California Greenhouse Gas Emissions for 2000 to 2018

Trends of Emissions and Other Indicators

Executive Summary

The annual statewide greenhouse gas (GHG) emission inventory is an important tool in tracking progress towards meeting statewide GHG goals. This document summarizes the trends in emissions and indicators in the California GHG Emission Inventory (“the GHG Inventory). The 2020 edition of the inventory includes GHG emissions released during 2000-2018 calendar years. In 2018, emissions from GHG emitting activities statewide were 425 million metric tons of carbon dioxide equivalent ($MMTCO_2e$), 0.8 $MMTCO_2e$ higher than 2017 levels and 6 $MMTCO_2e$ below the 2020 GHG Limit of 431 $MMTCO_2e$. The most notable highlights in the 2020 edition inventory include:

- California statewide GHG emissions dropped below the 2020 GHG Limit in 2016 and have remained below the 2020 GHG Limit since then.
- Transportation emissions decreased in 2018 compared to the previous year, which is the first year over year decrease since 2013.
- Since 2008, California’s electricity sector has followed an overall downward trend in emissions. In 2018, solar power generation has continued its rapid growth since 2013.
- Emissions from high-GWP gases increased 2.3 percent in 2018 (2000-2018 average year-over-year increase is 6.8 percent), continuing the increasing trend as they replace Ozone Depleting Substances (ODS) being phased out under the 1987 Montreal Protocol.

Overview of Emission Trends by Sector

The transportation sector remains the largest source of GHG emissions in the State. Direct emissions from vehicle tailpipe, off-road transportation sources, intrastate aviation, etc., account for 40 percent[a] of statewide emissions in 2018. Transportation emissions decreased in 2018 compared to the previous year, which is the first year over year decrease since 2013. Emissions from the electricity sector account for 15 percent of the inventory and showed a slight increase in 2018 due to less hydropower. The industrial sector trend has been relatively flat in recent years and remains at 21 percent of the inventory. Emissions from high-GWP gases have continued to increase as they replace ODS that are being phased out under the 1987 Montreal Protocol [5]. Emissions from other sectors have remained relatively constant in recent years. Figure 3 shows an overview of the emission trends by Scoping Plan sector. Figure 4 breaks out 2018 emissions by sector into an additional level of sub-sector categories.

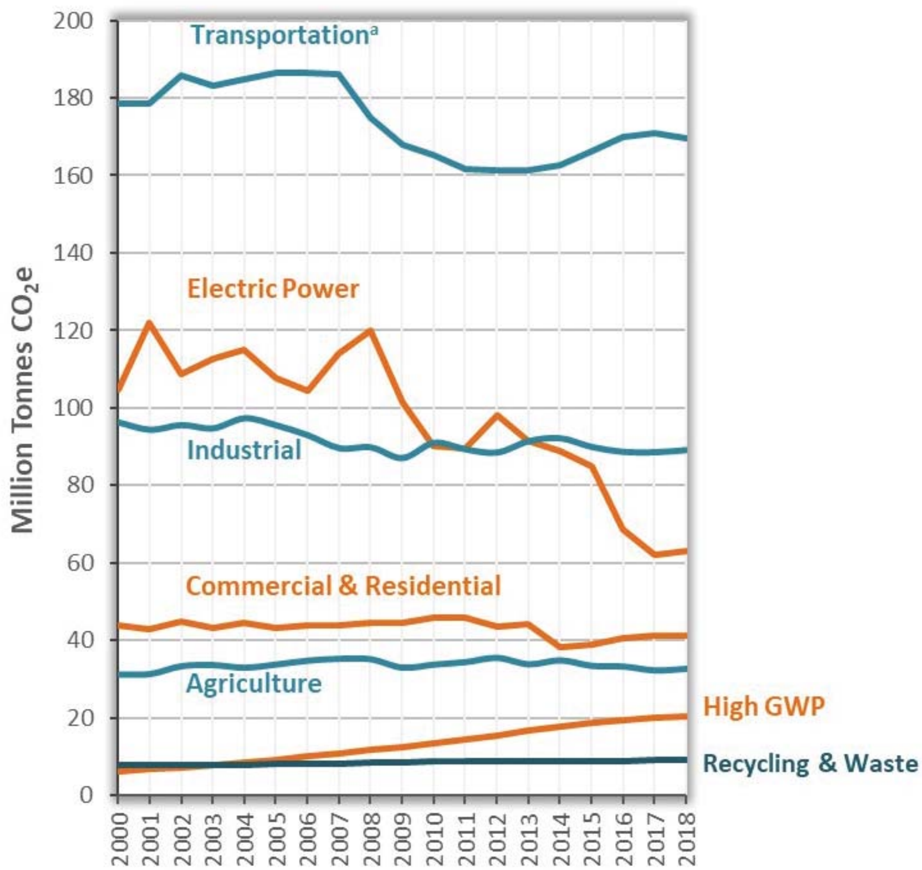


Figure 3. Trends in California GHG Emissions. This figure shows changes in emissions by Scoping Plan sector between 2000 and 2018. Emissions are organized by the categories in the AB 32 Scoping Plan.

[a] The transportation sector represents tailpipe emissions from on-road vehicles and direct emissions from other off-road mobile sources. It does not include emissions from petroleum refineries and oil extraction and production.

