series.

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G. Sulfur Hexafluoride from Use of Electrical Equipment (IPCC 2G1b)

1. Background

Sulfur hexafluoride gas (SF_6) is used by the electric power industry in gas-insulated substations, circuit breakers, and other switchgear because of its dielectric strength and arc-quenching characteristics. Fugitive emissions of SF_6 are the result of leaks through seals of gas-insulated substations and switch gear. SF_6 can also be released during equipment installation and servicing.

2. Methodology

2011+ emissions are reported through the Regulation for Reducing Sulfur Hexafluoride Emissions from Gas Insulated Switchgear (GIS) (ARB 2007d). Emissions for other years are based on USEPA national emission estimates based on information reported by participants in its SF_6 Emission Reduction Partnership for Electric Power Systems (USEPA 2008). 2000-2010 California emissions were estimated by calculating an emission factor based on national SF_6 emissions from USEPA. The emission factor is calculated using a multi-step process: the ratio of California's annual electricity generation to the total US electricity generation was multiplied by the USEPA's SF_6 emissions estimation in 2011. The result was then used to compare with the data directly reported to ARB in 2011 for the GIS regulation, which in turn creates a baseline to inform a generic CA:US SF_6 emission ratio. This ratio is used alongside each year's national estimate to create an estimate for California.

Equation 48: Previous method to estimate SF_6 emissions from use of electrical equipment

$$E_{CA,GHG} = G_{CA} \bullet F_{SF6}$$

Where,

$E_{CA,GHG}$ = California SF_6 emissions (grams)
G_{CA} = Total California electricity generation (watt-hours)
F_{SF6} = SF_6 emission factor

3. Data sources

Estimates of the national SF_6 emissions are from the 1990-2011 USEPA GHG inventory (USEPA 2012a), national and California electricity generation data are from the EIA (EIA 2013c). 2011 through 2014 emissions are reported directly (ARB 2007d). In-state electricity generation is from data discussed in section I.A. California electricity generation imports are from data discussed in section I.B.

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4. Changes in Estimates

No changes were made for the categories included in this section when compared with the estimates in the previous edition of ARB's GHG inventory.

5. Future Improvements

Staff will continue to use California specific data directly reported from ARB's GIS regulation for inventory purposes.

H. Carbon Dioxide Consumption (IPCC 2G4a)

1. Background

Carbon dioxide is used in chemical production, food processing, carbonated beverages, refrigeration, and for enhanced oil recovery (EOR) in petroleum production. Except in the case of EOR (where CO_2 is injected in underground reservoirs), the CO_2 used in these applications is eventually released in the atmosphere.

The CO_2 used for these applications is either produced as a by-product from energy production and industrial processes, as a by-product from EOR, or from naturally occurring CO_2 reservoirs (i.e., used to carbonate beverages). Only CO_2 extracted from naturally occurring CO_2 reservoirs and used for an anthropogenic purpose is included in this sector. This is because the other emission sources are already accounted for in other sectors (e.g., EOR is included in the energy sector) or the CO_2 is biogenic and not included in California's inventory (e.g., ethanol production).

2. Methodology

California's CO_2 consumption emissions are calculated from U.S. emissions, using an annual population scaling factor. USEPA updated their emission methodology for 2014 emissions, but the full time series of emissions were not yet available at the time of California's inventory publication. The growth in USEPA 2014 emissions compared to 2013 was used to estimate California's 2014 emissions.

Equation 49: Emissions from CO_2 consumption

$$E_{CA} = E_{US} \bullet Rpop$$

Where,

E_{CA} = California emissions from CO_2 consumption (g)

E_{US} = US emissions from CO_2 consumption (g)

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Rpop = Ratio of the population of California to the population of the entire US (dimensionless)

3. Data sources

Data for US emissions from CO_2 consumption are from the USEPA national GHG inventory (USEPA 2015g) for 2000-2013. Draft emissions were provided for 2014 ahead of the U.S. Inventory Release (USEPA 2016). Data for California and US population estimates were from the US Census Bureau (USCB Various-b).

For a list of individual activity and parameter values used in the equations, please consult the online documentation annex at: https://www.arb.ca.gov/cc/inventory/doc/methods_00-14/annex_2h_carbon_dioxide_consumption.pdf

4. Changes in Estimates

No changes were made to emission estimation methodologies for this sector compared to the previous inventory version.

5. Future Improvements

ARB staff will incorporate updated USEPA emission methodology or seek to obtain more specific data about California CO_2 consumption for future inventories.

I. Limestone and Dolomite Consumption (IPCC 2G4b)

1. Background

Limestone ($CaCO_3$) and dolomite ($CaCO_3MgCO_3$) are used by a wide variety of industries such as construction, agriculture, chemical and glass manufacture, metallurgy, and environmental pollution control. In some of these applications, limestone (or dolomite) is heated to a high temperature during the process and generates CO_2 as a by-product.

This section accounts for uses of limestone and dolomite resulting in CO_2 emissions in the following applications: flux stone (metallurgical furnaces), flue gas desulfurization systems, chemical stone, mine dusting or acid water treatment, acid neutralization, and sugar refining.

2. Methodology

The USEPA has developed estimates of the national GHG emissions from limestone and dolomite consumption based upon information from the US Geological Survey (USGS Various Years-a). ARB staff estimated emissions from

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limestone and dolomite consumption in California by apportioning U.S. emissions using the ratio of California to U.S. consumption of limestone and dolomite. This approach is consistent with USEPA's Emission Inventory Improvement Program guidance of 2004 (USEPA 2004).

Equation 50: CO_2 emissions from limestone and dolomite consumption

$$E_{CA} = E_{US} \bullet \left(\frac{C_{CA}}{C_{US}} \right)$$

Where,

E_{CA}	= California emissions from limestone and dolomite consumption (g)
E_{US}	= US emissions from limestone and dolomite consumption (g)
C_{CA}	= California limestone and dolomite consumption (tonnes)
C_{US}	= US limestone and dolomite consumption (tonnes)

3. Data sources

Data for US emissions from limestone and dolomite consumption are from the USEPA national GHG inventory (USEPA 2012a, USEPA 2014c). Data for California and national consumption of limestone and dolomite is from the US Geological Survey (USGS Various Years-a).

For a list of individual activity and parameter values used in the equations, please consult the online documentation annex at: https://www.arb.ca.gov/cc/inventory/doc/methods_00-14/annex_2i_limestone_and_dolomite_consumption.pdf

4. Changes in Estimates

There were no methodology changes for this sector compared to the previous inventory version.

J. Soda Ash Consumption (IPCC 2G4c)

1. Background

Sodium carbonate (Na_2CO_3), also called soda ash, is a strongly alkaline chemical used in a variety of industrial processes. The most important use of soda ash is in glass production, but it also enters in the fabrication of many common products such as soap and detergents, paper, textiles and processed food. As soda ash is consumed for these purposes, CO_2 is usually emitted. It is assumed that one mole of C is released for every mole of soda ash used.

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Note that some soda ash manufacturing processes also generate CO_2 emissions. However, according to the USEPA, in California soda ash is manufactured using sodium carbonate-bearing brines instead of trona ore. These complex brines are first treated with CO_2 in carbonation towers to convert the sodium carbonate into sodium bicarbonate, which then precipitates from the brine solution. The precipitated sodium bicarbonate is then calcined back into sodium carbonate. Although CO_2 is generated as a by-product, the CO_2 is recovered and recycled for use in the carbonation stage and is not emitted (USEPA 2012a). For this reason, there is no "Soda ash production" section (IPCC category 2B7) in the California GHG inventory.

2. Methodology

ARB staff used the estimation method recommended by the USEPA Emission Inventory Improvement Program guidance (USEPA 2004). This approach first estimates California's consumption by scaling the national consumption by the ratio of California population to that of the entire United States.

Equation 51: California soda ash consumption

$$C_{CA} = C_{US} \bullet R_{pop}$$

Where,

C_{CA} = California soda ash consumption (g)
C_{US} = US soda ash consumption (g)
R_{pop} = Ratio of the population of California to the population of the entire US (unitless)

Then, the emissions of CO_2 are estimated using the emission factor from IPCC 2006 Guidelines (IPCC 2006h).

Equation 52: CO_2 emissions from soda ash consumption

$$E = C_{CA} \bullet EF$$

Where,

E = CO_2 emissions from soda ash consumption (g)
C_{CA} = California soda ash consumption (g)
EF = CO_2 emission factor (g / g)

3. Data sources

Data for the US soda ash consumption are from the US Geological Survey (USGS Various Years-b), and population estimates for the United States and California come from the US Census Bureau (USCB Various-b). The emission

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factor for soda ash consumption is from the 2006 IPCC Guidelines (IPCC 2006h).

For a list of individual activity and parameter values used in the equations, please consult the online documentation annex at: https://www.arb.ca.gov/cc/inventory/doc/methods_00-14/annex_2j_soda_ash_consumption.pdf

4. Changes in Estimates

There were no changes in emission estimation methodology for this sector compared to the previous inventory version.

K. Fuel Consumption as Feedstock for Hydrogen Production (IPCC 2H3)

1. Background

In California, hydrogen (H_2) production by and for refineries generates substantial amounts of CO_2 because the most common processes use carbon-based feedstock inputs (e.g., methane from natural gas) as a source of hydrogen and emit the carbon as CO_2. Hydrogen production is not a direct part of the petroleum refining process but it provides the hydrogen gas needed to upgrade heavier fractions into lighter, more valuable products.

2. Methodology

2.1 CO_2 emissions

Yearly hydrogen production data from the Oil and Gas Journal's "Historical Worldwide Refinery Survey" database were provided to staff by the Western States Petroleum Association (Shires 2009). This database indicates that two basic types of H_2 production processes are used by California refineries: steam-methane reforming and partial-oxidation. Staff assumed that steam-methane reforming used either natural gas or refinery gas as the methane feedstock source and that partial-oxidation used various hydrocarbons as feedstocks. In the Oil and Gas Journal's database hydrogen gas production rates were reported in million cubic feet per day (MMCFd) capacity, and staff converted these capacity values into estimated production rates of million cubic feet per year (MMCF) by multiplying the original capacity value by 365 days per year. Staff assumed that these were standard cubic feet measured at 60° F and 1 atmosphere of pressure. In the absence of yearly data on the capacity factor (the amount of full capacity actually used), staff used the average capacity factor from ARB's Mandatory Reporting Program in 2009 (84.4 percent) and also used the respective amounts of refinery gas and natural gas used as feedstock in the same 2009 Mandatory Reporting data (42.1 percent refinery

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gas and 57.9 percent natural gas) and applied these to all previous years (2000-2008). For 2009+, Mandatory Reporting data was used for both hydrogen production and feedstock composition.

To estimate the CO_2 emissions from H_2 production, staff made stoichiometric assumptions for each process type as described below.

The steam-methane reforming process was assumed to generate 1 mole of CO_2 for every 4 moles of H_2 produced (when Natural Gas was the feedstock) or 1 mole of CO_2 for every 3.5 moles of H_2 produced (when Refinery Gas was the feedstock):

Equation 53: Steam-Methane reforming process: natural gas feedstock

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$$

Equation 54: Steam-Methane reforming process: refinery gas feedstock

$$CH_3 + 2H_2O \rightarrow CO_2 + 3.5H_2$$

The partial oxidation method was assumed to generate 1 mole of CO_2 for every 3 moles of H_2 produced. This molar ratio is based on the assumption that each carbon in the longer chain carbon molecules was bonded to 2 hydrogen atoms on average, since the other 2 carbon bonds (normally bonded to another 2 hydrogen atoms in methane for a total of 4 hydrogen atoms for each methane carbon) would be most often attached to another carbon atom in the chain.

Equation 55: Partial oxidation stoichiometric assumption

$$CH_2 + 2H_2O \rightarrow CO_2 + 3H_2$$

Based on these assumptions, CO_2 emissions associated with the use of feedstocks in the hydrogen production process (as separate from the fuel burned to produce the steam and heat for the process) can be derived from the volume of hydrogen produced in a given year:

Equation 56: CO_2 emissions from hydrogen production

$$E_{process} = V_{process} \bullet 1{,}195{,}250 \bullet R_{process} \bullet 44$$

Where,

$E_{process}$ = Emissions of CO_2 from feedstocks used in hydrogen production with a given process (grams)

$V_{process}$ = Volume of hydrogen produced with a given process (million cubic feet)

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1,195,250	= Moles of H_2 per million cubic feet (at 60° F and 1 atmosphere of pressure)
$R_{process}$	= stoichiometric molar ratio of CO_2 to H_2 for the given process = 1/4 for steam-methane (natural gas), 1/3.5 for steam-methane (refinery gas) and 1/3 for partial oxidation
44	= molecular weight of CO_2 (grams per mole)

With,

Process	= [steam-methane, partial oxidation]

2.2 Fuel consumed as feedstock

Staff estimated the amount of fuel consumed as feedstock by the hydrogen production processes using their heat content and combustion emission factor. Input fuels were assumed to be natural gas and refinery gas for methane-steam reforming, and various petroleum feedstocks for partial oxidation.

Equation 57: Amount of fuel consumed as feedstock for hydrogen production

$$Q_{fuel} = \frac{E_{process}}{(HC_{fuel} \bullet EF_{fuel})}$$

Where,

Q_{fuel}	= amount of the corresponding fuel consumed by a given hydrogen production process (in units of gallons for liquid fuels or standard cubic feet for gaseous fuels)
$E_{process}$	= Emissions of CO_2 from feedstocks used in hydrogen production with a given process (grams)
HC_{fuel}	= Heat content of the fuel (BTU per unit)
EF_{fuel}	= CO_2 emission factor of the fuel (grams per BTU)

With,

Process	= [steam-methane, partial oxidation]
Fuel	= [natural gas, refinery gas, petroleum feedstock]

3. Data Sources

For years 2000 to 2008, data on hydrogen production capacity from the Oil and Gas Journal's "Historical Worldwide Refinery Survey" database were provided to staff by the Western States Petroleum Association (Shires 2009), and later years were from the MRR (ARB 2015b). Estimates of the respective capacity factors and amounts of refinery gas and natural gas used in the steam-methane reforming process and hydrogen production and feedstocks used also came from the MRR (ARB 2015b). CO_2 emission factors and heat contents are from the MRR (ARB 2015b) or USEPA GHG Reporting Program (USEPA 2012b).

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4. Changes in Estimates

No changes were made to the methods used in this version of the GHG inventory, compared to the previous version.

5. Future Improvements

Staff plans to continue to identify data sets to further refine emissions estimates.

L. Lead Smelting (IPCC 2C5)

1. Background

In the process of lead production, the lead ore or the secondary materials such as lead batteries or scrap lead are heated in blast furnace which results in CO_2 emissions. The treatment of recycled batteries utilized in secondary lead production also generates CO_2 emissions. Lead smelting emissions were first reported in the 2015 edition of the GHG emission inventory, when ARB mandatory reporting data became available.

2. Methodology

2000 through 2010 California emissions were estimated from U.S. emissions scaled to California using annual population data.

Equation 58: CO_2 emissions from Lead production 2000-2010

$$E_{CA} = E_{US} \bullet R_{POP}$$

Where,

E_{CA} = California emissions from lead production (g)
E_{US} = US emissions from lead smelting (g)
R_{POP} = Ratio of population of California to the population of US

2011 through 2014 emissions were taken from facility level reports from USEPA GHGRP and California MRR, which were summed to calculate California's total emissions. Use of facility-specific, reported emissions is consistent with IPPC Tier 3 methodology.

3. Data sources

National CO_2 emissions from lead production for years 2000-2010 were obtained from the USEPA GHG Inventory (USEPA 2015g). Population data were obtained from the California Department of Finance (CDOF 2014). 2011 and

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2012 emissions were reported under USEPA's GHGRP (USEPA 2014d). 2013 and 2014 emissions were reported under ARB's MRR (ARB 2015b).

III. Agriculture, Forestry and Other Land Use

A. Enteric Fermentation (IPCC 3A1)

1. Background

The microbial fermentation that occurs in the digestive system of some animals is called enteric fermentation. It is a normal digestive process during which microbes break down indigestible carbohydrates (e.g., cellulose, hemi-cellulose) and reprocess them into nutrients that can be absorbed by the animal. This microbial fermentation process produces CH_4 as a by-product, which is then exhaled, eructated or passed out as gas by the animal. The amount of CH_4 produced and emitted by an animal depends on its anatomy and the amount and type of feed it consumes.

Among domesticated animal species, ruminants (e.g., cattle, buffalo, sheep, and goats) are the main emitters of CH_4. Ruminants have a large "fore-stomach" with four chambers in which microbial fermentation breaks down the feed they consume into products that can be absorbed and metabolized in the stomach and intestines. This fermentation-based digestive system enables ruminants to live on a diet of coarse plant material. Some non-ruminant domesticated animals (e.g., horses, mules, etc.) also rely on microbial fermentation as part of their digestive system although this microbial fermentation occurs in the caecum and the large intestine. Individuals of these species also emit CH_4 but less than ruminants of similar sizes because the capacity of their fermentation chambers is lower.

Aside from the type of digestive system, the quantity and quality of feed ingested by the animal also affects CH_4 emissions. The amount of food an animal consumes is a function of its size, its growth rate and production (e.g., milk production, wool growth, pregnancy, or work in the case of draft animals), and as the amount ingested increases so does the CH_4 production. As for the quality of the feed, coarser, more fibrous feed (i.e., straw, hay) generally also leads to higher CH_4 emissions than more concentrated feed such as grains.

2. Methodology

The USEPA has developed methods based on the 2006 IPCC guidelines to estimate the GHG emissions from enteric fermentation for the national GHG inventory (USEPA 2015g). For California's GHG inventory, ARB staff extracted

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California specific information from a detailed set of inventory data and model results obtained from the USEPA's Climate Change Division (Wirth 2015).

USEPA used two different methodologies to estimate enteric fermentation emissions: one for cattle and another for other livestock. For complete detail on these methodologies, see Annex 3.10 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks (USEPA 2013e).

2.1 Methane emissions from cattle

Because of their large population, large size, and the fact that they are ruminants, cattle are responsible for the majority of CH_4 emissions from enteric fermentation in the United States. Therefore, USEPA developed a more detailed methodology for cattle, the Cattle Enteric Fermentation Model (CEFM), which tracks cattle sub-populations at different growth and production stages. The methane production is then derived from the gross energy contained in each sub-population's feed intake and the methane conversion rate associated with its diet composition.

The CEFM is an implementation of the Tier 2 methodology of the IPCC guidelines, with the added refinement that cattle sub-populations are modeled on a monthly basis instead of a yearly basis. The steps involved in the CEFM are as follows:

(a) Characterization of cattle populations

The amount of methane emitted by cattle at different stages of their lifecycle varies greatly because of changes in size, growth rate or lactation. Also, while the emissions are reported on a yearly basis, some of these stages may last less than a year (e.g., calves become stockers; stockers enter a feedlot, etc.). USEPA uses a population transition matrix to simulate each stage of the cattle lifecycle on a per month basis to estimate the number of individuals in each cattle sub-population from birth to slaughter. The model disaggregates dairy and beef cattle populations into the categories of Table 32, based upon cattle population data from the U.S. Department of Agriculture statistics (USDA 2016) calving rates, average weights and weight gains, feedlot placement statistics, pregnancy and lactation, and death rates. Dairy cattle populations were scaled to better incorporate the current knowledge of California's dairy population. Dairy cattle population is from the U.S. Department of Agriculture (USDA) census (USDA 2016) which is compiled every 5 years. For the intermediate years that the USDA census does not cover, staff used the trends in California Department of Food and Agriculture (CDFA) annual population estimates (CDFA 2015) to fill in missing years.

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Table 32: Cattle population categories based on life-cycle

Dairy cattle	***Beef cattle***
Dairy cows	Beef cows
Bulls*	Bulls*
Dairy calves	Beef calves
Dairy replacements (7-11 months)	Beef replacements (7-11 months)
Dairy replacements (12-23 months)	Beef replacements (12-23 months)
	Heifer stockers
	Steer stockers
	Feedlot heifers
	Feedlot steers

*Bulls for dairy and beef cattle are combined in a single category

The cattle population numbers from this monthly lifecycle modeling may differ from the annual livestock population data published by the USDA National Agricultural Statistics Service (NASS). The reason being that USDA NASS population numbers are point estimates for a specific date (e.g., January 1 or July 1), whereas the Population transition matrix outputs represent an annual average based on the estimated monthly fluctuations.

(b) Characterization of cattle diets

To determine the digestible energy (DE, the percent of gross energy intake digested by the animal) and CH_4 conversion rates (Y_m, the fraction of gross energy converted to CH_4) for each of the cattle categories, the USEPA collected data on diets considered representative of different regions (California was one of these regions). Data from state livestock specialists for each of the diets were used to estimate feed chemical composition, DE and Y_m for each animal type.

DE values for dairy cows were estimated from results of a literature search. Y_m values for dairy cows were estimated using mechanistic models of the digestive processes occurring in cattle: AAMOLLY (Donovan and Baldwin 1999) and COWPOLL described in Kebreab, Johnson, et al. (2008). For grazing beef cattle, USEPA used diet descriptions to calculate weighted DE values for a combination of forage and supplemental diets. Y_m values for all grazing beef cattle were set at 6.5 percent. For feedlot animals, DE and Y_m values for 1990 were taken from the literature. DE and Y_m values for 2000 onwards were estimated using the MOLLY model as described in Kebreab, Johnson, et al. (2008). Values for 1991 through 1999 were linearly extrapolated based on values for 1990 and 2000.

(c) Calculation of gross energy intake

Gross Energy is derived based on several net energy (NE) estimates and feed characteristics. Net energy equations are provided in the IPCC Guidelines (IPCC 2006d). The general form of these equations is:

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Equation 59: Gross energy intake

$$GE = \frac{\left(\frac{NE_m + NE_{mobilized} + NE_a + NE_l + NE_p}{\frac{NE_{ma}}{DE}} \right) + \left(\frac{NE_g}{\frac{NE_{ga}}{DE}} \right)}{\frac{DE\%}{100}}$$

Where,

GE	= Gross energy (MJ/day)
NE_m	= Net energy required by the animal for maintenance (MJ/day)
$NE_{mobilized}$	= Net energy due to weight loss –mobilization of fat reserves– (MJ/day)
NE_a	= Net energy for animal activity (MJ/day)
NE_l	= Net energy for lactation (MJ/day)
NE_p	= Net energy required for pregnancy (MJ/day)
NE_{ma}	= Net energy available in a diet for maintenance (MJ/Day)
DE	= Digestible energy consumed (MJ/day)
NE_g	= Net energy needed for growth (MJ/day)
NE_{ga}	= Net energy available for growth in a diet (MJ/Day)
DE%	= Digestibility of the diet (digestible energy content in percent)

(d) Calculation of daily emissions

The daily emission factors for each category are computed from the gross energy value and the methane conversion factor, as follows:

Equation 60: Daily CH_4 emission factor for a cattle population category

$$EF = \frac{GE \bullet Y_m}{55.65}$$

Where,

EF	= Emission factor (kg CH_4 per head per day)
GE	= Gross energy intake (MJ per head per day)
Y_m	= CH_4 conversion rate, which is the fraction of gross energy in feed converted to CH_4 (unitless)
55.65	= the energy content of methane (MJ per kg)

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(e) Estimation of yearly emissions

Emissions are then summed for each month for each population category using the daily emission factor for a representative animal and the number of animals in the category, as shown in the following equation:

Equation 61: Yearly CH_4 emissions of a cattle population category

$$E = \sum_{month} EF \bullet D_{month} \bullet N_{month}$$

Where,

E	= Yearly CH_4 emissions of a cattle population category (kg)
EF	= Emission factor for the population category (kg CH_4 per head per day)
D_{month}	= number of days in the month
N_{month}	= number of animals in the population category during the month

With,

Month	= each month of the given year.

This yields the estimated yearly methane emissions for the cattle population category for the given year.

2.2 Methane emissions from other livestock

Following USEPA, ARB staff used the simpler Tier 1 IPCC method to estimate enteric fermentation emissions from bulls and other livestock.

Equation 62: CH_4 emissions of bulls and other livestock

$$E = N \bullet EF$$

Where,

E	= CH_4 emissions of a type of other livestock
N	= Number of individuals of the type of livestock (animals)
EF	= Methane emission factor for the type of livestock (kg per animal per year)

Other livestock population data, except for horses, come from the USDA NASS (USDA 2016) or CDFA (CDFA 2012). California horse population numbers are derived from the United Nations' Food and Agriculture Organization (FAO) FAOSTAT database (FAO 2012) and from an American Horse Council Report (AHC 2005). California's horse population is estimated as follows:

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Equation 63: Estimation of California's horse population

$$H_{CA,year} = H_{US,year} \bullet R$$

Where,

$H_{CA, year}$ = California's horse population for a given year (head)

$H_{US, year}$ = National horse population for a given year (head) from FAOSTAT

R = Ratio of California horse population to US horse population from AHC

Default methane emission factors for these livestock, shown in Table 33 below, are from IPCC Guidelines (IPCC 2006d).

Table 33: Methane emission factors for other livestock (kg/animal/year)

Livestock Type	***Emission Factor***
Horses	18
Sheep	8
Goats	5
Swine	1.5

3. Data Sources

All data used by ARB staff were from a detailed set of data and model results obtained from the USEPA Climate Change Division (Wirth 2015), from the CDFA annual directories (CDFA 2012), the USDA (USDA 2013a, USDA 2014b, USDA 2016), the United Nations Food and Agriculture Organization (FAO 2012), the American Horse Council (AHC 2005) and from the IPCC guidelines (IPCC 2006d).

For a list of livestock population numbers and parameter values used in the estimates, please consult the online documentation annex at: https://www.arb.ca.gov/cc/inventory/doc/methods_00-14/annex_3a_enteric_fermentation.pdf

4. Changes in Estimates

Dairy cattle populations were replaced to better incorporate the current knowledge of California's dairy population. The dairy cattle population is from the USDA census (USDA 2016), which is compiled every 5 years. For the intermediate years that the USDA census does not cover, staff used the trends in CDFA annual population estimates (CDFA 2015) to fill in missing years. This change resulted in minimal changes in emissions.

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B. Manure Management (IPCC 3A2)

1. Background

Anthropogenic CH_4 and N_2O emissions can result from manure management operations. CH_4 is produced by the anaerobic decomposition of manure. N_2O is produced as part of the nitrogen cycle through the microbial nitrification and denitrification of nitrogen in livestock manure and urine.

When livestock or poultry manure is stored or treated in systems that promote anaerobic conditions (such as liquid/slurry, lagoons, tanks, ponds or pits), the decomposition of organic material by methanogenic bacteria produces CH_4 emissions. Manure stored as a solid (e.g., in stacks or drylots) or deposited on pasture, range, or paddock lands, tends to decompose aerobically and produce little or no CH_4. Temperature, moisture, residency time are factors that affect the amount of CH_4 produced by bacteria. The quality of the feed also plays a role; manure from animals eating higher energy content feed has greater potential for CH_4 emissions.

Manure and urine composition, the type of bacteria involved in the process, and the amount of oxygen and liquid in the manure system influence the amount of N_2O emissions. Overall only a small portion of the excreted nitrogen is converted to N_2O during manure management operations.

Note that N_2O emissions from livestock manure and urine deposited on pasture, range, or paddock lands, and emissions from manure and urine spread onto fields either directly as "daily spread" or after it is removed from manure management systems are discussed and estimated in Section III.F.

2. Methodology

The USEPA developed methods to estimate the CH_4 and N_2O emissions from manure management for the national GHG inventory (USEPA 2013d). ARB staff extracted California specific information from a detailed set of data and parameters obtained from the USEPA Climate Change Division (Wirth 2015) and computed emissions for California's GHG inventory using USEPA's methodology.

USEPA methods are consistent with the Tier 2 methodology of the IPCC Guidelines (IPCC 2006d). For complete detail on these methodologies, see Annex 3.11 of the Inventory of U.S. Greenhouse Gas Emissions and Sinks (USEPA 2013d).

The estimation of CH_4 and N_2O emissions involves the following steps:

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2.1 Characterization of livestock populations

First, animal population data are compiled into livestock groups reflecting differences in diet, size and animal management systems (Table 34). Annual animal population data for cattle are from USEPA's Cattle Enteric Fermentation Model (CEFM) population transition matrix, with updated dairy population estimates as discussed in section III.A.2.1(a). Other species population data are from the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) (USDA 2016) except for horses. Horse population data were derived from the United Nations' Food and Agriculture Organization (FAO) FAOSTAT database (FAO 2012) and an American Horse Council Report (AHC 2005) as described in section III.A.2.2. Goat population data were obtained from the Census of Agriculture. Additional data sources and personal communications with experts used to make adjustments to these data are described in the USEPA inventory report (USEPA 2014b).

Table 34: Livestock groups used for manure management emissions estimates

Dairy Cattle	Beef Cattle	Swine	Poultry	Others
▪ Dairy Cows ▪ Dairy Heifers	▪ Beef Cows ▪ Bulls >500 lbs ▪ Calves <500 lbs ▪ Heifers >500 lbs ▪ Steers >500 lbs ▪ Feedlot Heifers > 500 lbs ▪ Feedlot Steers > 500 lbs	▪ Breeding ▪ Market <50 lbs ▪ Market 50-119 lbs ▪ Market 120-179 lbs ▪ Market 180+ lbs	▪ Layer Hens >1 yr ▪ Layers – Pullets ▪ Layers – Chickens ▪ Broilers ▪ Turkeys	▪ Sheep ▪ Goats ▪ Horses

2.2 Characterization of animal waste

Methane and nitrous oxide emissions estimates are based on the following animal characteristics for each of the relevant livestock groups:

- Typical animal mass (TAM), in kg per animal
- Volatile solids excretion rate (VS) in kg per year. Excreted volatile solids are the portion of organic matter in the diet that was not digested by the animal and is thus available for use by methanogenic bacteria. For cattle, it is calculated by the enteric fermentation model of Section III.A above. For other species values are based on measurements from the literature and are adjusted for the typical animal mass of animals in the group.
- Maximum methane producing capacity (B_0) of excreted volatile solids (m^3 of CH_4 per kg of VS). This is a characteristic of the volatile solids found in a particular livestock group's manure.
- Nitrogen excretion rate (Nex). This is the amount of Kjeldahl nitrogen excreted per animal per year (g of N per year). For cattle, it is calculated by the enteric fermentation model of Section III.A above. The values used for other species are based on measurements made on manure of each of the livestock groups.

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For further information about how to calculate VS for cattle, swine and poultry, as well as the sources of data for the VS, TAM and B_0 parameters see (USEPA 2014b).

2.3 Compilation of waste management system usage Data

USEPA compiled data on the distribution of the manure of the various livestock groups among waste management systems, by state and by year. Table 35 and Table 36 show the distribution of livestock manure among waste management systems in California. Note that the manure that is directly deposited on pasture, range or paddocks, or spread daily does not actually enter a "waste management system". This un-managed manure is listed here for completeness of the animal waste distribution. Estimates of nitrogen inputs from both managed and un-managed manure will be used in the Nitrous Oxide from Managed Soils category of the inventory (see III.F below).

Table 35: Waste distribution of cattle, goats, horses and sheep manure in California

Waste System	Beef cattle (not on feed)	Feedlot heifers and steers	Dairy Cows	Dairy Heifers	Goats	Horses	Sheep
Anaerobic digester			✓				
Anaerobic lagoon			✓				
Daily spread*			✓	✓			
Deep pit			✓				
Dry lot		✓		✓	✓	✓	✓
Liquid / slurry		✓	✓	✓			
Pasture*	✓		✓	✓	✓	✓	✓
Solid Storage			✓				

* Un-managed manure: manure that is directly deposited on pasture, rangeland, or paddock, or is spread daily on agricultural land.

Table 36: Waste distribution of swine and poultry manure in California

Waste System	Poultry - Layers	Poultry - Pullets	Poultry - Chickens	Poultry - Broilers	Poultry - Turkeys	Swine - Market	Swine - Breeding
Anaerobic digester						✓	✓
Anaerobic lagoon	✓	✓	✓			✓	✓
Deep pit						✓	✓
Liquid / slurry	✓	✓	✓			✓	✓
Pasture*				✓	✓	✓	✓
Poultry with bedding				✓	✓		
Poultry without bedding	✓	✓	✓				
Solid Storage	✓	✓	✓			✓	✓

* Un-managed manure: manure that is directly deposited on pasture, rangeland, or paddock.