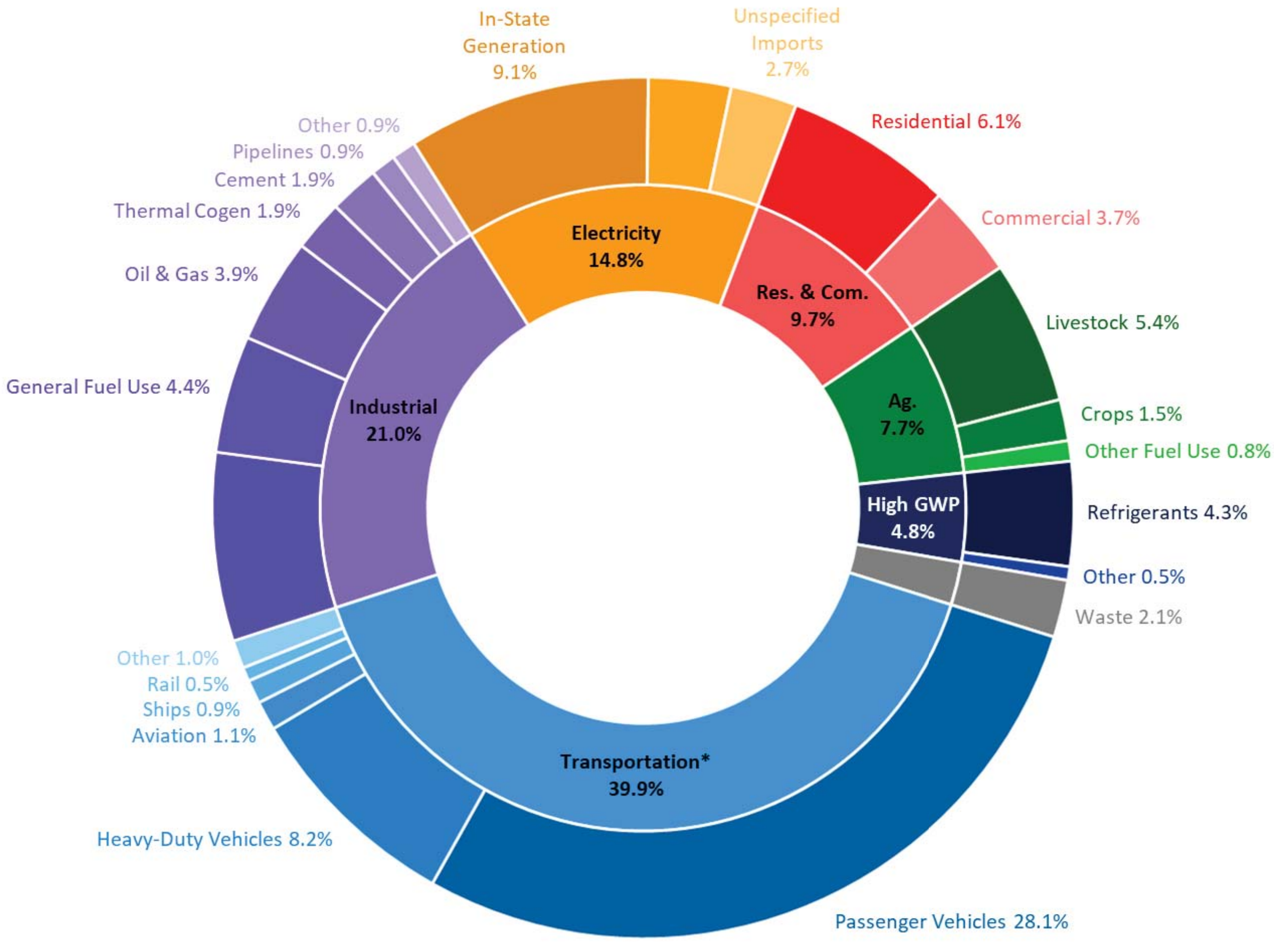


Figure 4. 2018 GHG Emissions by Scoping Plan Sector and Sub-Sector Category. This figure breaks out 2018 emissions by sector into an additional level of sub-sector categories. The inner ring shows the broad Scoping Plan sectors. The outer ring breaks out the broad sectors into sub-sectors or emission categories under each sector.

*The transportation sector represents tailpipe emissions from on-road vehicles and direct emissions from other off-road mobile sources. It does not include emissions from petroleum refineries and oil extraction and production, which are included in the industrial sector.

Agriculture

California's agricultural sector contributed approximately eight percent of statewide GHG emissions in 2018, mainly from CH_4 and N_2O sources. Sources include enteric fermentation and manure management from livestock, crop production (fertilizer use, soil preparation and disturbance, and crop residue burning), and fuel combustion associated with agricultural activities (water pumping, cooling or heating buildings, and processing commodities).

Approximately 70 percent of agricultural sector greenhouse gases are emitted from livestock. Livestock emissions in 2018 are 19 percent higher than 2000 levels. Livestock emissions are almost entirely CH_4 generated from enteric fermentation and manure management, and most of the livestock emissions are from dairy operations. GHG emissions from dairy manure management and enteric fermentation followed an increasing trend between 2000 and 2007, and year-to-year changes since 2007 have been relatively small.

Crop production accounted for 20 percent of agriculture emissions in 2018. Emissions from the growing and harvesting of crops have generally followed a declining trend since 2000. The long-term trend of emissions reduction from 2000 to 2018 corresponds to a reduction in crop acreage (which leads to an associated decrease in synthetic fertilizer use) [16] and large-scale changes in irrigation management practices. Specifically, California agriculture has been shifting from flood irrigation towards sprinkler and drip irrigation. The increase from 2017 to 2018 is due to climatic factors that affect the amount of N_2O produced from synthetic fertilizer (e.g. precipitation and min/max temperature). Figure 16 presents emissions from the livestock and crop production sectors.

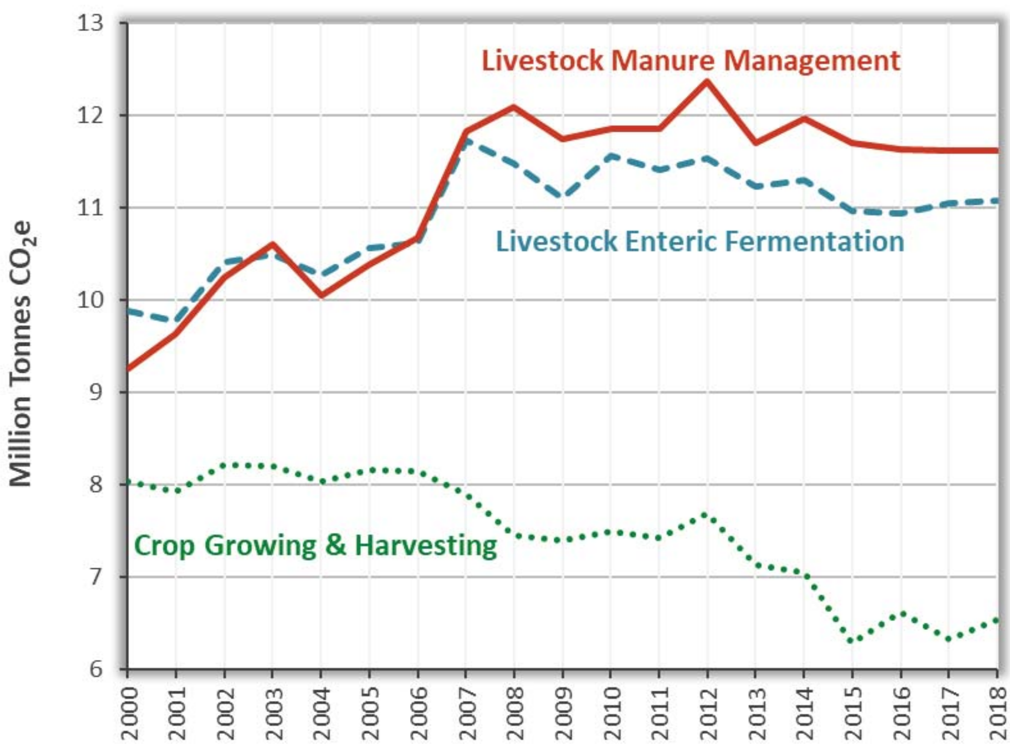


Figure 16. Agricultural Emissions. This figure presents the trends in emissions from livestock manure management and enteric fermentation, as well as emisisons from crop growing and harvesting, which include fertilizer application, soil preparation and distrubances, and crop residue burning.

INVESTING IN CALIFORNIA AGRICULTURE'S CLIMATE SOLUTIONS

California launched the country's first Climate Smart Agriculture programs in 2014. The programs provide technical and financial assistance for the state's farmers and ranchers to adopt practices that reduce greenhouse gas (GHG) emissions, increase carbon sinks, and protect agricultural lands. The programs support the improved resiliency of our farms, ecosystems and communities and some have earmarked funding for Socially Disadvantaged Farmers & Ranchers (SDFRs).*

SUSTAINABLE AGRICULTURAL LANDS CONSERVATION PROGRAM (SALCP)

SALCP funds projects that permanently protect at-risk farmland from sprawl development. It also provides planning grants to local governments to improve farmland conservation planning and policy development.

- Launched in 2014 by the Strategic Growth Council (SGC) in conjunction with the Department of Conservation (DOC)
- Amount awarded to date: $230.6 million
- GHG reductions: 19.5 million metric tons of carbon dioxide equivalent (CO_2e)
- Total projects to date: 149

HEALTHY SOILS PROGRAM (HSP)

HSP provides grants to farmers and ranchers to implement practices that increase carbon stored in soil and woody plants. The program also provides demonstration project funding to NGOs and academics in partnerships with farmers to encourage farmer-to-farmer learning and adoption of practices.