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2.4 Calculation of Methane Conversion Factors (MCF)

The methane conversion factor (MCF) is the portion of the maximum methane producing capacity of the manure that is achieved in given conditions. It varies with the waste management system and with temperature. Climate-based default values from the 2006 IPCC Guidelines (IPCC 2006d) are used for all dry systems. For lagoons and liquid systems, USEPA developed a country-specific methodology using the van't Hoff-Arrhenius equation to estimate MCFs that reflects the seasonal changes in temperatures, and also accounts for long-term retention time. State-specific MCF values are derived using monthly weighted-average temperatures for the state, calculated using the population estimates and average monthly temperature in each county. For lagoon systems MCF values also account for a variety of factors that may affect methane production in lagoon systems.

In the particular case of anaerobic digesters, the MCF reflects the proportion of methane actually released to the atmosphere. To estimate it, USEPA assumed that anaerobic digester systems produce 90 percent of the maximum CH_4 producing capacity; have a collection efficiency of 75 percent in the case of covered lagoon systems and 99 percent for complete mix and plug flow systems; and that the methane destruction efficiency from flaring or burning in an engine was 98 percent.

2.5 Estimation of methane emissions

Methane emissions of each combination of the livestock group and waste management system are then calculated using the following equations:

Equation 64: CH_4 emissions in in each animal group and manure management system

$$E_{group,system} = P_{group} \bullet WMS_{group,system} \bullet VS_{group} \bullet MCF_{group,system} \bullet B_{0,group} \bullet 662$$

Where,

$E_{group,\ system}$ = CH_4 emissions of the given livestock group in the particular waste management system (grams per year)

P_{group} = Number of animals in the livestock group (heads)

$WMS_{group,\ system}$ = Proportion of animals in the group whose manure is managed in the particular waste management system (fraction)

VS_{group} = Volatile Solids Production rate of livestock group (kg per head per year)

$MCF_{group,\ system}$ = Methane conversion factor for the given group in the particular waste management system (fraction)

$B_{o,\ group}$ = Maximum methane producing capacity of the VS in manure of the given animal group (m^3 per kg)

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662 = Density of methane (g / m^3), at 22°C and 1 atm.

With,

Group = livestock group from Table 34

System = waste management system from Table 35 and Table 36.

Equation 65: Total CH_4 emissions from manure management

$$E = \sum_{group,system} E_{group,system}$$

Where,

E = CH_4 emissions from manure management (grams per year)

$E_{group,\ system}$ = CH_4 emissions of the given livestock group in the particular waste management system (grams per year)

With,

Group = livestock group from Table 34

System = waste management system from Table 35 and Table 36.

2.6 Nitrous oxide emission factors

Direct N_2O emission factors for manure management systems (g N_2O-N/g excreted N) were taken from the most recent default IPCC factors (IPCC 2006d) and are presented below.

Table 37: Direct N_2O emission factors

Management system	Direct N as N2O EF
Anaerobic digester	0
Anaerobic lagoon	0
Daily spread	0
Deep pit	0.002
Dry lot	0.02
Liquid/slurry	0.005
Pasture	0
Poultry with bedding	0.001
Poultry without bedding	0.001
Solid storage	0.005

Indirect N_2O emission factors account for two fractions of nitrogen losses: volatilization of ammonia (NH_3) and NO_X (volatilized fraction) and runoff/leaching (runoff fraction). IPCC default indirect N_2O emission factors were used. These factors are 0.010 g N_2O-N/g N for volatilization and 0.0075 g N_2O-N/g N for runoff and leaching.

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USEPA has developed region-specific estimates of nitrogen losses for the volatilized fraction and the runoff/leaching fraction for the U.S using available data. Nitrogen losses from leaching are believed to be small in comparison to the runoff losses; therefore, the runoff/leaching fraction was set equal to the runoff loss factor. Values for individual combinations of animal group and waste management system are available in the online annexes to this document and in (USEPA 2014b).

2.7 Estimation of nitrous oxide emissions

Nitrous oxide emissions of each combination of livestock group and waste management system are then calculated using the following equation:

Equation 66: N_2O emissions in each animal group and manure management system

$$E_{group,system} = P_{group} \bullet WMS_{group,system} \bullet NER_{group} \bullet \begin{bmatrix} DEF_{system} + (VF_{group,system} \bullet VEF) \\ + (RF_{group,system} \bullet REF) \end{bmatrix} \bullet 1.5711$$

Where,

$E_{group, system}$ = N_2O emissions of the given livestock group in the particular management system (grams)

P_{group} = Number of animals in the livestock group (heads)

$WMS_{group, system}$ = Proportion of animals in the group whose manure is managed in the particular waste management system (fraction)

NER_{group} = Nitrogen excretion rate of animals in the group (g per year)

DEF_{system} = Direct N as N_2O emission factor for the particular management system (g N_2O-N per g N)

$VF_{group, system}$ = Volatilization fraction of N for the given animal group in the particular management system (fraction)

VEF = Indirect N as N_2O emission factor for re-deposited volatilized N (g N_2O-N per g N)

$RF_{group, system}$ = Runoff fraction of N for the given animal group in the particular management system (fraction)

REF = Indirect N as N_2O emission factor for runoff N (g N_2O-N per g N)

1.5711 = Molecular weight ratio of N_2O to N_2

With,

Group = livestock group from Table 34

System = waste management system from Table 35 and Table 36

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Equation 67: Total N_2O emissions from manure management

$$E = \sum_{group,system} E_{group,system}$$

Where,

E = N_2O emissions from manure management (grams per year)

$E_{group,\ system}$ = N_2O emissions of the given livestock group in the particular waste management system (grams per year)

With,

Group = livestock group from Table 34

System = waste management system from Table 35 and Table 36

3. Data Sources

All data used by ARB staff were from a detailed set of data and parameters obtained from the USEPA Climate Change Division (USEPA 2014b), and from the IPCC guidelines (IPCC 2006d).

For a complete list of livestock population numbers and parameter values used in the estimates, please consult the online documentation annex at: https://www.arb.ca.gov/cc/inventory/doc/methods_00-14/annex_3b_manure_management.pdf

4. Changes in Estimates

Only minor changes to dairy population numbers were made in the current estimation of emissions from manure management. These updates resulted in negligible adjustments in emissions estimates for the categories included in this section compared to the previous edition of ARB's GHG inventory.

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C. Land - Forests and Rangelands (IPCC 3B)

1. Background

Forest sector emissions and sequestration estimates are not included in the current GHG emission inventory. These estimates are under development.

2. Future Improvements

The ARB contracted researchers from University of California (UC) Berkeley to develop a new data-driven methodology for assessing carbon stock changes for all land in California except agricultural and urban areas. The new methods use California specific land based data sets and satellite remote sensing data. The covered ecosystems include forests, woodlands, shrub lands,

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grasslands, and wetlands. Data sources for the new method include Forest Inventory and Analysis (FIA) ground-based data (vegetation type, tree species and dimensions, percent canopy cover, etc.) from the USDA-Forest Service, remote sensing products from NASA's MODIS sensor, geospatial vegetation data (vegetation community type, canopy height, percent canopy cover) from the federal Landscape Fire and Resource Management Planning Tools Project (Landfire), geospatial fire and harvest occurrence data from CalFIRE, and ancillary data on shrub lands and grasslands.

The method enables analysts to retrospectively assess ecosystem carbon stock changes resulting from fire, human activities, and other processes. It will enable monitoring of changes on the land over time and periodic quantification of the GHG flux associated with changes in ecosystem carbon stocks. The research has generated a wealth of new data to support a planned update to the GHG inventory.

Additional work is needed to evaluate the data provided by the UC Berkeley research, to incorporate additional new data, and to identify further research needed to expand use of these tools. The sources and methods for quantifying ecosystem carbon and GHG flux in this sector are complex. Continued refinements will advance carbon quantification, attribution of GHG flux by disturbance process, and reduce uncertainty.

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D. Agricultural Residue Burning (IPCC 3C1b)

1. Background

Open burning of agricultural biomass is a common practice in California and a source of N_2O and CH_4 emissions. Carbon dioxide (CO_2) emissions from agricultural biomass burning is not considered a net source of emissions because the carbon released to the atmosphere as CO_2 from the combustion of agricultural biomass is assumed to have been absorbed during the previous (or a recent) growing season. Therefore, emissions from CO_2 are estimated but not included in California's GHG inventory total.

2. Methodology

The methodology for estimating GHG emissions from agricultural residue burning of agricultural biomass is consistent with the IPCC Tier 2 approach as it uses California specific emission factors. Researchers at University of California, Davis developed emission factors for six crops including, almond, walnut, wheat, barley, corn and rice (Jenkins, Turn et al. 1996). These six crops account for a majority of the orchard and field biomass burned in California. Emissions are calculated as follows:

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Equation 68: GHG emissions from residue burning

$$E_{GHG,crop} = A_{crop} \bullet 0.404685642 \bullet FB_{crop} \bullet MR_{crop} \bullet EF_{GHG,crop}$$

Where,

$E_{GHG,\ crop}$ = Emissions of the given GHG from the given crop residue burning (g)

A_{crop} = Harvested area of the given crop (acres)

0.404685642 = Acres to hectares conversion factor

FB_{crop} = Fraction of harvested area on which crop residues are burned (unitless)

MR_{crop} = Mass of the given crop's residue (g dry matter per ha)

$EF_{GHG,\ crop}$ = Emission factor for the given GHG and crop (unit mass of GHG per unit mass of residue dry matter)

With,

GHG = [CO_2b, CH_4, N_2O]

Crop = [Almond, Barley, Corn, Rice, Walnut, Wheat]

3. Data Sources

Harvested crop acreage was obtained from the U.S. Department of Agriculture (USDA 2016). The fractions of crop acreage on which residues are burned, and the mass of residue burned are taken from survey data gathered and published by Jenkins, Turn et al. (1992) and assumed to have remained constant since, except for rice. The 1991 rice straw burning phase-down law required the incremental reduction of rice straw burning in the Sacramento Valley. Rice straw burning decreased over a period of ten years, with progressively fewer acres of rice fields burned each year. An ARB progress report (ARB 2003) on the phase down of rice straw burning provided the percent of acres planted that were actually burned per year until 2002. For later years, the percent of rice acres burned was based upon data compiled by Les Fife, Sacramento Valley Basinwide Air Pollution Control Council Burn Coordinator. Given that more than 96 percent of rice grown in California is grown in the Sacramento Valley, staff used the percent of rice acreage burned in the Sacramento Valley as the value for the rest of the state acreage. Emission factors are taken from a study report by UC researchers (Jenkins, Turn et al. 1996).

For a list of parameter values used in the equations, please consult the online documentation annex at: https://www.arb.ca.gov/cc/inventory/doc/methods_00-14/annex_3d_agricultural_residue_burning.pdf

4. Changes in Estimates

No change was made to this inventory category.

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5. Future Improvements

Local air districts have phased down agricultural burning in many regions to protect public health and reduce criteria pollutant emissions. This decline in agricultural burning is not accounted for in the current version of California's GHG inventory, except for rice. Future inventory versions will explore metrics to account for agricultural burning phase downs.

E. Carbon Dioxide from Liming (IPCC 3C2)

1. Background

Liming is used to reduce soil acidity and thus improve plant growth in agricultural fields and managed forests. Adding carbonates to soils in the form of "lime" (e.g., calcic limestone ($CaCO_3$), or dolomite ($CaMg(CO_3)_2$) leads to CO_2 emissions as the carbonate in limes dissolve and release bicarbonate ($2HCO_3^-$), which evolves into CO_2 and water (H_2O).

2. Methodology

ARB staff used methods consistent with the Tier 1 methodology of the 2006 IPCC Guidelines (IPCC 2006e). Total CO_2 emissions from liming are estimated as follows:

Equation 69: CO_2 emissions from liming

$$E = \left[\left(M_L \bullet EF_L\right) + \left(M_D \bullet EF_D\right)\right] \bullet 3.6642$$

Where,

E	= CO_2 emissions from liming (g)
M_L	= Mass of limestone applied to soils (g)
EF_L	= Limestone C emissions factor (0.12 g C per g limestone)
M_D	= Mass of dolomite applied to soils (g)
EF_D	= Dolomite C emissions factor (0.13 g C per g dolomite)
3.6642	= Molecular weight ratio of CO_2 to C

To estimate the mass of limestone and dolomite applied to soils from reported amount of "lime" (not distinguishing between limestone and dolomite) applied to agricultural soils, staff used the following equations:

Equation 70: Mass of limestone applied to soils

$$M_L = L_{AG} \bullet \frac{T_L}{(T_L + T_D)}$$

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Equation 71: Mass of dolomite applied to soils

$$M_D = L_{AG} \bullet \frac{T_D}{(T_L + T_D)}$$

Where,

M_L	= Mass of limestone applied to soils (g)
M_D	= Mass of dolomite applied to soils (g)
L_{AG}	= Total "lime" applied to agricultural soils in California (g)
T_L	= Total limestone sold or used in California (g)
T_D	= Total dolomite sold or used in California (g)

Reported data for total "lime" applied to agricultural soils in California (L_{AG}) was not available for 2013 and 2014. 2013 and 2014 L_{AG} was estimated using the percent change in total agricultural acres in production for 2012 compared to 2013 and 2014, respectively.

3. Data Sources

Data for the mass of "lime" applied to agricultural soils are from yearly editions of the *Fertilizing Materials Tonnage Report* published by the California Department of Food and Agriculture (CDFA Various Years). The total crop acreage for 2012 through 2014 was from United States Department of Agriculture National Agricultural Statistics Service (USDA 2016). Limestone and dolomite sold or used in California are reported in the *Minerals Yearbook* by the U.S. Geological Survey (USGS Various Years-a). Limestone and dolomite emission factors are from the 2006 IPCC Guidelines (IPCC 2006e).

For a list of individual activity and parameter values used in the equations, please consult the online documentation annex at:
https://www.arb.ca.gov/cc/inventory/doc/methods_00-14/annex_3e_carbon_dioxide_from_liming.pdf

4. Changes in Estimates

No change was made to the methods or data used for these estimates.

F. Nitrous Oxide from Managed Soils (IPCC 3C4 & 3C5)

1. Background

The large scale input of nitrogen into soils has greatly increased the nitrogen availability for microbial processes such as nitrification and denitrification. N_2O is an intermediate gaseous product of denitrification and a by-product of nitrification that leaks from microbial cells into the soil and ultimately into the atmosphere. N_2O emissions occur from agricultural crops, and also from

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residential and commercial sources such as lawns, business parks, and golf courses. There are many sources of nitrogen input into soils aside from synthetic fertilizers: application of organic fertilizers, manure and sewage sludge; decomposition of crop residues; and mineralization of N in soil organic matter following drainage of organic soils (histosols). All these human activities increase the supply of mineral nitrogen, and therefore N_2O emissions from soils. These emissions are called *direct emissions* because they occur directly from the soils to which N is applied, and are reported under IPCC category 3C4.

In addition to the direct emissions of N_2O from managed soils, emissions of N_2O also take place through two indirect pathways. The first indirect pathway is the volatilization of a portion of the applied nitrogen as NH_3 and oxides of N (NO_x). Eventually, this volatilized N is deposited onto soils and the surface of lakes and other waters where nitrification and denitrification processes cause additional N_2O emissions. The second pathway is the leaching and runoff from land of N from synthetic and organic fertilizer additions, crop residues, mineralization of N in soil organic matter following drainage of organic soils, and urine and dung deposition from grazing animals. This nitrogen ends up in the groundwater, in riparian zones receiving drain or runoff water, or in the ditches, streams, rivers and estuaries (and their sediments) into which the land drainage water eventually flows. Once in waterbodies, the nitrogen will enhance nitrification and denitrification processes that produce N_2O emissions. These *indirect emissions* are reported under IPCC category 3C5.

Emissions from agricultural use of nitrogen and commercial and residential use of nitrogen are calculated using the same methodology. All nitrogen applied to commercial and residential lands is assumed to be synthetic.

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2. Methodology

ARB staff used emission factor equations, which are based on the USEPA Emission Inventory Improvement Program (EIIP) guidance (USEPA 2004b) and the Tier 1 methodology of the 2006 IPCC guidelines (IPCC 2006e).

2.1 Emission Estimation

N_2O emissions are estimated separately for direct emissions and indirect emissions. The following equations describe the IPCC methods and steps in calculating N_2O emissions from managed soils.