- Launched in 2017 by California Department of Food & Agriculture (CDFA)
- Amount awarded to date: $41.5 million
- GHG reductions annually: 109,809 metric tons of CO_2e
- Total projects to date: 646
- Funding for SDFRs: $7.3 million for 130 projects

ALTERNATIVE MANURE MANAGEMENT PROGRAM (AMMP)

AMMP provides grants to dairy and livestock producers to transition from manure lagoons to dry manure handling and storage, including composting of manure and pasture-based systems to reduce potent methane emissions. The program also funds demonstration projects to showcase alternative manure practices and accelerate their adoption through farmer-to-farmer education.

- Launched in 2017 by CDFA
- Amount awarded to date: $69.1 million
- GHG reductions over 5 years: 1.1 million metric tons of CO_2e in the form of methane
- Total projects to date: 117

STATE WATER EFFICIENCY & ENHANCEMENT PROGRAM (SWEEP)

SWEEP funds on-farm water use efficiency projects, including solar-powered water pumps and soil moisture monitoring equipment that decrease water and energy use, thus reducing GHG emissions.

- Launched in 2014 by the CDFA
- Amount awarded to date: $80.5 million
- GHG reductions annually: 80,077 metric tons of CO_2e
- Total projects to date: 828
- Funding for SDFRs: $8.39 million for 128 projects

CLIMATE SMART AGRICULTURE TECHNICAL ASSISTANCE (TA) PROGRAM

The TA program provides grants to technical service providers to assist farmers and ranchers to develop HSP, SWEEP and AMMP projects, apply for funding and implement the projects.

- Launched in 2019 by CDFA
- Amount awarded to date: $2.1 million, including $525,000 earmarked to support SDFRs
- Total grants to date: 33
- In 2020, technical assistance providers assisted 177 SDFRs, 743 small or mid-scale farms, and 107 non-English speakers

***** SDFRs are "Socially disadvantaged farmers and ranchers," defined in California Food and Agricultural Code Section 512 as: "a farmer or rancher who is a member of a socially disadvantaged group… whose members have been subjected to racial, ethnic, or gender prejudice because of their identity as members of a group without regard to their individual qualities." Note: SDFR data has only been collected for some grant cycles.

Photo credits:
TA: Jason Halley,
HSP: USDA NRCS

CLIMATE SMART AGRICULTURE IN ACTION

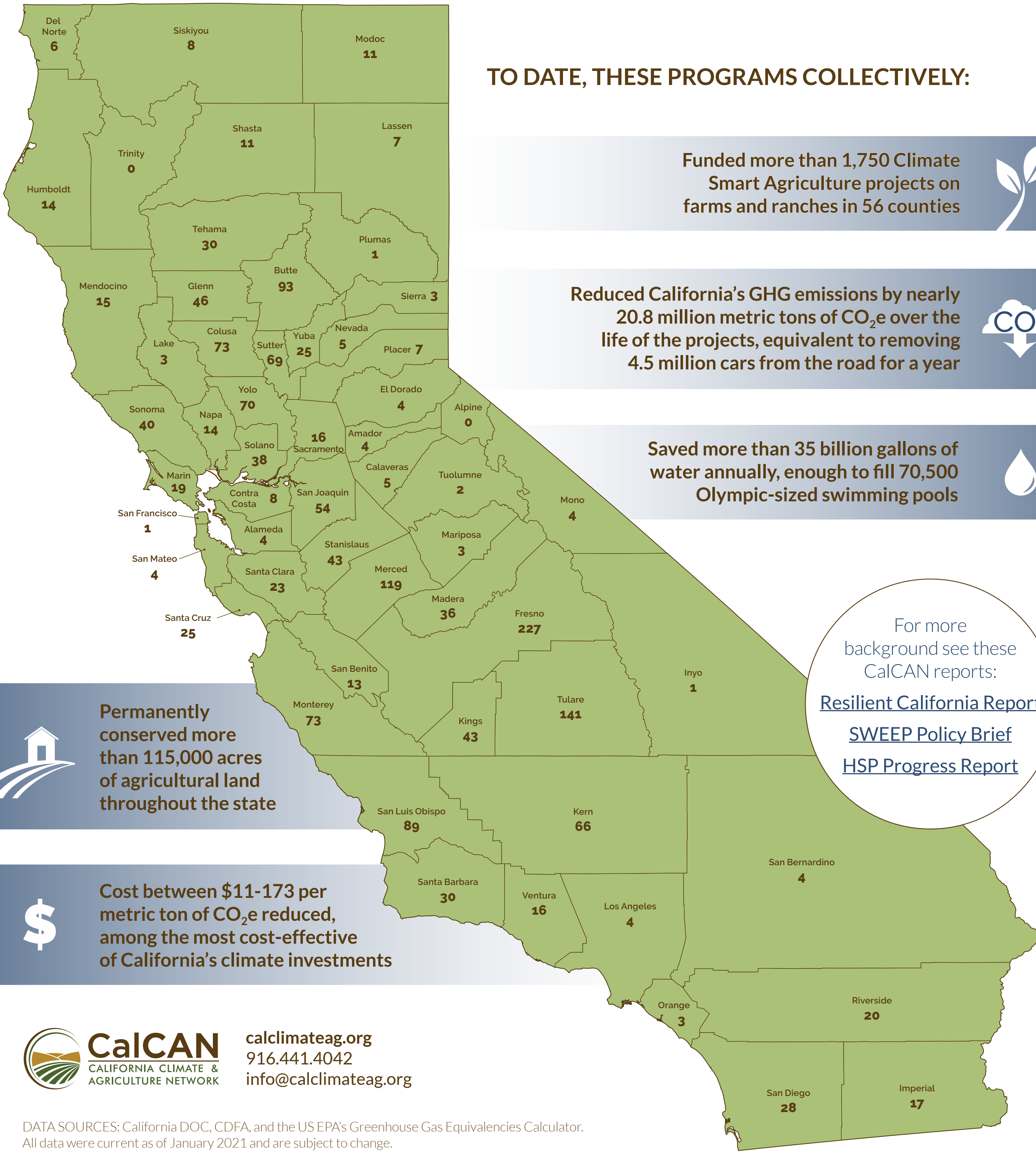
Stories from farmers and ranchers about the many benefits of these programs are available on the [CalCAN website](#).

Xiong Pao Her in Fresno County, SWEEP grantee

Leonardi Dairy in Humboldt County, AMMP grantee

Boonville Barn Collective in Mendocino County, HSP grantee

PROJECTS BY COUNTY



TO DATE, THESE PROGRAMS COLLECTIVELY:

Funded more than 1,750 Climate Smart Agriculture projects on farms and ranches in 56 counties

Reduced California's GHG emissions by nearly 20.8 million metric tons of CO_2e over the life of the projects, equivalent to removing 4.5 million cars from the road for a year

Saved more than 35 billion gallons of water annually, enough to fill 70,500 Olympic-sized swimming pools

Permanently conserved more than 115,000 acres of agricultural land throughout the state

Cost between $11-173 per metric ton of CO_2e reduced, among the most cost-effective of California's climate investments

For more background see these CalCAN reports:

[Resilient California Report](#)