(a) Direct N2O emissions (IPCC category 3C4)

Direct N_2O emissions are calculated with the following equation:

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Equation 72: Direct N_2O emissions from managed soils

$$E_{direct} = \left\{ \begin{array}{l} [N_{SF} + N_{OF} + N_{MM} + N_{CR}] \bullet EF_1 \\ + N_{UM,CPP} \bullet EF_{2,CPP} + N_{UM,SGH} \bullet EF_{2,SGH} \\ + A_{OS} \bullet EF_3 \end{array} \right\} \bullet 1.5711$$

Where,

E_{direct}	= Direct N_2O emissions from managed soils (kg N_2O)
N_{SF}	= N from synthetic fertilizers applied to soils (kg N)
N_{OF}	= N from organic fertilizers applied to soils (kg N)
N_{MM}	= N from managed manure spread on soils (kg N)
N_{CR}	= N in crop residues that is returned to soils (kg N)
$N_{UM, CPP}$	= N from un-managed manure from grazing cattle, poultry and pigs (kg N)
$N_{UM, SGH}$	= N from the un-managed manure from grazing sheep, goats and horses (kg N)
A_{OS}	= Area of drained organic soil (histosols) (ha)
EF_1	= Emission factor: proportion of N applied to agricultural soils that is emitted as N_2O
$EF_{2, CPP}$	= Emission factor: proportion of N from cattle, poultry and pigs un-managed manure that is emitted as N_2O
$EF_{2, SGH}$	= Emission factor: proportion of N from sheep, goats and horses un-managed manure that is emitted as N_2O
EF_3	= Emission factor: N emitted as N_2O per unit area of cultivated of organic soils (kg N per ha)
1.5711	= Molecular weight ratio of N_2O to N_2

(b) Indirect N2O emissions (IPCC category 3C5)

Indirect N_2O emissions are calculated with the following equations:

Equation 73: Indirect N_2O emissions from managed soils

$$E_{indirect} = E_V + E_{LR}$$

Where,

$E_{indirect}$	= Indirect N_2O emissions from managed soils (kg N_2O)
E_V	= Indirect N_2O emissions through nitrogen volatilization (kg N_2O)
E_{LR}	= Indirect N_2O emissions through nitrogen leaching and runoff (kg N_2O)

(b.i) Emissions from volatilization (E_V)

Indirect emissions from volatilized N are estimated as follows:

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Equation 74: Indirect N_2O emissions from volatilization

$$E_V = \left[N_{SF} \bullet V_1 + (N_{OF} + N_{MM} + N_{UM}) \bullet V_2\right] \bullet EF_4 \bullet 1.5711$$

Where,

E_V	= Emissions of N_2O from volatilization (kg)
N_{SF}	= N from synthetic fertilizers applied to soils (kg N)
N_{OF}	= N from organic fertilizers applied to soils (kg N)
N_{MM}	= N from managed manure applied to soils (kg N)
N_{UM}	= N from un-managed manure [$N_{UM, CPP}$ + $N_{UM, SGH}$] (kg N)
V_1	= Fraction of synthetic fertilizer N that volatilizes (unitless)
V_2	= Fraction of organic fertilizer and manure N that volatilizes (unitless)
EF_4	= Emission factor: proportion of N volatilized and re-deposited on soils that is emitted as N_2O

(b.ii) Emissions from leaching and runoff (E_{LR})

Indirect emissions from N lost to leaching and runoff are estimated as:

Equation 75: Indirect N_2O emissions from N lost to leaching and runoff

$$E_{LR} = \left[N_{SF} + N_{OF} + N_{MM} + N_{UM}\right] \bullet L \bullet EF_5 \bullet 1.5711$$

Where,

E_{LR}	= Emissions of N_2O from leaching and run-off (kg)
N_{SF}	= N from synthetic fertilizers applied to soils (kg N)
N_{OF}	= N from organic fertilizers applied to soils (kg N)
N_{MM}	= N from managed manure applied to soils (kg N)
N_{UM}	= N from un-managed manure [$N_{UM, CPP}$ + $N_{UM, SGH}$] (kg N)
L	= Leaching factor: proportion of N lost by leaching and runoff for regions where the soil water-holding capacity is exceeded as a result of rainfall and/or irrigation.
EF_5	= Emission factor: Proportion of N lost to leaching and runoff that is emitted as N_2O

The values for the emission, volatilization and leaching-runoff factors are given in Table 38.

Table 38: Factors for the estimation of N_2O emissions from soil management

Emission factor	***Description***	***Default Value***
EF1	Proportion of N applied to agricultural soils that is emitted as N_2O	0.01
EF2, CPP	proportion of N deposited on pastures, rangelands, and paddocks by cattle, poultry and pigs [PRP–CPP] that is emitted as N_2O	0.02
EF2, SGH	proportion of N deposited on pastures, rangelands, and paddocks	0.01

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Emission factor	Description	Default Value
	by sheep, goats, horses [PRP–SGH] that is emitted as N_2O	
EF3	N emitted as N_2O per unit area of drained organic soils (kg N per ha)	8
EF4	Proportion of N volatilized and re-deposited on soils that is emitted as N_2O	0.01
EF5	Proportion of N lost to leaching and runoff that is emitted as N_2O	0.0075
V1	Fraction of synthetic fertilizer N that volatilizes	0.1
V2	Fraction of organic fertilizer and manure N that volatilizes	0.2
L	Leaching rate: fraction of N lost by leaching and runoff for regions where the soil water-holding capacity is exceeded as a result of rainfall and/or irrigation	0.3

Source: IPCC 2006 guidelines.

2.2 Calculation of nitrogen inputs from various sources

To limit the number of subcategories in the inventory, staff compiled the nitrogen inputs from synthetic and organic fertilizers, animal manure, and crop residues and aggregated them into the following categories.

(a) Synthetic fertilizer for residential and commercial use

Nitrogen fertilizer applied to residential and commercial soils was calculated from estimates of total turf grass area in California, the fraction of turf grass that is residential or commercial, and recommended nitrogen application rates for residential or commercial uses (Equation 76 and Equation 77). Fertilizer use was not differentiated into synthetic versus organic due to lack of activity data; therefor, all nitrogen was assumed to be synthetic.

Equation 76: Residential Nitrogen Use

$$N_{Res} = \frac{F_{Res} \bullet A_{Turf} \bullet R_{Fert,Res}}{907.185}$$

Where,

N_{Res} = Amount of N from fertilizer applied to residential turf (short tons)

F_{Res} = Fraction of turf acreage that is residential

A_{Turf} = Total area of turf grass in California (ha)

$R_{Fert,Res}$ = Average N fertilizer application rate for residential turf (kg N/ ha)

1/907.185 = conversion factor from kg to short tons

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Equation 77: Commercial Nitrogen Use

$$N_{Com} = \frac{F_{Com} \bullet A_{Turf} \bullet R_{Fert,Com}}{907.185}$$

Where,

N_{Com} = Amount of N from fertilizer applied to commercial turf (short tons)

F_{Com} = Fraction of turf acreage that is commercial

A_{Turf} = Total area of turf grass in California (ha)

$R_{Fert,Com}$ = Average N fertilizer application rate for commercial turf (kg N/ ha)

1/907.185 = conversion factor from kg to short tons

(b) Synthetic and organic fertilizers for agricultural use

Nitrogen in synthetic and organic fertilizers applied to agricultural soils was calculated using the harvested crop acreage multiplied by the crop-specific recommended nitrogen application rate (Table 39). Organic nitrogen applied to soils was subtracted from the total nitrogen use to obtain the synthetic fertilizer use.

Equation 78: Agricultural Nitrogen Use

$$N_{Ag,i,j} = A_{i,j} \bullet R_{Fert,i}/2{,}000$$

Where,

i refers to the year

j refers to crop

$N_{Ag,i,j}$ = Amount of total (synthetic + organic) N fertilizer applied to agricultural soil (tons)

$A_{i,j}$ = Area harvested (ac)

$R_{Fert,j}$ = Crop-specific N fertilizer application rate (lbs N/ ac)

1 / 2,000 = conversion from pounds to short tons

Table 39. Crop-specific nitrogen application rates used to calculate organic and synthetic fertilizer used by agricultural in California

Crop	Nitrogen Applied per Acre (lbs)	Crop	Nitrogen Applied per Acre (lbs)
ALMONDS	200	MELONS, HONEYDEW	163
APPLES	42	MELONS, WATERMELON	151
APRICOTS	75	MINT, OIL	150
ARTICHOKES	215	NECTARINES	104
ASPARAGUS	150	OATS	62.5
AVOCADOS	165	OKRA	150
BARLEY	177	OLIVES	135

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Crop	Nitrogen Applied per Acre (lbs)	Crop	Nitrogen Applied per Acre (lbs)
BEANS, DRY EDIBLE	91	ONIONS, DRY	212
BEANS, GREEN, LIMA	129	ONIONS, GREEN	212
BEANS, SNAP	129	ORANGES	110
BEETS	187.5	PARSLEY	150
BROCCOLI	190	PEACHES	151
BRUSSELS SPROUTS	235	PEANUTS	150
CABBAGE, CHINESE	235	PEARS	160
CABBAGE, HEAD	235	PEAS, CHINESE (SUGAR & SNOW)	129
CARROTS	216	PEAS, GREEN, (EXCL SOUTHERN)	129
CAULIFLOWER	238	PECANS	200
CELERY	259	PEPPERS, BELL	275
CHERRIES, SWEET	60	PEPPERS, CHILE	300
CHERRIES, TART	60	PERSIMMONS	60
CHESTNUTS	200	PISTACHIOS	175
CHICORY	150	PLUM-APRICOT HYBRIDS	125
CITRUS, OTHER	110	PLUMS	125
CORN, GRAIN	213	POMEGRANATES	100
CORN, SILAGE	245	POTATOES	248
COTTON	174	PRUNES	150
CUCUMBERS	150	PUMPKINS	108
DAIKON	150	RADISHES	216
DATES	246	RICE	130
EGGPLANT	150	RYE	80
ESCAROLE & ENDIVE	193	SAFFLOWER	104
FIGS	100	SORGHUM, GRAIN	120
GARLIC	150	SORGHUM, SILAGE	120
GRAPEFRUIT	110	SPINACH	193
GRAPES, RAISIN TYPE	44	SQUASH	108
GRAPES, TABLE TYPE	43	SUGARBEETS	187.5
GRAPES, WINE TYPE	27	SUNFLOWER	90
GREENS, COLLARD	193	SWEET CORN	213
GREENS, KALE	193	SWEET POTATOES	126
GREENS, MUSTARD	193	TANGELOS	110
GREENS, TURNIP	193	TANGERINES	110
GUAVAS	150	TOMATOES, IN THE OPEN	177
HAY, (EXCL ALFALFA)	140	TRITICALE	177
HAY, ALFALFA	15	TURNIPS	216
HAYLAGE, (EXCL ALFALFA)	140	VEGETABLES, MIXED	150
HAYLAGE, ALFALFA	15	VEGETABLES, OTHER	150
HERBS, DRY	150	WALNUTS, ENGLISH	200
HERBS, FRESH CUT	150	WHEAT	177
JOJOBA	150	WHEAT, SPRING, (EXCL DURUM)	177
KIWIFRUIT	110	WHEAT, SPRING, DURUM	177
LEMONS	130	WHEAT, WINTER	177
LETTUCE	193	WILD RICE	130
LIMES	130	STRAWBERRIES	193
MACADAMIAS	200	RASPBERRIES	90
MELONS, CANTALOUP	163		

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(c) Animal manure nitrogen applied to soils

The amount of nitrogen in animal manure is estimated in the manure management section (see III.B.2above). The amount of N in managed manure applied to soils (N_{MM}) is calculated as the total N excreted by animal groups in manure management systems minus the amount of nitrogen lost to volatilization, runoff and direct N_2O emissions during the manure management phase. The amount of N applied to soils in un-managed manure is equal to the total N excreted by animal groups depositing their urine and dung directly on the land (i.e. pasture, rangeland and paddocks) and animal groups whose manure is spread daily.

(d) Crop residue nitrogen

The amount of nitrogen from crop residues (N_{CR}) comprises above-ground and below-ground residues N and includes N-fixing crops. The nitrogen is returned to the soil as the crop is renewed. Crops are generally renewed on an annual basis, with some exceptions such as alfalfa which is typically renewed every four years. Since the combustion of residue causes most of its nitrogen to be volatilized, an adjustment must be made for burning of crop residue. N_{CR} is calculated using the following equations, the variables and regression parameters used in the equations are from the IPCC guidelines (Table 11.2 in IPCC 2006e) unless the source is noted otherwise:

Equation 79: Amount of nitrogen input from crop residues

$$N_{CR} = \sum_{crop} \left(N_{AGR,crop} + N_{BGR,crop} \right)$$

Where,

N_{CR} = Amount of N in crop residues that is returned to soils (kg)

$N_{AGR,\ crop}$ = Amount of N in the above-ground residues of the given crop (kg)

$N_{BGR,\ crop}$ = Amount of N in the below-ground residues of the given crop (kg)

With,

Crop = crops listed in Table 41.

The amount of nitrogen in the above-ground residues of a given crop ($N_{AGR,\ crop}$) is calculated as follows:

Equation 80: Amount of nitrogen in the above-ground residues of a crop

$$N_{AGR,crop} = A_{NBR,crop} \bullet M_{AGR,crop} \bullet NC_{AGR,crop}$$

Where,

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$N_{AGR, crop}$ = Amount of N in a given crop above-ground residues that is returned to soils (kg)
$A_{NBR, crop}$ = Area of the given crop that is not burned after harvest and is renewed (kg)
$M_{AGR, crop}$ = Mass of above-ground residue left after harvest of the given crop (kg dry matter per ha)
$NC_{AGR, crop}$ = Nitrogen content of above-ground residues of the given crop (fraction)

With,
Crop = crops listed in Table 41.

The amount of above-ground residue of a given crop ($M_{AGR, crop}$) can be estimated from its harvested yield using:

Equation 81: Amount above-ground residues of a crop

$$M_{AGR,crop} = \beta_{0,crop} + \beta_{1,crop} \bullet M_{Yield,crop}$$

Where,
$M_{AGR, crop}$ = Mass of above-ground residue left after harvest of the given crop (kg dry matter per ha)
$\beta_{0,crop}$ = Intercept of linear regression of the given crop's above-ground residue on its yield
$M_{Yield, crop}$ = Mass harvested yield of the given crop (kg dry matter per ha)
$\beta_{1, crop}$ = Slope of linear regression of the given crop's above-ground residue on its yield

With,
Crop = crops listed in Table 41.

The amount of nitrogen in the below-ground residues of a given crop ($N_{BGR, crop}$) is calculated as follows:

Equation 82: Amount of nitrogen in the below-ground residues of a crop

$$N_{BGR,crop} = A_{NBR,crop} \bullet (M_{Yield,crop} + M_{AGR,crop}) \bullet R_{BA,crop} \bullet NC_{BGR,crop}$$

Where,
$N_{BGR, crop}$ = Amount of N in a given crop below-ground residues that is returned to soils (kg)
$A_{NBR, crop}$ = Area of the given crop that is not burned after harvest and is renewed (ha)
$M_{Yield, crop}$ = Mass of harvested yield of the given crop (kg dry matter per ha)
$M_{AGR, crop}$ = Mass of above-ground residue left after harvest of the given crop (kg dry matter per ha)

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$R_{BA,\ crop}$ = Ratio of below-ground residue to above-ground biomass of the given crop

$NC_{BGR,\ crop}$ = Nitrogen content of below-ground residues of the given crop (fraction)

With,

Crop = crops listed in Table 41.

The area of a given crop that is not burned in the given year and is renewed ($A_{NBR,\ crop}$) is calculated as follows:

Equation 83: Area of the given crop that is not burned and is renewed

$$A_{NBR,crop} = A_{H,crop} \bullet (1 - (F_{AB,crop} \bullet F_{RC,crop}) \bullet F_{AR,crop}$$

Where,

$A_{NBR,\ crop}$ = Area of the given crop that is not burned after harvest and is renewed (ha)

$A_{H,\ crop}$ = Area of the given crop that is harvested (ha)

$F_{AB,\ crop}$ = Fraction of the given crop harvested area on which residues are burned (see Agricultural Residue Burning section III.D)

$F_{RC,\ crop}$ = Fraction of the residue combusted when crop residues are burned

$F_{AR,\ crop}$ = Fraction of the given crop area that is renewed each year

With,

Crop = crops listed in Table 41.