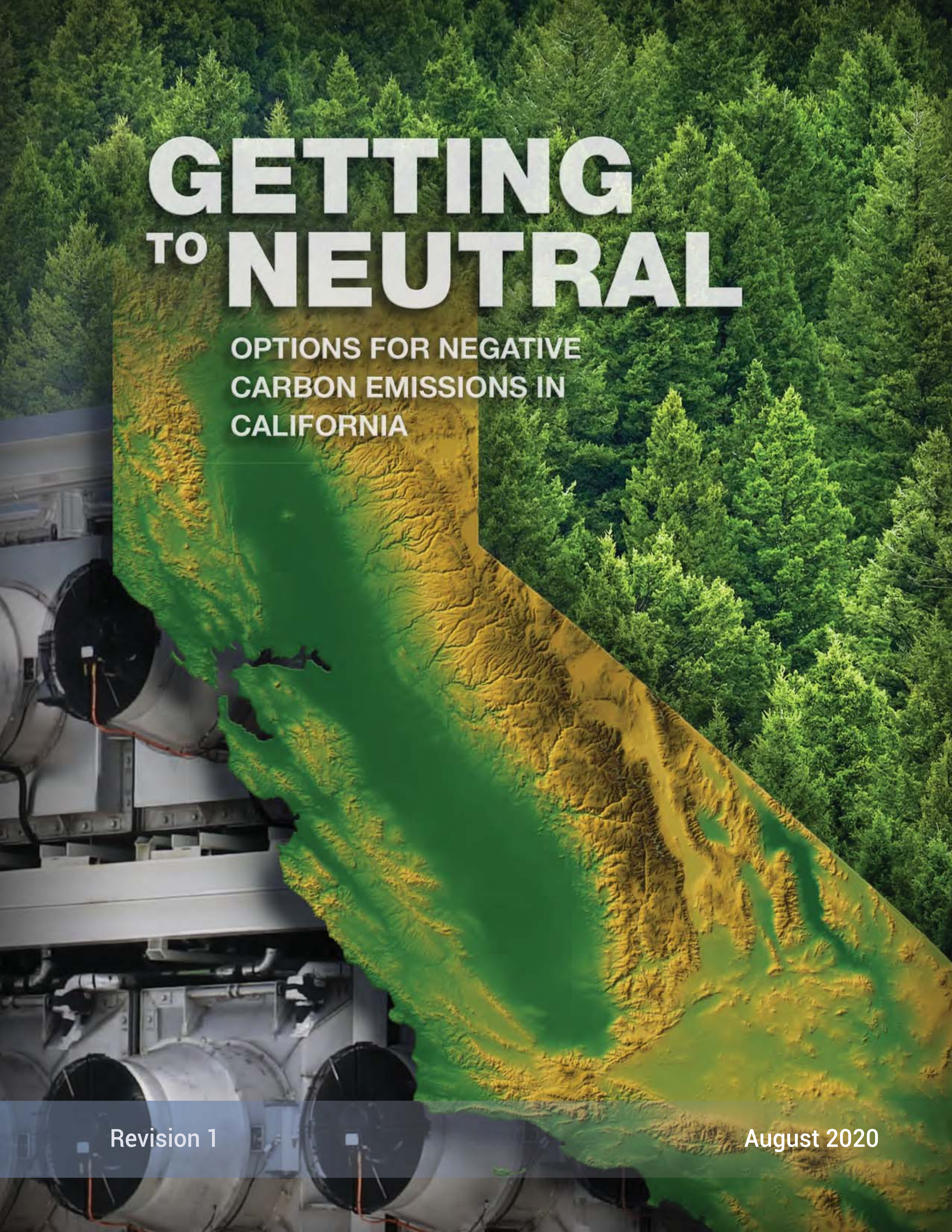
[SWEEP Policy Brief](#)

[HSP Progress Report](#)

CalCAN CALIFORNIA CLIMATE & AGRICULTURE NETWORK

calclimateag.org
916.441.4042
info@calclimateag.org

DATA SOURCES: California DOC, CDFA, and the US EPA's Greenhouse Gas Equivalencies Calculator.
All data were current as of January 2021 and are subject to change.



GETTING TO NEUTRAL

OPTIONS FOR NEGATIVE CARBON EMISSIONS IN CALIFORNIA

Revision 1

August 2020

Acknowledgements

We gratefully acknowledge the support of the Livermore Laboratory Foundation and the ClimateWorks Foundation, which made this study possible.

This study was greatly improved by twenty-five reviewers who graciously provided their time to improve the accuracy and clarity of the work, including Dick Cameron (The Nature Conservancy), Ed Rubin (Carnegie Mellon University), Emily McGlynn (University of California, Davis), Granger Morgan (Carnegie Mellon University), Hanna Bruenig (Lawrence Berkeley National Laboratory), Jan Mazurek (ClimateWorks Foundation), Jeremy Martin (Union of Concerned Scientists), Julia Levin (Bioenergy Association of California), Lynn Brickett (Department of Energy), Mark Rigby (Detroit Edison Energy Services), Michelle Passero (The Nature Conservancy), Sarah Forbes (Department of Energy), Shaffiq Jaffer (Total), Ian Rowe (Department of Energy), James Mulligan (World Resources Institute), Emily Wimberger (Rhodium Group), Ryan McCarthy (Weideman Group Inc.), and Rob Oglesby.

We greatly appreciate the technical suggestions and information supplied by Sabine Fuss (Mercator Institute), George Minter and Ron Kent (SoCalGas), Michael Boccodoro (Dairy Cares), John Hake (East Bay Municipal Utility District), Mark Philbrick (U.S. Department of Energy), Tim Olsen (California Energy Commision), Dieter Smiley (California Public Utilities Commission), Rob Williams (U.C. Davis), Corinne Scown (Lawrence Berkeley National Laboratory), Greg Kester (California Association of Sanitation Agencies), Flyn van Ewijk and Jim Macias (Fulcrum BioEnergy), Rebecca Hollis (Clean Energy Systems), Scott Frazier (Bright Energy Storage), and Cliff Gladstein (Gladstein Associates).

This report could not have been created without the design, editorial, and publication support of Jeannette Yusko, Gabriele Rennie, Katie Lindl, and Christine Hartmann of LLNL. We are deeply grateful for their patience, insights, attention to detail, creativity, and teamwork.

LLNL-TR-796100

Getting to Neutral

Options for Negative Carbon Emissions in California

Authors

Sarah E. Baker, Joshuah K. Stolaroff, George Peridas, Simon H. Pang, Hannah M. Goldstein, Felicia R. Lucci, Wenqin Li, Eric W. Slessarev, Jennifer Pett-Ridge, Frederick J. Ryerson, Jeff L. Wagoner, Whitney Kirkendall and Roger D. Aines, Lawrence Livermore National Laboratory, Livermore, CA 94550

Daniel L. Sanchez Department of Environmental Science, Policy, and Management, University of California, Berkeley

Bodie Cabiyo, Energy and Resource Group, University of California, Berkeley

Joffre Baker, Negative Carbon Consulting, Half Moon Bay, California.

Sean McCoy, University of Calgary, Canada

Sam Uden, School of Earth and Environmental Sciences, University of Queensland, Australia

Ron Runnebaum, Department of Viticulture & Enology, University of California, Davis, CA, 95616 and Department of Chemical Engineering, University of California, Davis, CA, 95616

Jennifer Wilcox, Peter C. Psarras, Hélène Pilorgé, Noah McQueen, and Daniel Maynard, Worcester Polytechnic Institute, Worcester, MA 01609

Colin McCormick, Georgetown University/Valence Strategic, Washington, DC

Cite report as:
Sarah E. Baker, Joshuah K. Stolaroff, George Peridas, Simon H. Pang, Hannah M. Goldstein, Felicia R. Lucci, Wenqin Li, Eric W. Slessarev, Jennifer Pett-Ridge, Frederick J. Ryerson, Jeff L. Wagoner, Whitney Kirkendall, Roger D. Aines, Daniel L. Sanchez, Bodie Cabiyo, Joffre Baker, Sean McCoy, Sam Uden, Ron Runnebaum, Jennifer Wilcox, Peter C. Psarras, Hélène Pilorgé, Noah McQueen, Daniel Maynard, Colin McCormick, *Getting to Neutral: Options for Negative Carbon Emissions in California*, January, 2020, Lawrence Livermore National Laboratory, LLNL-TR-796100

An accessible version of the entire report is available at:
https://www-gs.llnl.gov/content/assets/docs/energy/Getting_to_Neutral.pdf

Editorial Note:

Only minor editorial corrections have been made in this revision of the original report that was published in January 2020. No numerical content or assumptions have been changed or added.

Preface

This report is an assessment of negative emissions pathways—ones that physically remove CO_2 from the atmosphere—that can help California achieve carbon neutrality by 2045, or sooner. It integrates original research findings with current published research on three main pillars of negative emissions: natural and working lands, carbon capture from biomass conversion to fuels, and direct air capture.

The focus and scope of this report is unique: it only addresses practices and technologies for removing carbon dioxide from the air. It also encompasses the entire breadth of strategies, from land management to the latest technological options, and it evaluates the cost of every step of the solution, from waste biomass collection to carbon dioxide transport and geologic storage. The methods are intended to be transparent; details of the calculations and underlying data are included in the report body and appendices.

This study intentionally avoids any discussion of policies and does not include current incentives; it provides a range of options, tradeoffs and costs that can be used to inform future policies. The key finding of this report is that carbon neutrality is achievable.

Table of Contents

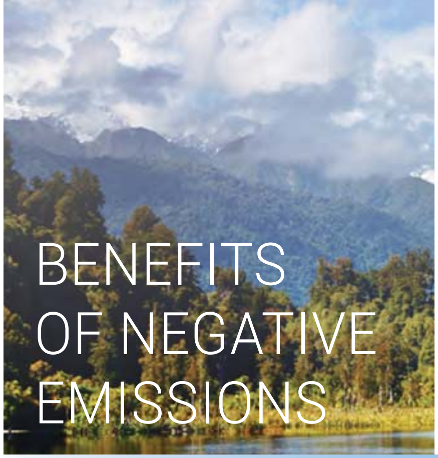
EXECUTIVE SUMMARY

California can achieve its goal of carbon neutrality by 2045 through negative emissions

To reach its ambitious goal of economy-wide carbon-neutrality by 2045, California will likely have to remove on the order of 125 million tons per year of CO_2 from the atmosphere. California can achieve this level of **negative emissions** at modest cost, using resources and jobs within the State, and with technology that is already demonstrated or mature. This is our conclusion after a comprehensive, first-of-its-kind, quantitative analysis of natural carbon removal strategies, negative emissions technologies, and biomass and geologic resources in the State, using methods that are transparently detailed in this report. We also find that realizing this goal will require concerted efforts to implement underground carbon storage at scale, build new CO_2 pipelines, expand collection and processing of waste biomass, and accelerate learning on important technologies, like direct air capture.

Background

California has established itself as a worldwide climate leader through several landmark climate policies and targets, and has made considerable progress in top-priority emission reductions: using energy more efficiently, reducing the



BENEFITS OF NEGATIVE EMISSIONS

Negative emissions strategies add to other critical means of climate change mitigation. They hold important co-benefits for California:

- Air quality improvements, by replacing fossil transportation fuels and reducing biomass combustion and wildfires.
- Water quality improvements, by enhancing and restoring natural ecosystems.
- Protection of life and property, by reducing wildfires.
- Economic development opportunities for the Central Valley and other areas in need.
- Keep California on the leading edge of technological innovation that will have global impact.

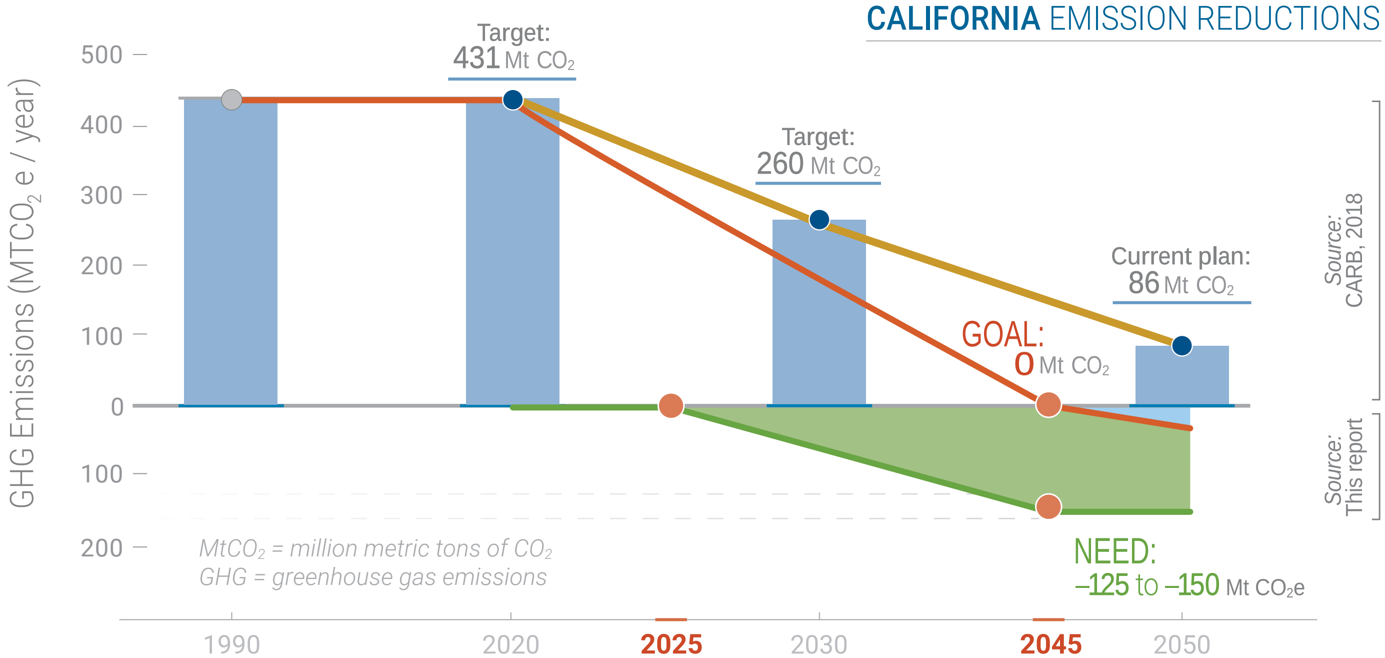


Figure ES-1. *Goals of California's emissions plan extrapolated to 2045 (CARB, 2017) with negative emissions estimates from this report.*

California can add to its growing legacy of ***pioneering practices, technologies,*** *and* ***policies*** *that are required worldwide in order to* ***meet the global climate challenge.***

Three pillars to reach **125** *million tons of negative emissions*

25 Mton/ yr

Capture & store carbon through ***natural and working lands***

84 Mton/ yr

Convert ***waste biomass*** *to fuels and store CO_2*

16 Mton/ yr

Implement ***direct air capture*** *and CO_2 storage*

KEY FINDINGS

By redoubling efforts to reduce and avoid existing emissions, and proactively pursuing negative emission pathways, **California can achieve its ambitious carbon-neutral goal by 2045.**

By increasing the uptake of carbon in its natural and working lands, converting waste biomass into fuels, and removing CO_2 directly from the atmosphere with purpose-built machines, **California can remove on the order of 125 million metric tons of CO_2 per year** from the atmosphere by 2045, and achieve economy-wide net-zero emissions.