Table 40: Fraction of crop area renewed each year ($F_{AR,\ crop}$) and fraction of residue combusted when crop residues are burned ($F_{RC,\ crop}$)

Crop	FAR, crop	FRC, crop
Alfalfa hay	0.25	0
Other hay	0.5	0
Corn for grain	1	0.8
Corn for silage	1	0
Wheat winter	1	0.9
Wheat durum	1	0.9
Barley	1	0.9
Sorghum for grain	1	0
Sorghum for silage	1	0
Oats	1	0
Rice	1	0.8
Potatoes	1	0
Dry Edible Beans	1	0

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Crop renewal data is from cost studies of the UC Davis Agricultural Economics department, and assuming half of non-legume hay crop is annual; residue combusted data from IPCC 2006 Volume 4 Chapter 2 Table 2.6 and assuming barley same as wheat.

The nitrogen input to soils from crop residues ($N_{CR,\ crop}$) are shown in Table 41.

Table 41: Amount of nitrogen input to soils from crop residues (1,000 metric tons)

Crop	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Alfalfa hay	25.7	25.4	28.8	27.5	26.5	25.8	26.9	25.7	26.0	25.2	23.6
Other hay	6.1	7.2	7.5	7.8	7.9	8.6	8.8	8.1	9.3	8.0	8.4
Corn for grain	7.4	5.8	5.4	4.8	5.5	4.7	3.8	7.3	7.0	6.1	7.4
Corn for silage	6.8	6.5	8.0	7.9	7.9	8.7	8.6	9.5	10.3	7.9	8.9
Wheat winter	9.4	9.2	7.8	8.7	9.3	7.5	5.1	7.4	11.6	9.1	9.9
Wheat durum	0.3	3.0	3.1	4.3	3.6	2.4	2.3	3.0	5.6	6.0	3.4
Barley	1.7	1.6	1.4	1.0	1.2	1.0	1.0	0.7	0.9	0.8	1.2
Sorghum for grain	0.2	0.2	0.2	0.2	0.3	0.2	0.2	0.2	0.2	0.0	0.0
Sorghum for silage	0.0	0.0	0.1	0.1	0.2	0.2	0.3	0.3	0.5	0.0	0.0
Oats	0.3	0.3	0.4	0.5	0.3	0.3	0.3	0.4	0.3	0.5	0.4
Rice	15.6	15.4	17.6	16.0	20.6	16.2	16.5	18.0	17.6	19.8	18.6
Potatoes	1.2	1.0	1.3	1.3	12.5	1.0	1.1	1.0	1.1	1.1	1.0
Dry Edible Beans	0.9	0.7	0.7	0.6	0.5	0.6	0.5	0.5	0.4	0.6	0.6
Total (NCR)	**75.8**	**76.2**	**82.4**	**80.6**	**96.3**	**77.2**	**75.5**	**82.0**	**90.8**	**85.0**	**83.3**

(e) Area of drained organic soil (AOS)

In California, the Sacramento-San Joaquin Delta was once a 540 square mile tidal marsh where peat soils (termed organic soils or histosols) accreted for thousands of years. Peat is made of partially decayed organic matter that accumulates under waterlogged —and thus anaerobic— conditions. The layer of peat in the Delta is up to 50 feet thick. In the late 1800's Delta land was "reclaimed" with levees and since then it has been drained and used for crops and as pasture land. Drainage exposes peat to oxygen and triggers rapid microbial oxidation which results in the continuous release of large amounts of the stored carbon to the atmosphere as CO_2. Peat oxidation is the principal cause of land subsidence in the Delta, some "islands" are now down to 25 feet below mean sea level. Subsidence continues at a rate of 1 to 3 inches per year. As organic soils oxidize, the N-rich organic matter mineralizes thereby increasing N_2O emissions from these soils.

The area of drained organic soils in the Sacramento-San Joaquin Delta was determined with a Geographic Information System (GIS) using the following steps:

- Download the Soil Survey Geographic (SSURGO) database from U.S. Department of Agriculture, Natural Resources Conservation Service website for counties comprising the Delta (Contra Costa, Sacramento, San Joaquin, Solano and Yolo).

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- Use the NRCS soil classification and attributes to identify all organic soils.
- Overlay the organic soils with the 2001 National Land Cover Data (NLCD 2001) downloaded from the USGS website to identify all areas of organic soils that are drained (i.e. developed, grassland/pasture, cultivated).
- Calculate the sum of area in ha of drained organic soils.

3. Data Sources

Organic fertilizer use data was obtained from *Fertilizing Materials Tonnage Reports*, published by the California Department of Food and Agriculture (CDFA Various Years). Data was not available for 2013 and 2014; usage was assumed to be the same as 2012. Crop yield and acreage harvested data were taken from USDA National Agricultural Statistics Service (USDA 2016). The amount of manure returned to soils as fertilizer is estimated in section III.B above. Variables and regression parameters for the crop residues estimates are from the IPCC guidelines (Table 11.2 in IPCC 2006e). The data for the fraction of crop area renewed each year are from cost studies of the UC Davis Agricultural Economics department, and assume half of non-legume hay crop is annual. The fraction of crop harvested area on which residues are burned is discussed in the Agricultural Residue Burning section (III.D). Residue combusted data are from IPCC 2006 Guidelines Volume 4 Chapter 2 Table 2.6 and assume barley values are the same as wheat. Drained organic soils area was estimated based on the Soil Survey Geographic (SSURGO) database from U.S. Department of Agriculture, Natural Resources Conservation Service and the 2001 National Land Cover Database (Homer, Dewitz et al. 2007) downloaded from the USGS website. The emission factors and conversion factors were from IPCC guidelines (IPCC 2006e). The total area of turf grass in California was 1,115,900 ha in 2005 for both residential and commercial uses (Milesi, Running et al. 2005). 66% of total acreage was assumed to be residential and 33% commercial based on the median of 10 surveys conducted in the United States (Milesi, Elvidge et al. 2009). The rate of nitrogen application for residential use ($R_{Fert, Res}$) was 170.8 kg N/ha/year from the average of recommended fertilization rates (UCD 2014). The rate of nitrogen application for commercial use ($R_{Fert, Com}$) was 225 kg N/ha/year and is the average of multiple sources.

For a list of individual activity and parameter values used in the equations, please consult the online documentation annex at: https://www.arb.ca.gov/cc/inventory/doc/methods_00-14/annex_3f_nitrous_oxide_from_soil_management.pdf

4. Changes in Estimates

No changes were made to estimates in this sector, compared to the previous inventory.

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5. Future Improvements

Simple emission factor models can not reflect variations in emissions due to the many factors (such as climate, soil, cropping systems and agricultural practices) that affect N_2O emissions. Process-based models can quantify the physical, chemical, biological and physiological processes associated with nitrification and denitrification in managed soils. Modeling is generally considered to be more accurate, but it also requires more extensive input data. USEPA started using the DAYCENT model in 2005 to calculate N_2O emissions from major agricultural crops (USEPA 2007a). ARB has sponsored a study to explore the possibility of using the DeNitrification DeComposition (DNDC) model to estimate GHG emissions from California agricultural systems. ARB staff are in the process of developing the data necessary to parameterize and validate DNDC for agricultural crops grown in California.

G. Rice Cultivations (3C7)

1. Background

Methane is produced by the anaerobic decomposition of organic material in flooded rice fields. It escapes to the atmosphere mostly through the rice plants aerenchyma system. The amount of CH_4 emitted annually per unit area is a function of: the number and duration of crops grown, the flooding regime before and during the cultivation period, the amount of organic and inorganic soil amendments, the soil type and temperature, and the rice cultivar.

2. Methodology

The current IPCC guidelines (IPCC 2006b), recognizing that the natural conditions and agricultural management of rice production may be highly variable, advise that it is good practice to account for this variability by disaggregating the total harvested area into sub-units (e.g., different water regimes, residue management practices, amendments).

California state legislation passed in 1991 mandated a phased reduction of rice straw burning in the Central Valley, to reduce air pollution. While 99 percent of rice acreage was burned in 1990, rice straw burning was down to 15 percent of harvested acreage in 2001 and has been below 10 percent in 2011 and 2012 (cf. section III.D). Agronomic studies (Bird, Eagle et al. 2002) have shown that alternatives to burning such as straw incorporation into the soil, rolling, or baling and removing the straw did not reduced grain yields. However there was an increase in weeds when straw was incorporated, and in particular when the fields were not winter flooded. Since a market for rice straw did not develop, most growers either incorporate or roll the straw in contact with the soil and about 60 percent of rice fields are flooded in the winter. A positive

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outcome of this change in management practices is that waterfowl on the Pacific Flyway benefit significantly from the wetlands created when fields are flooded during the winter. The downside of winter flooding is that methane is produced under anaerobic conditions of the winter-flooded fields, with significantly more methane produced when the residue is incorporated or rolled compared to burned or baled (Bossio, Horwath et al. 1999).

To reflect these practices, ARB staff performed a literature review seeking published measurement of methane emissions from rice fields in California with treatments including incorporation or rolling of straw with and without winter flooding. Staff retained 5 treatments without winter flooding and 6 treatments with winter flooding from (Bossio, Horwath et al. 1999); (Fitzgerald, Scow et al 2000) and (McMillan, Goulden et al. 2007). Averaging over the treatments provided yearly methane emission factors of 139.6 kg CH_4/ha without winter flooding (EF_{wowf}) and 265.5 kg CH_4/ha with winter flooding (EF_{wwf}).

The emissions computation is:

Equation 84: CH_4 emissions from rice cultivation

$$E = A \bullet 0.6 \bullet EF_{wwf} + A \bullet 0.4 \bullet EF_{wowf}$$

Where,

E	= Amount of CH_4 emitted by rice cultivation (g)
A	= Harvested rice area (ha)
EF_{wwf}	= California specific CH_4 emission factor with winter flooding (g/ha)
EF_{wowf}	= California specific CH_4 emission factor without winter flooding (g/ha)

3. Data Sources

Harvested rice area data are from the crop production summary reports published by the U.S. Department of Agriculture's National Agricultural Statistics Service (USDA 2016). The California-specific emission factor is from literature review cited in methodology section.

For a list of individual activity and parameter values used in the equations, please consult the online documentation annex at: https://www.arb.ca.gov/cc/inventory/doc/methods_00-14/annex_3g_rice_cultivations.pdf

4. Changes in Estimates

No changes were made to the version of the inventory, compared to previous versions.

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IV. Waste

A. Landfills (IPCC 4A1)

1. Background

Landfills are sites for solid waste disposal in which refuse is buried between layers of dirt so as to fill in or reclaim low-lying ground or excavated pits; they are the oldest form of waste treatment. There are numerous types of landfills accepting different types of waste. The GHG inventory is concerned only with landfills that contain and/or receive biodegradable, carbon-bearing waste. The Department of Resources Recycling and Recovery (CalRecycle) — previously known as California Integrated Waste Management Board (CIWMB) — has identified 372 such landfills in the State. Most of the waste contained in these landfills (95 percent) is currently under a control system that reduces the emissions of methane, the principal GHG pollutant generated by landfills, by combustion of the gas.

Landfilled carbon-bearing waste degrades mainly through anaerobic biodegradation. In an anaerobic environment (i.e., without oxygen from the air), water (H_2O) is the source of oxygen (O) for oxidation and becomes the limiting reactant for biodegradation. The water content of a landfill determines how fast the waste degrades. If water is not available, the waste does not degrade. This anaerobic biodegradation process generates approximately equal amounts of CO_2 and CH_4 gas as a byproduct:

Equation 85: Anaerobic biodegradation process

$$\boxed{2C + 2H_2O \rightarrow CO_2 + CH_4}$$

A large fraction (49 percent to 62 percent) of the carbon in the waste will not degrade under these anaerobic conditions and is effectively sequestered. This carbon will remain sequestered as long as the landfill's anaerobic conditions persist.

The various gases produced as the waste degrades are collectively called "landfill gas". Landfill gas is an odor nuisance, a source of air toxics and may even be a physical danger to those living near a landfill because the methane it contains is combustible. For these reasons, most landfills in the State (holding about 95 percent of the waste) are equipped with a gas collection system. However, although those collection systems are designed to collect landfill gas, it is known that a portion of the gas does escape into the atmosphere.

Once collected, landfill gas can simply be vented to the air if the only reason for the collection was to address offsite gas migration issues. Alternatively, the

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collected landfill gas may be stripped of its non-methane components via carbon adsorption, of which the main purpose is to reduce odors and/or volatile organic compounds (VOC) and toxics. Carbon adsorption allows most (99 percent) of the CH_4 to escape. Most commonly, the collected landfill gas is combusted, either in a flare (to destroy odors and VOC and toxic components in the gas), or in an engine or turbine to generate electricity.

2. Methodology

ARB staff requested site-specific landfill gas collection data through landfill surveys, but received answers for only certain years and for about half of the landfilled waste (e.g., approximately 52 percent in 2006, the latest data year reported in the surveys to ARB). In 2013, CalRecycle conducted another survey and shared the results with ARB, increasing the amount of data collected (even if only for 1 additional year, 2010). Finally, the USEPA GHG Reporting Program (GHGRP) now provides similar data for the larger landfills (about 82% of the waste received in 2012), starting in 2012 and continuing each year thereafter. The combined datasets represent about 90 percent of the landfilled waste. Therefore, to fill in the missing landfills and the missing years, staff opted to use a model to estimate landfill emissions for all sites, and used the survey data to supplement and enhance these predictions where available.

Staff used the Mathematically Exact First-Order Decay (FOD) model from the 2006 IPCC Guidelines (IPCC 2006f). In summary, this model assumes that a fixed fraction of the waste available at any moment will degrade. The amount that degrades over a given amount of time is determined by a factor (k), which is tied to the moisture content in the landfill. The k values used in the model were obtained from USEPA and are a function of the annual precipitation occurring at each landfill; rainfall being used as a surrogate for landfill moisture content. The model assumes that the waste carbon is biodegraded into equal amounts of CO_2 and CH_4 (see Equation 85).

2.1 Model Equations

The inputs to the model are the amount of anaerobically degradable organic carbon (ANDOC), the delay in months before waste begins to decay anaerobically (M), the rate at which waste decays (k), and the fraction of degraded carbon that is converted into CH_4 (F_{CH4}). Of these four inputs, three are set by using default values: a six month default for M, a 50 percent default for F_{CH4} and USEPA defaults based on rainfall levels for k. Only ANDOC requires a more detailed method of derivation, which is the focus of Equation 86 below. The inputs for calculating ANDOC are therefore important determinants of landfill emissions estimates.

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(a) Anaerobically Degradable Organic Carbon (ANDOC)

Equation 86: Anaerobically degradable organic carbon

$$ANDOC = WIP \bullet 0.9072 \bullet \sum_{component} (FW_{component} \bullet DOC_{component} \bullet DANF_{component})$$

Where,

ANDOC = Anaerobically Degradable Organic Carbon: the amount of waste carbon that is biodegradable in an anaerobic environment (Mg (i.e., 10^6 grams) of carbon)

WIP = Waste-in-Place: the landfilled waste (wet weight) as reported to the California Integrated Waste Management Board (tons)

0.9072 = Short ton to Mg (a.k.a. tonne or metric ton) conversion

$FW_{component}$ = Fraction of a given waste component in the landfilled waste

$DOC_{component}$ = Degradable Organic Carbon (DOC) content of the given waste component.

$DANF_{component}$ = Decomposable Anaerobic Fraction (DANF) of the given waste component.

With,

Component = [Newspaper, Office Paper, Corrugated Boxes, Coated Paper, Food, Grass, Leaves, Branches, Lumber, Textiles, Diapers, Construction/Demolition, Medical Waste, Sludge/Manure]

(a.i) Waste-In-Place (WIP)

CalRecycle staff provided ARB staff with Waste-in-Place (WIP) data in two basic forms: 1) the cumulative amount of waste deposited, by landfill, up to the year 1990 and, 2) the amounts deposited, by landfill, each year from 1991+ for those landfills still receiving waste after 1990. CalRecycle staff also furnished the amounts of green waste and sludge used as daily cover by each landfill from 1995+. CalRecycle staff provided data on 372 landfills known to contain waste that is biodegradable. Landfills containing only inert waste, like ash and masonry from demolition sites, were excluded. ARB staff also received WIP data from their survey and used them to update the CalRecycle data.