California can achieve this amount of negative without buying offsets from outside the State. This approach addresses local emissions without the risk of leakage or offshoring, so the overwhelming majority of the **money is spent on local jobs and local industry.**

These negative emissions pathways come with important co-benefits to air and water quality, resilience to a changing climate, and **protection of life and property.**

California can achieve this goal at a **cost of less than $10 billion per year,** less than 0.4% of the State's current gross domestic product.

Some of the removed carbon will be bound in natural systems or soils, but the bulk will need to be **permanently** and **safely stored deep underground.**

Only moderately and highly mature technologies are required to achieve this negative emissions potential; however, accelerating demonstration and deployment for some of them is a key need.

To realize these benefits, **concerted efforts are required to broaden uptake of new land management practices, establish infrastructure, including waste biomass processing plants,** to produce carbon-negative fuels **and pipelines to transport CO_2** to underground permanent storage sites.

The importance of achieving this level of negative emissions stretches far beyond California – the Golden State can demonstrate to the world that carbon neutrality is achievable.

carbon footprint of its electricity supply, putting cleaner cars on the road, reducing emissions from transportation fuels, and more.

Despite this progress, substantial challenges remain in rapidly decarbonizing the transportation, agriculture, and industrial sectors, and delays are possible. Certain greenhouse gas emissions (such as methane and nitrous oxide) are difficult to eliminate. Some fossil fuel uses, such as in aviation, cannot yet be eliminated in a straightforward way.

The goal of being entirely carbon neutral by 2045 is substantially more ambitious than the State's previous long-term goal of achieving an 80% reduction from 1990 emission levels by 2050. In addition to further intensifying decarbonization efforts in the areas that the State has already championed, the new goal requires ingenuity and innovation that goes beyond today's success stories.

California can attain this new goal if it now also invests in solutions that directly remove carbon dioxide from the atmosphere. The function of these negative emissions is to neutralize any residual emissions and provide a new cushion of security over and above current efforts. We estimate that the State should aim to remove on the order of 125 million metric tons of carbon dioxide (Mt CO_2) annually from the atmosphere by 2045, as shown in Figure ES-1 on page 1.

Negative Emissions:
A Logical Next Step for California

We analyzed how California can use resources and technology to achieve our goal of 125 million tons of negative emissions per year. We define negative emissions as CO_2 that is physically removed from the atmosphere, such as through biomass growth or direct air capture. It does not include reductions in current or projected emissions. We drew from existing literature, standard tools, and our own expertise to assess the feasibility and cost of more than 50 negative emissions pathways. We selected the lowest cost and most productive pathways to create a negative emissions strategy that has three pillars (Figure ES-2):

1. Capture and store as much carbon as possible through better management of natural and working lands
2. Convert waste biomass to fuels and store the CO_2
3. Remove CO_2 directly from the air using purpose-built machines and store the CO_2

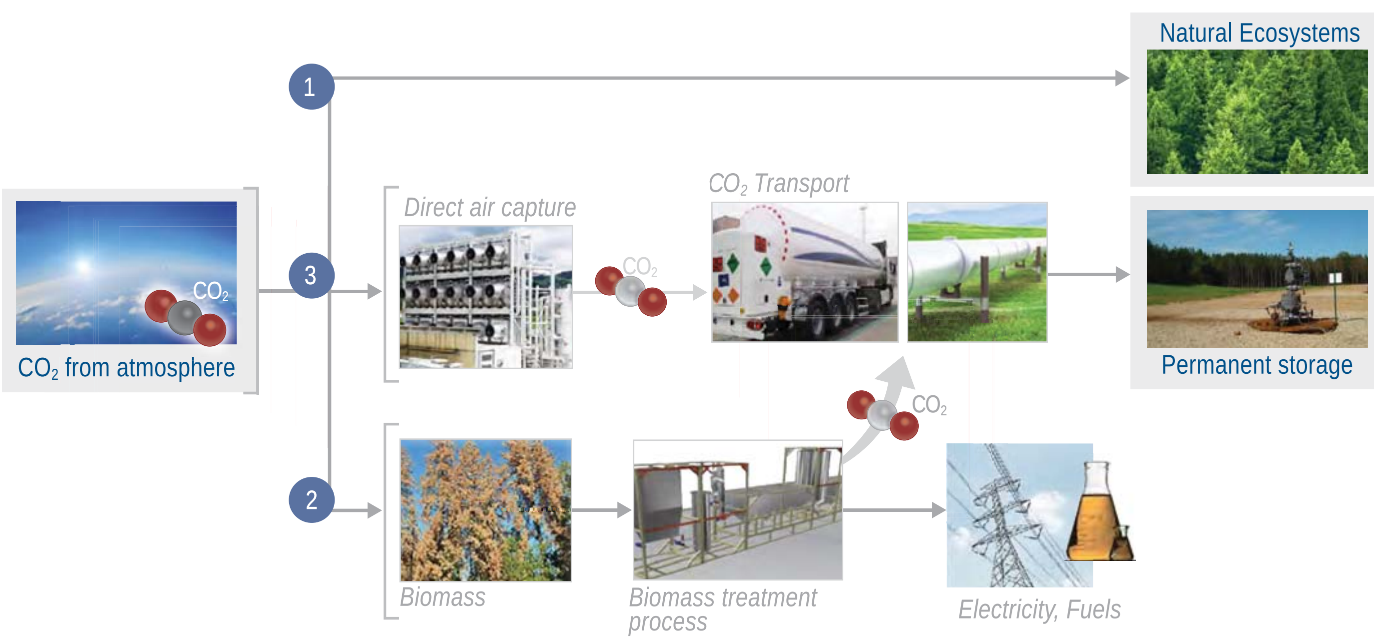


Figure ES-2. *The three main pathways to negative emissions (removing CO_2 from the atmosphere) for California are restoring natural ecosystems, converting waste biomass to fuels while capturing the CO_2 generating during processing, and direct air capture machines.*

1st Carbon-Reduction Pillar: Natural Solutions

Using the Power of Nature to Remove CO_2 from the Atmosphere

Natural solutions encompass activities such as changes to forest management to increase forest health and carbon uptake, restoration of woodlands, grasslands and wetlands, and other practices that increase the amount of carbon stored in trees and soils. These approaches are among the least expensive we examined, averaging $11 per ton of CO_2 removed from the atmosphere. In addition, they have important co-benefits to air and water quality, ecosystem and soil health, resilience to a changing climate, and protection of life and property through fire risk reduction. Unfortunately they are limited by land and ecosystem availability. Details on land treatment measures, costs, and uncertainty can be found in **Chapter 2.**

2nd Carbon-Reduction Pillar: Waste Biomass

Convert Waste Biomass to Fuels and Store CO_2

Waste biomass is widely available across California, with about 56 million bone dry tons per year available from trash, agricultural waste, sewage and manure, logging, and fire prevention activities (Figure ES-3). Today, this biomass returns its carbon to the atmosphere when it decays or burns in prescribed fires or wildfires, or is used to produce energy at a power plant that vents its carbon emissions. Details on the waste biomass sources and quantities we used in our analysis, and associated constraints, collection costs, and current uses, can be found in **Chapter 3**.

Converting this biomass into fuels with simultaneous capture of the process CO_2 emissions holds the greatest potential for negative emissions in the State. A broad array of processing

All of California can participate in gathering the biomass needed for negative emissions

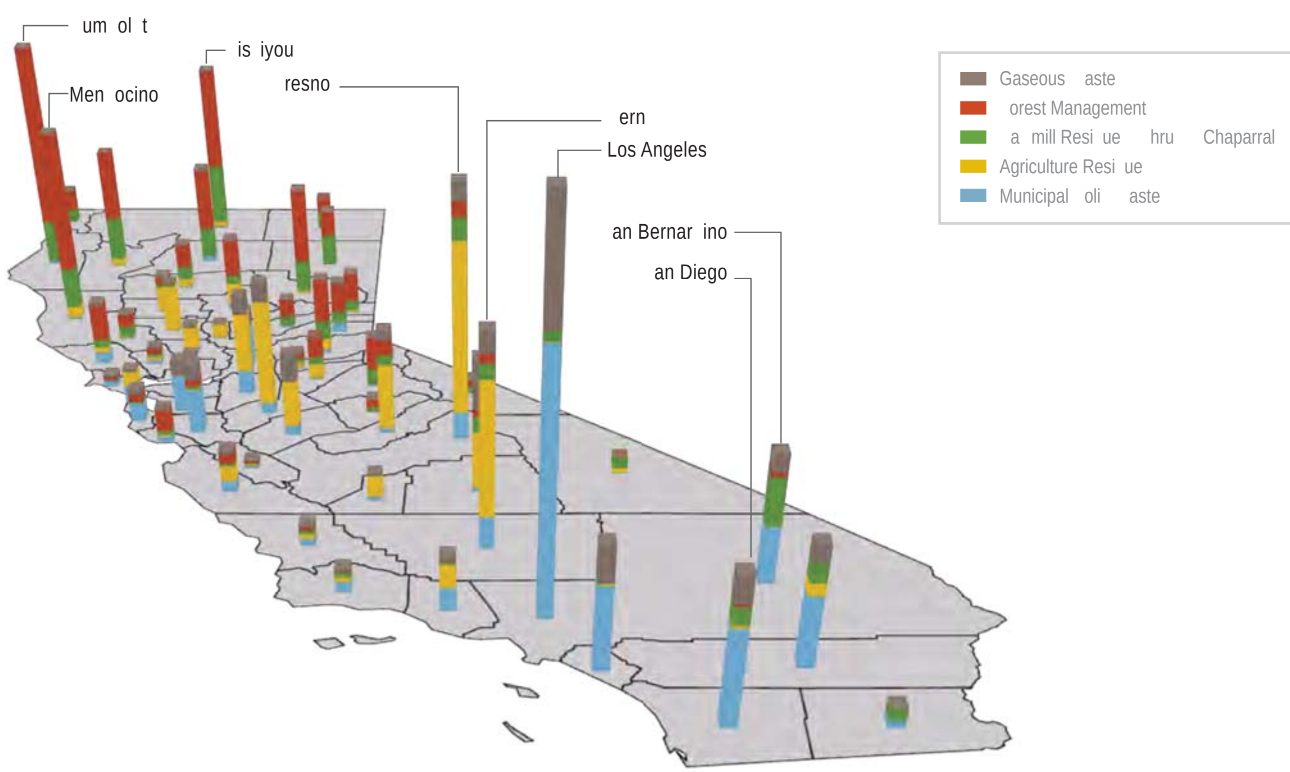


Figure ES-3. All of California can participate in collecting the biomass needed for negative emissions. *Our study assumed contributions across counties and resource types. In sum, 56 million bone-dry tons of waste biomass will be available in 2045, at a typical carbon content of 50%. Gaseous waste comes from landfills and anaerobic digesters. Forest management refers to residue produced from forest management treatments like mechanical thinning for fire control. Sawmill residue refers to the residue produced at the sawmill facilities. Shrub & chaparral refers to mostly shrubby evergreen plants located in semi-arid desert region of California. Agriculture residue includes orchard & vineyard residues, field residues, row residues, row culls, almond hulls, almond shells, walnut shells, rice hulls and cotton gin trash. Municipal solid waste includes paper, carboard, green waste and other organics.*

options is available, and includes collecting biogas from landfills, dairies, and wastewater treatment plants for upgrading to pipeline renewable natural gas; conversion of woody biomass to liquid fuels and biochar through pyrolysis; and conversion of woody biomass to gaseous fuels through gasification. Gasifying biomass to make hydrogen fuel and CO_2 has the largest promise for CO_2 removal at the lowest cost and aligns with the State's goals on renewable hydrogen. We link biomass processing technologies to each source of biomass and compare these processing technologies in terms of the amount and cost of CO_2 that can be derived from a given biomass source in **Chapter 4**.

3rd Carbon-Reduction Pillar:
Direct Air Capture

Machines to Remove CO_2 from the Air and Permanently Store it Underground

Direct air capture is more expensive than most negative emissions options for California, but has a nearly unlimited technical capacity, provided its energy needs (primarily heat) can be met from a low-carbon source. This option will inevitably have to be used to some extent, depending on the degree of adoption of other, less expensive options. Captured CO_2 must be directed to permanent storage. We envision facilities located near the highly suitable permanent geologic storage sites in California's Central Valley, as well as a smaller set that utilize geothermal heat where it is available in the Salton Sea region. Because land use for renewables would be very large for the amount of power needed for this amount of direct air capture (roughly 250 MW per million tons per year), natural gas power (with gas sourced nearby in California fields) at the direct air capture plant is the second best option after geothermal heat. Almost all the CO_2 from combustion would be captured and stored, resulting in a net reduction in atmospheric CO_2. Direct air capture technology options and associated costs are described in **Chapter 5**; Direct air capture and other technologies that have not been deployed at scale will get less expensive as more units are deployed. We describe how these costs decrease with technology learning in **Chapter 8**.

Where Will the Carbon Go?
Back into the Ground

Beyond carbon stored in plants and soils through natural solutions, putting the captured carbon away involves storing it permanently and safely thousands of feet underground as CO_2, in porous rock of the same kind that makes up California's oil and gas fields. The presence of oil and gas in these fields is, in fact, a clear demonstration of nature's ability to trap fluids underground over millions of years. California's deep sedimentary rock formations in the Central Valley represent world-class CO_2 storage sites that would meet the highest standards, with storage capacities of at least 17 billion tons of CO_2 according to our estimates – many decades' worth of capacity to store carbon from negative emissions pathways at the scale contemplated here.