Yearly amounts of deposited waste are necessary inputs for the IPCC FOD model to work properly. Yearly data were not available before 1990, however, only the cumulative WIP totals in 1990 were known. This required staff to estimate how much of these cumulative amounts were deposited each year from the landfills' opening year to 1990 (or up to their closure year if they closed before 1990). ARB staff inquired about the opening and closure dates for all landfills, required data to estimate annual disposal amounts, giving the range of years over which the waste should be distributed. CalRecycle staff had closure dates for all 372 landfills of interest, but did not have a complete list of

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opening dates, so an estimate was made for those cases where the opening date was missing. Once these dates were established, the cumulative total of WIP in each landfill was distributed over the pre-1990 years (from opening to 1990, or opening to closure if before 1990) in a manner commensurate to the trend in California's population over those years. As a result, a larger proportion of the waste in place was distributed in the later years of this range than in the earlier ones, since the population kept growing over the time period.

(a.ii) Components of the Waste-in-Place

To determine its degradable organic carbon (DOC) and decomposable anaerobic fraction (DANF), the WIP must first be disaggregated into its component parts. Disaggregation was done on the basis of waste characterization studies from CalRecycle and the USEPA. The CalRecycle studies were conducted in 1999, 2004 and 2008; the 1999 study was used to characterize waste for 1996 to 2002, the 2004 study for 2003 to 2006, the 2008 study for 2007 to 2011, and the 2014 study for 2012 and beyond, as suggested by CalRecycle's staff. For years prior to 1995, staff used the USEPA study that best applied to a given year. The USEPA did waste characterization studies in 1960, 1970, 1980, 1990 and 1995. Staff used the waste profiles from those studies as follows: up to 1964 (1960 survey), 1965-1974 (1970 survey), 1975-1984 (1980 survey), 1985-1992 (1990 survey) and 1993-1995 (1995 survey). Applying these profiles allowed disaggregating the waste deposited each year into its component parts. The components of interest to estimate TDOC (i.e., those containing biodegradable carbon content) are listed in Table 42.

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Table 42: Waste characterization profile

Waste Component	Up to 1964	1965 -1974	1975 -1984	1985 -1992	1993 -1995	1996 -2002	2003 -2006	2007-2011	2012 +
Newspaper	6.4%	6.4%	5.9%	4.8%	3.9%	4.3%	2.2%	1.2%	1.5%
Office Paper	10.7%	11.3%	12.0%	13.1%	15.0%	4.4%	2.0%	0.7%	0.7%
Corrugated Boxes	10.8%	13.5%	11.5%	10.5%	10.3%	4.6%	5.7%	3.7%	3.1%
Coated Paper	2.2%	2.0%	2.4%	2.1%	1.8%	16.9%	11.1%	11.2%	12.0%
Food	14.8%	11.3%	9.5%	12.1%	13.4%	15.7%	14.6%	16.5%	18.1%
Grass	12.1%	10.3%	10.1%	9.0%	6.6%	5.3%	2.8%	3.4%	3.8%
Leaves	6.1%	5.1%	5.0%	4.5%	3.3%	2.6%	1.4%	2.8%	3.1%
Branches	6.1%	5.1%	5.0%	4.5%	3.3%	2.4%	2.6%	1.8%	1.7%
Lumber	3.7%	3.3%	5.1%	7.0%	7.3%	4.9%	9.6%	13.7%	11.9%
Textiles	2.1%	1.8%	1.7%	3.3%	4.5%	2.1%	4.4%	5.6%	5.8%
Diapers	0.1%	0.3%	1.4%	1.6%	1.9%	6.9%	4.4%	3.7%	4.3%
Construction/Demolition	2.6%	2.5%	3.5%	3.9%	4.5%	6.7%	12.1%	9.8%	8.0%
Medical Waste	-	-	-	-	-	0.0%	0.0%	0.1%	0.1%
Sludge/Manure	-	-	-	-	-	0.1%	0.1%	0.7%	0.6%

* Dash indicates no data available; percentage assumed to be zero.

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The amounts of green waste and sludge used as daily cover were included with the landfill WIP. Green waste was split based on USEPA studies (Table 43).

Table 43: Waste characterization of daily green waste cover material

Daily Cover Waste Component	***Assumed Content Percentage***
Grass	50%
Leaves	25%
Branches	25%

(a.iii) Degradable Organic Carbon (DOC) content

Staff obtained values for the DOC content of solid waste components from USEPA (Newspaper, Office Paper, Corrugated Boxes, Coated Paper, Food, Grass, Leaves, Branches) (USEPA 2010b) and from the 2006 IPCC Guidelines (Lumber, Textiles, Diapers, Construction/Demolition, Medical Waste, Sludge/Manure) (IPCC 2006f). These values are summarized in Table 44.

Table 44: Degradable Organic Carbon (DOC) content of different MSW components

Waste Component	***DOC Fraction (Mg DOC / Mg wet waste)***	***Source***
Newspaper	0.471	USEPA
Office Paper	0.385	USEPA
Corrugated Boxes	0.448	USEPA
Coated Paper	0.330	USEPA
Food	0.148	USEPA
Grass	0.133	USEPA
Leaves	0.291	USEPA
Branches	0.442	USEPA
Lumber	0.430	CEC
Textiles	0.240	IPCC
Diapers	0.240	IPCC
Construction/Demolition	0.040	IPCC
Medical Waste	0.150	IPCC
Sludge/Manure	0.050	IPCC

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(a.iv) Decomposable Anaerobic Fraction (DANF)

Theoretically, all biodegradable carbon-bearing waste can degrade, but only a portion actually degrades in the special anaerobic environment of landfills. The carbon in the waste that does not decompose remains sequestered.

Values for the DANF of different MSW components came from USEPA (Newspaper, Office Paper, Corrugated Boxes, Coated Paper, Food, Grass, Leaves, and Branches) (USEPA 2010b), the CEC (lumber)(CEC 2006) and the

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IPCC guidelines (default of 50 percent anaerobic decomposition for Textiles, Diapers, Construction/Demolition, Medical Waste, and Sludge/Manure) (IPCC 2006f).

Table 45: Decomposable anaerobic fraction (DANF) of the DOC of different MSW components

Waste Component	Decomposable Anaerobic Fraction	Source
Newspaper	0.150	USEPA
Office Paper	0.870	USEPA
Corrugated Boxes	0.442	USEPA
Coated Paper	0.243	USEPA
Food	0.865	USEPA
Grass	0.474	USEPA
Leaves	0.073	USEPA
Branches	0.231	USEPA
Lumber	0.233	CEC
Textiles	0.500	IPCC
Diapers	0.500	IPCC
Construction/Demolition	0.500	IPCC
Medical Waste	0.500	IPCC
Sludge/Manure	0.500	IPCC

(a.v) Overall waste profile and estimate of landfilled carbon sequestration

With the data described above, staff calculated the overall waste profile for California (Table 46). Staff also estimated the amount of non-decomposable organic carbon in landfills, that is, the carbon which is expected to remain sequestered until removed from the anaerobic conditions present in landfills.

Table 46: Overall waste profile for California - Percentage of each component in the overall waste in place

Waste Type	Up to 1964	1965 - 1974	1975 - 1984	1985 - 1992	1993 - 1995	1996 - 2002	2003 - 2006	2007 - 2011+	2012 +
1. Biodegradable Carbon	23.2%	22.9%	22.9%	23.3%	22.9%	20.8%	18.9%	19.2%	19.1%
a. Decomposable	10.5%	10.4%	10.3%	11.0%	11.6%	8.4%	7.4%	7.2%	7.3%
b. Sequestered	12.7%	12.5%	12.5%	12.3%	11.3%	12.4%	11.4%	12.0%	11.8%
2. Other Materials	76.8%	77.1%	77.1%	76.7%	77.1%	79.2%	81.1%	80.8%	80.9%

Most of the waste in landfills is non-biodegradable. Of that portion that is biodegradable (19 percent to 23 percent) most (49 percent to 62 percent) will not decompose in a landfill environment and instead will remain permanently sequestered.

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(b) Change in ANDOC

Next, staff used the IPCC FOD model to calculate the change in ANDOC over time, determining how much of the anaerobically degradable organic carbon remains at the end of each year:

Equation 87: Change in anaerobically degradable organic carbon in landfills

$$ANDOCstock_{Year(i+1)} = \left\{ \begin{array}{l} ANDOCstock_{year(i)} \bullet e^{-k} \\ + ANDOCadded_{year(i-1)} \bullet [\frac{1}{k} \bullet (e^{-k \bullet [1-\frac{M}{12}]} - e^{-k}) - \frac{M}{12} \bullet e^{-k}] \\ + ANDOCadded_{year(i)} \bullet [\frac{1}{k} \bullet (1 - e^{-k \bullet [1-\frac{M}{12}]}) + \frac{M}{12}] \end{array} \right\}$$

Where,

$ANDOCstock_{Year(i+1)}$ = stock of ANDOC remaining un-decomposed at the end of inventory year i, and thus present in the landfill at the beginning of the next year (year i+1), (g)

$ANDOCstock_{Year(i)}$ = stock of ANDOC present in the landfill at the beginning of inventory year i, i.e., remaining un-decomposed at the end of the previous year (i-1), (g)

$ANDOCadded_{Year(i-1)}$ = ANDOC added during the previous inventory year (year i-1), (g)

$ANDOCadded_{Year(i)}$ = ANDOC added during inventory year i, (g)

M = Assumed delay before newly deposited waste begins to undergo anaerobic decomposition (months), default value = 6 months

k = Assumed rate constant for anaerobic decomposition; k = ln2/half-life (years); the half-life being the number of years required for half of the original mass of carbon to degrade (Table 47).

This calculation is performed iteratively for all subsequent years, starting with the landfill opening year and ending with the inventory year of interest.

Table 47: Assumed rate constant values for anaerobic decomposition (k)

Average Rainfall (Inches/Year)	***k value***
<20	0.02
20-40	0.038
>40	**0.057**

Source: USEPA

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(c) Methane Generation

Equation 88: Methane generation in landfills

$$G_{CH4} = F_{CH4} \bullet \left\{ \begin{array}{l} ANDOCstock_{year(i)} \bullet (1 - e^{-k}) \\ + ANDOCadded_{year(i-1)} \bullet [\frac{1}{k} \bullet (e^{-k \bullet [1 - \frac{M}{12}]} - e^{-k}) - \frac{M}{12} \bullet e^{-k}] \\ + ANDOCadded_{year(i)} \bullet [1 - \frac{M}{12} - \frac{1}{k} \bullet (1 - e^{-k \bullet [1 - \frac{M}{12}]})] \end{array} \right\}$$

Where,

G_{CH4} = CH_4 generated during inventory year i (g)

F_{CH4} = Fraction of decomposing carbon that is converted into CH_4, default value = 0.5

$ANDOCstock_{Year(i)}$ = Stock of ANDOC present in the landfill at the beginning of inventory year i (g)

$ANDOCadded_{Year(i-1)}$ = ANDOC added during the previous inventory year (year i-1)

$ANDOCadded_{Year(i)}$ = ANDOC added during inventory year i (g)

M = Assumed delay before newly deposited waste begins to undergo anaerobic decomposition (months), default value = 6 months

k = Assumed rate constant for anaerobic decomposition; k = ln2/half-life (years); the half-life being the number of years required for half of the original mass of carbon to degrade (Table 47).

(d) Emissions Estimates

Equation 89: CH_4 emissions from landfills

$$E_{CH4} = G_{CH4} \bullet CE_{LFG} \bullet (1 - DE_{LFG}) + G_{CH4} \bullet (1 - CE_{LFG}) \bullet (1 - O_{CH4})$$

Where,

E_{CH4} = Emissions of CH_4 from landfill (g)

G_{CH4} = Amount of CH_4 generated by the landfill during the inventory year (g)

CE_{LFG} = Landfill Gas Collection Efficiency, the fraction of generated landfill gas captured by the collection system (default value = 0.75)

DE_{LFG} = Landfill Gas Destruction Efficiency, the fraction of CH_4 in the captured landfill gas oxidized to CO_2 (default values = 0.99

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for combustion/thermal oxidation, and 0.01 for carbon filtration)

O_{CH4} = Fraction of uncollected CH_4 that is oxidized to CO_2 in the landfill cover (default value = 0.1)

CalRecycle staff provided information about which landfills have gas collection systems and what control method they use, if any. Responses to an ARB survey allowed staff to update a portion of the CalRecycle numbers. For years where CalRecycle data was lacking on the year of collection system installation (primarily years 1991 - 2003), staff used existing regulatory requirements to help estimate the installation dates. Staff intends to improve the accuracy of collection system installation dates in the future.

Staff assumed that a landfill gained the full benefits of gas collection beginning with the year in which the system was first installed. In the future, as the exact month of installation and start-up operation becomes available, it may be possible to adjust the first year of the collection efficiency to account for how much of that first year it was actually in operation.

CalRecycle staff also provided the type of control landfills are using, including: simple venting to the atmosphere, carbon adsorption, or combustion (flaring, engines, thermal oxidizers, etc.). In the case of combustion, ARB staff assumed that 99 percent of the CH_4 was converted into CO_2 and 1 percent escaped as CH_4. For carbon adsorption, 1 percent of the CH_4 was assumed captured and 99 percent released. For venting 100 percent of the CH_4 was assumed released. These defaults were used if specific landfill survey data detailing any of these was not available.

Each site with a gas collection system was assigned a default of 75 percent collection efficiency and a default of 10 percent oxidation for the uncollected landfill gas as it migrates through the landfill cover into the air. Using these default values (75 percent for collection efficiency and 10 percent for oxidation fraction) has been the object of some debate. Staff recognizes that many values can be found for these factors in the literature and that some site-specific measurements and local estimates do exist. However, given the current lack of rigorous, scientifically-based measurement data, staff chose to use the default values established by USEPA. As better data become available through current and future research, staff will update the collection efficiency and oxidation factors for estimating landfill gas emissions.

(d.i) Use of site specific survey data

Using the FOD model from the IPCC guidelines (IPCC 2006f), staff estimated the amount of carbon sequestered and the amount of CH_4 emitted by each of the 372 landfills of interest in California.

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ARB and CalRecycle staff also surveyed landfill operators and some landfills report to the USEPA's GHG Reporting Program (GHGRP), these data provided site-specific landfill gas collection data for certain years of operations (136 of the 372 landfills submitted site specific survey data, while 107 report to USEPA's GHGRP). These data were used either to replace or to improve the model's estimates for that landfill.

When staff received landfill gas collection data for a particular year, it used the information in place of the model estimate. However, this data included only the amount of gas collected, and not the amount generated since landfill operators only know what is measured at the point of collection. To estimate the amount of gas generated, a default collection efficiency of 75 percent was used and the amount of collected gas was divided by 0.75 to obtain an estimate of the generated gas. Then, the estimate of gas generated—based on the amount of gas collected—was used to replace the model estimate for that year.

When an actual value for the CH_4 fraction in landfill gas was reported in the survey, staff used it instead of the general default landfill gas composition assumption of 50 percent CH_4 and 50 percent CO_2. However, because CO_2 specific fractions were not obtained from the site specific survey data (only CH_4 fractions were obtained), it was assumed that whatever was not reported as CH_4 was CO_2. Staff recognizes that N_2 gas and small amounts of O_2 are expected to be present, and therefore not all of the remaining gas (i.e., the fraction that is not CH_4) is CO_2. Nevertheless, the amounts of these other gases were considered to be negligible for the purpose of estimating the CO_2 emissions from landfills. As data improves, this conservative assumption may be revisited.

When landfill gas collection data was provided for some of the years and not others, staff used the provided years to improve the model estimates for the missing years by interpolating or extrapolating using the model predicted trend for that landfill. For example, if the years 1990-1993 were missing from a set of survey data for a particular landfill, but the year 1994 was available, then the years 1990-1993 were extrapolated from this 1994 data point by following the trend the model showed for that landfill. So if the model indicated that the CH_4 generation in 1993 was 3 percent lower than the 1994 predicted value, the available 1994 value from the survey was multiplied by 97 percent to estimate the 1993 point, and so on. This method of filling missing data preserves a consistent trend that smoothly joins the survey data. The same methodology was used to estimate CO_2 emissions when missing survey data were encountered.

An exception was made to these procedures in the case of survey-reported first years of operation of a collection system. These reported values were not used as a substitute for model estimates, as it was not known if the indicated

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first year represented a full year of operation. Staff assumed that the second year of reported data was a complete year and used that year as the starting point, ignoring data from the first year. For surveys with collection system data dating back to 1990, staff assumed that the 1990 value represented a full year of operations and always made use of it. Staff made this assumption since data was not available to indicate if 1990 was the first year of operation and no survey data was available for 1989.

(d.ii) Emissions from landfill gas combustion

Emissions of N_2O from the combustion of landfill gas are included in the inventory. These emissions are a function of the BTU content of the landfill gas being burned. The amount of landfill gas burned (LFG) is determined from model output for the amount of gas collected and from CalRecycle data indicating which landfills burn their captured gas.

Equation 90: N_2O emissions from landfill gas combustion

$$E_{N2O} = LFG \bullet F_{CH4} \bullet HC_{CH4} \bullet EF_{CH4}$$

Where,

EN_2O	= N_2O emissions from landfill gas combustion (grams)
LFG	= Landfill gas captured and burned (standard cubic feet)
FCH_4	= CH_4 fraction of landfill gas (unitless)
$HCCH_4$	= Heat content of CH_4 (BTU / standard cubic foot)
$EFCH_4$	= N_2O emission factor of CH_4 (grams per BTU)

3. Data Sources

The First order decay model is from the 2006 IPCC guidelines (IPCC 2006f). Waste characterization data was obtained from studies made by CalRecycle (CalRecycle 2009) and by the USEPA (USEPA Various Years-a). Degradable Organic Carbon (DOC) content and values for Decomposable Anaerobic Fraction (DANF) were taken from USEPA (USEPA 2010b). DANF data for lumber comes from the California Energy Commission (CEC 2006). Default values used for DANF and DOC content of waste in place, and CH_4 combustion emission factors were taken from the 2006 IPCC Guidelines (IPCC 2006f). Default collection capture efficiency and CH_4 oxidation factor values were obtained from the USEPA through personal correspondence (Weitz 2007). Landfill gas collection, geographic coordinates and control data for California landfills were provided by CalRecycle staff through personal communication (Walker 2007). Average precipitation data for the landfills was extracted from a map published by the NRCS (NRCS 2007). Methane and nitrous oxide emissions factors are from IPCC Guidelines (IPCC 2006f). USEPA GHG

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Reporting Program (USEPA 2012b) provided data on landfill gas collection for 107 landfills reporting to them.

For a list of yearly activity and parameter values used in the equations, please consult the online documentation annex at: https://www.arb.ca.gov/cc/inventory/doc/methods_00-14/annex_4a_landfills.pdf

4. Changes in Estimates

The 2016 edition GHG inventory uses the latest 2014 Waste Characterization Survey from CalRecycle (CalRecycle 2014). Minor changes to the 2008 Waste Characterization were made to be consistent with the 2014 version.

5. Future Improvements

Staff will continue to follow ongoing research and data developments to help improve estimates of landfill gas emissions. CalRecycle and ARB are funding joint research to improve understanding of emissions from landfills. Once more is understood about emissions from California's diverse set of landfills, ARB may updated the assumptions regarding collection efficiency used in the inventory calculations. Other information sources that staff will evaluate include ARB's Landfill Methane Control Measure and USEPA's GHGRP.

B. Composting of Organic Waste (IPCC 4B)

1. Background

Composting of organic waste such as food scraps, yard trimmings, branches, leaves, grass and organic municipal solid waste, is common in California as a way to divert such waste from landfills. Over the last 20 years, the amount of organic waste composted in California has increased over 3-fold (CalRecycle Various Years). Composting is a controlled decomposition process that destroys pathogens in the waste material, reduces its volume greatly and yields a stable organic-rich soil-like mixture called compost. This section is concerned with emissions from industrial-scale composting facilities and does not include small-scale backyard composting. These industrial facilities predominantly use a process called windrow composting in which large amounts of organic waste undergo decomposition in long rows. The windrows are actively managed (e.g. shredding, aeration, watering, etc.) to maximize the aerobic decomposition of the organic feedstock. During the composting process a large fraction of the degradable organic carbon (DOC) in the waste material is converted into carbon dioxide. However, studies have indicated that some anaerobic pockets occur in the piles where methanogenic bacteria produce some methane, and some nitrous oxide is emitted as the byproduct of nitrifying or denitrifying bacteria (ARB 2010a).

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2. Methodology

The methodology staff used to calculate the CH_4 and N_2O emissions from industrial composting is similar to that used for the Inventory of U.S Greenhouse Gas Emissions and Sinks (USEPA 2010a). These methodologies are consistent with Tier-1 and Tier-2 methods of the IPCC Guidelines (IPCC 2006g), and incorporates California-specific data when available.

2.1 Methane Emissions

Emissions of CH_4 and N_2O were estimated by multiplying the amount of composting feedstock processed in California by an appropriate emission factor.

Equation 91: GHG emissions from composting

$$E_{GHG} = Q * EF_{GHG} * 907.2$$

Where,

E_{GHG}	= emissions of the given GHG during the composting process (g)
Q	= amount of organic waste feedstock composted (ton)
EF_{GHG}	= emission factor for methane emissions during the composting process (g/kg)
907.2	= factor to convert tons into kilograms (kg/ton)

With,

GHG	= [CH_4, N_2O]

The amount of composting feedstock processed in California was obtained from CalRecycle's *California Compost -and Mulch- Producing Infrastructure Studies* (CalRecycle Various Years). These reports published in 2001, 2004 and 2010 estimated amount of composting feedstock that was processed in California during the years 2000, 2003 and 2008 respectively. Using these three data points for 2000, 2003 and 2008, a linear regression was calculated (R^2 = 0.71). The best fit equation was used along with details on percentage of product by product type and bulk densities to estimate feedstock tonnages of compost only for each of the years 1990+. Specific details of the method used are available upon request.

Staff used a methane emission factor of 4.1 g/kg and a nitrous oxide emission factor of 0.09 g/kg which are based on the studies used to determine IPCC and USEPA emissions factors as well as more up-to-date compost emission studies (ARB 2010a).

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3. Data Sources

The estimates for composting feedstock were obtained from three CalRecycle reports (CalRecycle Various Years). The emission factors for methane and nitrous oxide were obtained from a study that was used to support the generation of a lifecycle compost emission factor (ARB 2010a).

For a list of yearly activity and parameter values used in the equations, please consult the online documentation annex at:
https://www.arb.ca.gov/cc/inventory/doc/methods_00-14/annex_4b_composting_of_organic_waste.pdf

4. Changes in Estimates

No changes to methods have been made in this version.

5. Future Improvements

In the future, the composting fugitive emission factors for both methane and nitrous oxide need to be improved. The current factors are more representative of a global average (and consistent with IPCC and USEPA values); however, future emission factors would ideally be California-specific.

C. Wastewater Treatment and Discharge (IPCC 4D)

1. Background

Wastewater from households, commercial activities, and industrial production contains soluble organic matter, suspended particles, pathogenic organisms, and chemical contaminants. In California, a large percentage of wastewater is collected and processed in centralized wastewater treatment plants. Methane is emitted from wastewater when it is treated in anaerobic conditions. Nitrous oxide is emitted as the result of the nitrification and denitrification processes, which take place at wastewater treatment plants, but also in the water bodies where effluent is discharged.

The magnitude of CH_4 emissions is determined by the amount of degradable organic component in the wastewater, the temperature, and the type of treatment system. The more organic material and the higher the temperature of the wastewater, the more CH_4 will be generated. The degradable organic material content in wastewater is quantified by its Biochemical Oxygen Demand (BOD) and Chemical Oxygen Demand (COD). The BOD measures the amount of biodegradable organic material present in wastewater, while the COD measures all organic materials both biodegradable and non-biodegradable.

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N_2O emissions are associated with the degradation of nitrogen compounds present in the wastewater. N_2O is generated during the nitrification and denitrification processes, which occur at wastewater treatment plants and in water bodies that receive discharges of wastewater or treatment plant effluent. Emissions of N_2O at wastewater treatment plants are generally small compared to the emissions from effluent discharged into aquatic environments.

2. Methodology

Most CH_4 and all N_2O emissions from wastewater treatment and discharge were estimated using methodologies and parameter values from the Inventory of U.S Greenhouse Gas Emissions and Sinks: 1990-2013 (USEPA 2015b). These methodologies are consistent with Tier-1 and Tier-2 methods of the IPCC Guidelines (IPCC 2006b), and incorporate USEPA improvements and California-specific data when available. A number of parameters used in emission calculations were updated to California-Specific data in this inventory version, as described in more detail in the data sources section.

The method to estimate emissions from non-citrus fruits wastewater was updated to avoid double counting. The previous methodology included emissions from apples and wine grapes as part of "all other non-citrus fruits". However, apple and wine grape emissions were also calculated as a separate category; and hence were calculated twice. In the updated methodology, the following equation was used to separate apples and wine grapes from non-citrus fruits:

Updated amount of non-citrus fruit = Total amount non-citrus fruit- (amount of apples + amount of wine grapes)

2.1 Methane Emissions

Methane emissions from wastewater are estimated from the volume of wastewater generated, organic loading in wastewater (measured in BOD or COD), and percentage of wastewater that is centrally treated (aerobic or anaerobic systems), anaerobically digested or treated in septic systems. The volume of wastewater discharged into municipal sewage system is estimated from the state population. The volume of wastewater generated from a particular industrial sector is estimated from the quantity of product it manufactured or processed.

(a) Methane emissions from domestic wastewater

Methane emissions from the treatment of domestic wastewater are estimated using the following equations:

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Equation 92: Total CH_4 emissions from domestic wastewater treatment

$$E_{Domestic,CH4} = E_{Septic,CH4} + E_{Aerobic,CH4} + E_{Anaerobic,CH4} + E_{Digester,CH4}$$

Equation 93: CH_4 emissions from Septic Systems

$$E_{Septic,CH4} = P \bullet R_{BOD5} \bullet 365.2425 \bullet f_{Septic} \bullet B_o \bullet MCF_{Septic}$$

Equation 94: CH_4 emissions from Centrally Treated Aerobic Systems

$$E_{Aerobic,CH4} = \left\{ \begin{array}{l} P \bullet R_{BOD5} \bullet 365.2425 \bullet f_{central} \bullet f_{aerobic} \bullet \\ (f_{aerobic,woPT} + (f_{aerobic,wPT} \bullet (1 - f_{BOD}))) \bullet f_{NWM} \bullet B_o \bullet MCF_{aerobic,NWM} \end{array} \right\}$$

Equation 95:CH_4 emission from Centrally Treated Anaerobic Systems

$$E_{Anaerobic,CH4} = \left\{ \begin{array}{l} P \bullet R_{BOD5} \bullet 365.2425 \bullet f_{central} \bullet f_{anaerobic} \bullet \\ (f_{anaerobic,woPT} + (f_{anaerobic,wPT} \bullet (1 - f_{BOD}))) \bullet B_o \bullet MCF_{anaerobic} \end{array} \right\}$$

Equation 96:CH_4 emissions from Anaerobic Digesters

$$E_{Digester,CH4} = V_{biogas} \bullet f_{CH4} \bullet 0.02831 \bullet 662 \bullet (1 - D_{CH4})$$

Equation 97: Volume of biogas produced in anaerobic digesters

$$V_{biogas} = W_{Digester} \bullet \frac{R_{biogas}}{R_{wastewater}} \bullet 365.2425$$

Where,

$E_{Domestic, CH4}$ = Emissions of methane from domestic wastewater treatment (gram)

$E_{Septic, CH4}$ = Emissions of methane from Septic Systems (gram)

$E_{Aerobic, CH4}$ = Emissions of methane from Centrally Treated Aerobic Systems (gram)

$E_{Anaerobic, CH4}$ = Emissions of methane from Centrally Treated Anaerobic Systems (gram)

$E_{Digester, CH4}$ = Emissions from Anaerobic Digesters (gram)

P = California population (person)

R_{BOD5} = Rate of per capita biological organic demand (BOD_5) production (gram / person / day)

0.02831 = Average number of days per year (day)

f_{septic} = Fraction of California wastewater treated in septic systems (unitless)

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B_o = Maximum methane production capacity (g CH_4/g BOD_5)
MCF_{septic} = Methane correction factor for septic systems (unitless)
$f_{central}$ = Fraction of wastewater centrally treated in California (unitless)
$f_{aerobic}$ = Fraction of wastewater treated aerobically in California (unitless)
$f_{aerobic, woPT}$ = Fraction of aerobic systems that do not employ primary treatment (unitless)
$f_{aerobic, wPT}$ = Fraction of aerobic systems that employ primary treatment (unitless)
f_{BOD} = Fraction of BOD removed during primary treatment (unitless)
f_{NWM} = Fraction of aerobic systems that are not well managed and in which some anaerobic degradation occurs (unitless). *Currently, it is assumed that all aerobic systems are well managed and produce no CH_4.*
$MCF_{aerobic, NWM}$ = Methane correction factor for aerobic systems that are not well managed (unitless)
$f_{anaerobic}$ = Fraction of wastewater treated anaerobically in California (unitless)
$f_{anaerobic, woPT}$ = Fraction of anaerobic systems that do not employ primary treatment (unitless)
$f_{anaerobic, wPT}$ = Fraction of anaerobic systems that employ primary treatment
$MCF_{anaerobic}$ = Methane correction factor for anaerobic systems
V_{biogas} = Volume of biogas produced (ft^3)
f_{CH4} = Fraction of methane in biogas (unitless)
0.02831 = Factor used to convert between m^3 and ft^3 (m^3/ft^3)
662 = Density of methane (g/m^3)
D_{CH4} = Methane destruction efficiency from flaring or burning in engine (unitless)
$W_{Digester}$ = Total wastewater flow to treatment plants that have anaerobic digesters (gal)
R_{biogas} = Rate of per capita digester gas production (ft^3/person/day)
$R_{wastewater}$ = Rate of per capita wastewater production (gal/person/day)
365.2425 = Average number of days produced per year (USNO 2004)

(b) Methane emissions from industrial wastewater

(b.i) Processing of pulp and paper, fruits, vegetables, red meat and poultry

For each of the type of product processed in industrial wastewater treatment plants, the CH_4 emissions are estimated using the following equation:

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Equation 98: CH_4 emissions from industrial wastewater treatment

$$E_{CH4,product} = Q_{product} \bullet W_{product} \bullet COD_{product} \bullet f_{COD,product} \bullet B_o \bullet MCF$$

Where,

$E_{CH4,\ product}$ = Emissions of methane from the treatment of wastewater associated with processing the given product (gram)

$Q_{product}$ = Quantity of the given product processed (tonne)

$W_{product}$ = Wastewater outflow associated with processing the given product (liter / tonne)

$COD_{product}$ = Chemical Oxygen Demand (COD) of the wastewater associated with the processing of the given product (gram / liter)

$f_{COD,\ product}$ = Proportion of COD anaerobically degraded by the treatment of the wastewater associated with the processing of the given product (unitless)

B_o = Maximum methane producing potential of industrial wastewater (g CH_4/ g COD)

MCF = Methane correction factor, indicating the extent to which the organic content (measured as COD) degrades anaerobically (unitless)

With,

Product = [Pulp and Paper, Red meat, Poultry, Potatoes, Other vegetables, Apples, Citrus Fruits, Non-citrus fruits, and Wine grapes]

(b.ii) Petroleum refining

For petroleum refining emissions associated with wastewater treatment systems, the following equation was used:

Equation 99:CH_4 Emissions from petroleum refineries wastewater treatment systems

$$E_{CH4} = W \bullet COD \bullet B_o \bullet MCF$$

Equation 100: Wastewater flow from petroleum refineries

$$W = V \bullet 35$$

Where,

E_{CH4} = Methane emissions from wastewater treatment systems at petroleum refining facilities (gram)

W = Wastewater flow (m^3)

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COD	= COD loading in wastewater entering anaerobic treatment system (g/m^3)
B_o	= Maximum methane production capacity (g CH_4/ g COD)
MCF	= Methane conversion factor (unitless)
V	= Volume of petroleum finished product produced by California's refineries (barrel)
35	= wastewater flow generation rate of petroleum refineries (gal/barrel)

2.2 Nitrous Oxide Emissions

The methodologies for estimating N_2O emissions from domestic wastewater focus on emissions from municipal wastewater treatment plants and estimate the amount of nitrogen in wastewater on the basis of human protein consumption. The nitrogen from industrial wastewater is factored into the estimation by applying a coefficient to account for industrial and commercial co-discharge into municipal sewage treatment plants. This factor is estimated at 25 percent as in the USEPA national inventory. Emissions of nitrous oxide occur from wastewater in treatment plants and from effluents discharged into surface waters. When the sewage sludge is removed from the treatment plant, it is used in land application, composting or landfilled, therefor, does not enter waterbodies. Thus, the nitrogen from the sewage sludge is excluded from the effluent emission calculations. N_2O emissions from sewage sludge applied to soil are included in the inventory, in the Soils Management Section III.F.

Emissions of nitrous oxide occur from wastewater in treatment plants and from effluents discharged into surface waters, thus:

Equation 101: N_2O emissions from wastewater treatment

$$E_{N2O} = E_{N2O,Plant} + E_{N2O,Effluent}$$

Where,

E_{N2O}	= Total N_2O emissions from wastewater treatment (gram)
$E_{N2O,\ plant}$	= N_2O emissions from centralized wastewater treatment plants (gram)
$E_{N2O,\ effluent}$	= N_2O emissions from wastewater effluent discharged into aquatic environments (gram)

(a) <u>Emissions at the wastewater treatment plants</u>

Plant emissions ($E_{N2O,\ plant}$) are estimated with the following equations:

Equation 102: N_2O emissions at the water treatment plant

$$E_{N2O,plant} = E_{N2O,wNDN} + E_{N2O,woNDN}$$

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Equation 103: N_2O emissions from centralized wastewater treatment plant with nitrification/ denitrification

$$E_{N2O,wNDN} = P_{NDN} \bullet EF_{wNDN} \bullet F_{IC}$$

Equation 104: N_2O emissions from centralized wastewater treatment plant without nitrification/ denitrification

$$E_{N2O,woNDN} = \left[(P \bullet f_{central}) - P_{ND}\right] \bullet EF_{woNDN} \bullet F_{IC}$$

Where,

$E_{N2O,\ plant}$	= Total N_2O emissions from centralized wastewater treatment plants (gram)
$E_{N2O,\ wNDN}$	= N_2O emissions from centralized wastewater treatment plants with nitrification/denitrification (gram)
$E_{N2O,\ woNDN}$	= N_2O emissions from centralized wastewater treatment plants without nitrification/denitrification (gram)
P_{NDN}	= California population served by biological denitrification (person)
EF_{wNDN}	= Emission factor for with nitrification/denitrification (gram/person)
F_{IC}	= Factor for industrial and commercial co-discharged nitrogen into the sewer system (unitless)
P	= California population (person)
$F_{central}$	= Fraction of population using centralized wastewater treatments plants as opposed to septic systems (unitless)
EF_{woNDN}	= Emission factor for without nitrification/denitrification (gram/person)

(b) <u>Emissions from nitrogen-containing effluent discharged into water bodies</u>

Effluent emissions ($E_{N2O,\ Effluent}$) are estimated using the following equation:

Equation 105: N_2O emissions from wastewater effluent

$$E_{N2O,Effluent} = \left\{\left[(P - (P_{NDN} \bullet 0.9)) \bullet R_{protein} \bullet f_N \bullet F_{NCN} \bullet F_{IC}\right] - N_{sludge}\right\} \bullet EF_{effluent} \bullet 1.5711$$

Where,

$E_{N2O,\ Effluent}$	= Effluent N_2O emissions (gram)
P	= California population (person)
P_{NDN}	= California population served by biological denitrification (person)

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0.9	= Factor to scale the population served by biological denitrification to reflect the amount of N removed by denitrification (unitless)
$R_{protein}$	= Rate of per capita protein consumption (gram/person/year)
f_N	= fraction of N in protein (gram N/gram protein)
F_{NCN}	= Factor for non-consumed protein added to wastewater (unitless)
F_{IC}	= Factor for industrial and commercial codischarged protein into the sewer system (unitless)
N_{sludge}	= Sewage sludge N not entering aquatic environment (gram N/year)
$EF_{Effluent}$	= Emission factor for effluent water (g N_2O-N/ gram sewage N produced)
1.5711	= Molecular weight ratio of N_2O to N_2 (unitless)

3. Data Sources

California population came from the California Department of Finance (CDOF 2015). The fraction of Californians using centrally treated facilities and septic systems was obtained from the California Wastewater Training and Research Center (CWTRC 2003). The proportions of wastewater treated aerobically or anaerobically, and with or without primary treatment are derived from USEPA's Clean Watershed Needs Surveys (USEPA Various Years-b). California-specific wastewater flow data (gallons per day) and biosolids quantity for wastewater treatment facilities in California were requested from USEPA (USEPA 2015d), under section 503 of the Clean Water Act. The amount of nitrogen in biosolids was estimated using a default value of 5 percent (IPCC 2000).

The production data for fruits and vegetables, red meat, and poultry are from the United States Department of Agriculture National Agriculture Statistics Services (USDA 2016). The volume of petroleum finished product produced by California's refineries was obtained from the CEC Weekly Fuel Watch Reports The rate of wastewater flow of refineries was determined to be 35 gallons per barrel of petroleum finished product based on a CEC report (O'Brien 2010) and on a study of water use and wastewater treatment alternatives for oil refineries in New Mexico (Timm 1985).

Other factors used in the equations are from USEPA 1990-2014 GHG Inventory (USEPA 2015b). The fraction of California's population served by biological denitrification was estimated as proportional to the US population served by biological denitrification (USEPA 2015b, Table 7-15). 2014 data was not available from USEPA, and was extrapolated based on previous years. Table 45 contains the data used to calculate the California population served by biological denitrification.

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Table 48: Population served by biological denitrification.

Year	US Population served by biological denitrification (Millions)	CA to US population ratio	CA population served by biological denitrification
2000	2.636668	0.120500937	317,721
2001	2.58346	0.121110533	312,884
2002	2.530252	0.121471592	307,354
2003	2.477044	0.121985385	302,163
2004	2.423836	0.122104228	295,961
2005	2.370628	0.121771779	288,676
2006	2.31742	0.121478761	281,517
2007	2.264212	0.121343766	274,748
2008	2.211004	0.12120011	267,974
2009	2.157796	0.120862598	260,797
2010	2.104588	0.120614998	253,845
2011	2.05138	0.120576945	247,349
2012	3.00	0.120498465	361,495
2013	3.1	0.1212799	375,968
2014	3.114614*	0.12169246	379,025*

**Extrapolated based on previous years*

For a list of yearly activity and parameter values used in the equations, please consult the online documentation annex at: https://www.arb.ca.gov/cc/inventory/doc/methods_00-14/annex_4c_wastewater_treatment_and_discharge.pdf

4. Changes in Estimates

The calculation methodology remains the same as previous inventories, but some data sources have been updated to include California-Specific data:

4.1 Domestic wastewater

Staff updated the data source for wastewater flow and biosolids quantity from generalized national data to California-specific data, as described in the previous section. This resulted in an average increase in emissions of 8 percent compared to the previous emission inventory.

4.2 Industrial wastewater

California-specific pulp and paper production processed was used (CPBIS 2015), and the methodology for non-citrus fruit wastewater was updated to avoid double counting of emissions. These changes resulted in an average decline of 61% in industrial wastewater treatment emissions compared to the previous inventory, primarily due to changes in pulp and paper assumptions.

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5. Future Improvements

Staff is working with USEPA to obtain a California-specific assessment for the fraction of centralized wastewater facilities that use aerobic or anaerobic treatment. The California Association for Sanitation Agencies (CASA) is conducting a survey to collect facility-level data from municipal wastewater treatment facilities. CASA and Los Angeles County Sanitation District will process the survey data, and ARB plans to evaluate the potential use of these data to better inform emissions estimations for this sector.

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DATA STORAGE AND MANAGEMENT

Greenhouse gas inventories involve a wide range of human activities. Estimating the amount of GHGs generated by these activities requires using a multiplicity of data sources and a diverse set of methodologies. Storing, cataloging and documenting such a multifaceted set of information is challenging.

ARB staff has designed a custom relational database to hold California's GHG inventory information and created a set of web pages to disseminate it.

1. Inventory Database

The GHG inventory database uses Microsoft Access software. Two main types of GHG estimation methodologies are stored in this database, using different amounts of detailed information.

1.1 Methodologies involving simple algebraic formulas. (e.g., fuel combustion, wastewater treatment, etc.)

In this case the formulas are stored as text strings in the database with the values for activity level and all other parameters involved in the formulas. The GHG estimates are recomputed in the database by a set of Visual Basic routines that parse the formula and query the database for the necessary data. The references for the origin of the formulas and the source of all data values are also stored in the database. Cases where data were not available and their values were estimated through interpolation, extrapolation or other methods are also documented in the data tables.

1.2 Methodologies requiring a complex model (e.g., EMission FACtors (EMFAC) model, cattle enteric fermentation model, landfill emission model).

In this case, only the values for activity level and GHG estimates (model output) are stored in the database. The references for the origin of the models and the source of data values are also stored in the database. Cases where model input data were not available and their values were estimated through interpolation, extrapolation or other methods are not documented in the data tables (that information is available through the model reference however).

1.3 Inventory Organization

GHG emissions in California span a wide range of sources and activities. Categorization of emissions can vary, depending on the purpose and intended use of inventory data. ARB's GHG emission inventory uses three different categorization methods to allow multiple uses:

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1. IPCC – Follows IPCC categorization to ensure comparability with international inventories
2. Scoping Plan – Follows the categories identified in the ARB 2008 Scoping Plan in support of AB32
3. Economic Sectors – Allows for comparison with other ARB emission inventories that are similarly categorized

Data organized using each categorization method is available on the GHG emission inventory website.

2. Inventory Web Pages

Information is extracted and summarized from the database to produce Inventory tables and documentation pages for dissemination through ARB's Climate Change web site.

2.1 Inventory tables

A set of queries and reports is used to summarize and tabulate the GHG estimates by categories defined in the scoping plan, by IPCC category of emission and removal, by economic sector, by GHG and by year. The GHG emissions are expressed in millions of metric tonnes of CO_2 equivalent. The CO_2 equivalence calculations are based upon the IPCC Fourth Assessment Report's (IPCC 2007) global warming potentials. Detailed inventory tables are publicly available as PDF documents and as MS Excel spreadsheets by following the corresponding links on the GHG Inventory and Documentation website at: https://www.arb.ca.gov/cc/inventory/data/data.htm. Other, simplified, inventory tables are generated in similar fashion, summarizing the inventory by categories and by year. These summary tables are also available through the GHG Inventory web site. An interactive query tool is also available to select a subset of the inventory in a table, view it or download it to your computer, find out how each of the emission values was estimated, and plot the data (https://www.arb.ca.gov/app/ghg/2000_2014/ghg_sector.php).

2.2 Documentation pages

Each of the emission values contained in the detailed inventory table discussed above has its own html documentation page. The goal of these pages is summarize all the information that was used by ARB staff to produce the particular emission value. With this information, members of the public may assess the methodology used to derive the GHG estimates and independently verify the estimates.

These pages are created by an automated set of queries extracting information from the GHG inventory database. Each of the html documentation pages features the following items:

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- The date on which the page was last updated.
- The identification of the estimate: its IPCC category, economic sector classification, the GHG estimated and the year of the estimate.
- The estimated emissions (both the mass of gas and its CO_2 equivalent), units, the basis of the estimate (the algebraic formula or the name of the mathematical model), and the reference for the origin of the model or formula.
- The activity that resulted in the GHG emissions (if applicable), the data type (data point, compilation of statistics, result from a calculation, mathematical model) and the reference. In the case where the amount of activity is itself the result of a calculation, the formula and its source are given.
- The parameters and constants used in the calculation of the GHG estimate and/or the activity including the value, unit, and reference.
- The calculated amount of GHG emitted per unit of activity, derived from the data listed above.

The html documentation pages are publicly available on ARB's Climate Change website through a hierarchical index based on the same categorization as the detailed inventory table discussed above: IPCC category, economic sector, GHG and year. This index is located at: https://www.arb.ca.gov/cc/inventory/doc/doc_index.php. The documentation pages are also available within the interactive query tool by clicking on emissions values in the query result table.

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LIST OF ACRONYMS

A

AB: Assembly Bill
AHC: American Horse Council
ANDOC: Anaerobically Degradable Organic Carbon
ARB: Air Resources Board
ASTM: American Society for Testing and Materials

B

BOD: Biochemical Oxygen Demand
BOE: California State Board of Equalization
BTU: British Thermal Unit

C

CALEB: California Energy Balance
CalFire: California Department of Forestry and Fire Protection
CalRecycle: California Department of Resources Recycling and Recovery
CDFA: California Department of Food and Agriculture
CDOF: California Department of Finance
CEC: California Energy Commission
CEFM: Cattle Enteric Fermentation Model (USEPA)
CEIDARS: California Emission Inventory Development and Reporting System (ARB)
CEMS: Continuous Emission Monitoring System
CH_4: Methane
CHP: Combined Heat and Power
CKD: Cement Kiln Dust
CO: Carbon Monoxide
CO_2: Carbon Dioxide
COD: Chemical Oxygen Demand
CORINAIR: CORe INventory AIR emissions (EEA)

D

DANF: Decomposable Anaerobic Fraction
DBH: Diameter at Breast Height
DE: Digestible Energy
DOC: Degradable Organic Carbon
DOGGR: Division of Oil, Gas & Geothermal Resources (CA Department of Conservation)

E

EEA: European Environment Agency

Archive

This is an archive document Current ARB Inventory Available at: www.arb.ca.gov/cc/inventory/inventory.htm

EF: Emission Factor
EIA: Energy Information Administration
EIIP: Emission Inventory Improvement Program (USEPA)
EMEP: European Monitoring and Evaluation Programme (EEA)
EMFAC: EMission FACtors model (ARB).
EOR: Enhanced Oil Recovery

F

FAO: United Nations Food and Agriculture Organization
FAOSTAT: Statistics Division of the FAO
FHWA: Federal Highway Administration
FIA: Forest Inventory and Analysis program (USDA-FS)
FOD: First Order Decay model (IPCC)
FRAP: Fire and Resource Assessment Program (CalFire)

G

GE: Gross Energy
GHG: Greenhouse Gas
GIS: Geographic Information System
GPP: Gross Primary Production
GWP: Global Warming Potential

H

HC: Heat Content
HFC: Hydrofluorocarbon
HWP: Harvested Wood Products

I

IPCC: International Panel on Climate Change (UN)
IUPAC: International Union of Pure and Applied Chemistry

L

LADWP: Los Angeles Department of Water and Power
LFG: Landfill Gas
LKD: Lime Kiln Dust
LPG: Liquefied Petroleum Gas

M

MCF: Methane Conversion Factor
MSW: Municipal Solid Waste
MW: Mega Watt
MWh: Mega Watt hour

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N

N: Nitrogen
N_2O: Nitrous Oxide
NASS: National Agricultural Statistics Service (USDA)
NE: Net Energy
NEP: Net Ecosystem Production
NLA: National Lime Association
NLCD: National Land Cover Data (USGS)
NO_x: Nitrogen oxides
NPP: Net Primary Production
NRCS: Natural Resources Conservation Service (USDA)
NSCR: Non-Selective Catalytic Reduction
NSP: Net System Power report (CEC)

O

ODS: Ozone Depleting Substance

P

PCA: Portland Cement Association
PFC: Perfluorocarbon
PFPE: Perfluoropolyether
PIER: Public Interest Energy Research (CEC)
PIIRA: Petroleum Industry Information Reporting Act (CEC)
PM: Particulate Matter
PNW: Pacific Northwest
PSW: Pacific Southwest

Q

QFER: Quarterly Fuels and Energy Report (CEC)

R

ROG: Reactive Organic Compound

S

SCR: Selective Catalytic Reduction
SEDS: State Energy Data System (EIA)
SIP: State Implementation Plan (USEPA)
SOC: Soil Organic Carbon
SSURGO: Soil Survey Geographic database (USDA-NRCS)

T

TDOC: Total Degradable Organic Carbon
THC: Total Hydrocarbon
TOC: Total Organic Carbon

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TOG: Total Organic Gases

U

UC: University of California
UNFCCC: United Nations Framework Convention on Climate Change
USCB: United States Census Bureau
USDA: United States Department of Agriculture
USDA-FS: United States Department of Agriculture – Forest Service
USDOT: United States Department of Transportation
USEPA: United States Environmental Protection Agency
USGS: United States Geological Survey
UTO: Useful Thermal Output

V

VMT: Vehicle Miles Traveled
VS: Volatile Solids

W

WCI: Western Climate Initiative
WIP: Waste in Place
WMS: Waste Management System
WSPA: Western States Petroleum Association

Archive