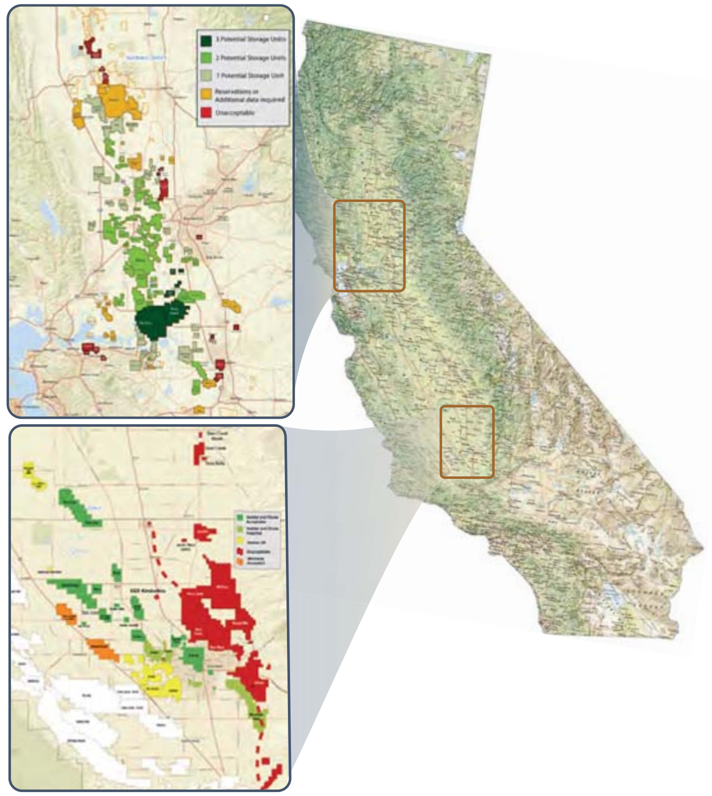


Figure ES-4. Two prospective areas for underground geologic storage. *Oil and gas fields are highlighted. Color indicates the degree of conformance with existing State and Federal standards for geologic CO_2 storage, as well as additional safety constraints. White fields have not been evaluated.*

Until now, the locations and storage capacities of suitable, permanent storage sites within the State have been based on high-level, low-resolution, basin-scale assessments. We advance this understanding to location-specific knowledge by assessing the storage capacity associated with California's oil and gas fields, as well as deep saline aquifers that share the same geology, for two extremely well studied areas with publicly available data: Kern County and the Sacramento-San Joaquin Delta (Figure ES-4). Both these regions have been sites of extensive oil and/or gas production, which results in the availability of geologic data. We used these data to evaluate CO_2 storage capacity, storage security, and the ability to comply with the strict regulations and standards that govern current underground CO_2 storage.

We conclude that these areas contain ample safe and effective storage sites. At depths below 3,000 feet, CO_2 converts to a liquid-like form that has about the same density and viscosity as oil. The fact that the geologic barriers in these regions have held oil and gas and other fluids underground for millions of years means that they are well-suited to secure storage of CO_2. Site-specific factors such as faulting and man-made penetrations will need to be evaluated carefully for each site storage operation, but our review of about 50% of the likely good storage zones in the Central Valley indicates that at a minimum 17 billion tons can be stored there, with the upper limit being 200 billion tons. 17 billion tons would provide more than 100 years of capacity at the rate that we anticipate California will require negative emissions. These findings are detailed in **Chapter 6**.

Transporting the Carbon to Its Burial Grounds

Transportation is a critical aspect of the negative emissions system. Our analysis shows that forest biomass resources are concentrated in the northwestern region of the state; agricultural residue resources in the Central Valley, and municipal solid waste and gaseous waste resources in the populated areas of the southern region. Promising CO_2 storage locations are mainly in the Central Valley. The transport problem is: What is the best way to move carbon from the biomass source regions to the storage sites?

There are multiple options for the mode of transport (truck, rail, pipeline) and the form of carbon to be transported. CO_2 by pipeline is the lowest cost option for large volumes. In **Chapter 7,** we assess various configurations of truck, rail, and pipeline transport as well as options for siting processing facilities. Many strategies yield reasonable costs, but a shared CO_2 trunk pipeline and use of existing rail lines are key to keeping costs low. For this study, a model was used to choose the lowest-cost transport mode for each county and carbon source type for several technology scenarios. The system-wide average transport cost is \$10—18 per ton of CO_2 removed, depending on the technology scenario.

Necessary Systems and Infrastructure

The advantage of natural solutions is that they can be implemented with little infrastructure; however, their success depends on securing funds to implement them. Success also depends on the broad dissemination of practices across a large land area with potentially numerous owners and managers who must adopt the required practices.

Collecting California's full amount of waste biomass will require a concerted effort from farmers, landowners, waste handlers, and state agencies. In most cases, the biomass in our accounting did not have other current uses or economic value, such as that which would have been pile burned or landfilled. In other cases, we assume a change in biomass use to achieve negative emissions. If certain biomass types or sectors are not available for negative emissions, this only means that system costs will increase, and not that negative emissions cannot be achieved. We present cost sensitivity to potential biomass availability constraints in **Chapter 9**. Additionally, the lowest cost pathway to negative emissions requires building the capacity to handle California's full amount of waste biomass, requiring the construction of a fleet of gasification, pyrolysis, and biogas upgrading/purification plants, which we estimate to be on the order of 50 to 100 facilities, the largest of which would be located in the Central Valley. These state-of-the-art, low-emissions facilities will reduce air pollution from existing burning of biomass, and also displace polluting fuels from the road.

Transport and geologic storage of CO_2 are essential to achieve the required negative emissions. While these steps are comparatively inexpensive, together requiring \$10—20 per ton, they may be the most time-constrained aspect. While construction of CO_2 pipelines from biomass processing facilities to geologic storage is the lowest cost transport option, numerous logistical and regulatory hurdles may impede pipeline construction. Additionally, secure storage sites where the CO_2 can be stored permanently have to be characterized and selected carefully according to rigorous State and Federal geologic criteria, and require the consent of several land and mineral owners. Although sites like this can readily be found in California's Central Valley, it is not realistic to expect them to be situated immediately next to the CO_2 source as a rule, and the best geology may not coincide with the quickest legal and permitting lines of sight.

The Cost of Removing Carbon

Our analysis shows that by increasing the uptake of carbon in natural and working lands, converting waste biomass into fuels, removing carbon dioxide directly from the atmosphere with purpose-built machines, and safely and permanently storing captured CO_2, California can remove 125 million metric tons of CO_2 per year from the atmosphere by 2045, and achieve net-zero statewide emissions. The lowest-cost set of strategies to do this, according to our assessment, is one which prioritizes gasification of biomass to hydrogen. This scenario is shown in Figure ES-5, where negative emissions pathways are ordered from least to most expensive. The width of the bar represents the quantity of CO_2 removed at full deployment. The costs shown include biomass collection, plant capital and operating expenses, transport, CO_2 storage, and revenue from sale of coproducts at market rates. The quantity of conventional direct air capture is chosen so that the sum of all pathways removes 125 million tons annually, although direct air capture can remove much more if needed.

The total cost of the scenario with the lowest-cost set of technologies is \$8 billion per year, or \$65 per ton CO_2, which is quite modest compared to California's current gross domestic product (0.34%) and compared to previous estimates of the cost of negative emissions. We also investigate other scenarios with different technology choices, product selling prices, direct air capture costs, and biomass availability and find that the total system cost lies in the range of \$5—15 billion for most reasonable sets of assumptions. Higher system costs are possible, but can be avoided by investors and policymakers who actively work to minimize costs.

These scenarios are achievable with biomass conversion and air capture technologies that are either already deployed today, or ready to be piloted at scale. The speed at which the State deploys new technologies will directly impact the cost and practical realization of negative carbon emissions. Therefore, a critical part of making these estimates a reality is initiating at-scale and near-scale technology pilots as soon as possible.

ACTIONS

Scale up and **accelerate** implementation of natural solutions.

Ensure eligibility and economic viability of **negative emission pathways** under the **State's climate programs.**

Facilitate **collection** and **distribution** of a reliable waste biomass supply.

Ensure a viable permitting and siting framework for needed infrastructure, such as **biomass conversion, CO_2 transport and safe, permanent CO_2 storage.**

Buy down the cost of critical technologies such as **direct air capture** by accelerating learning.

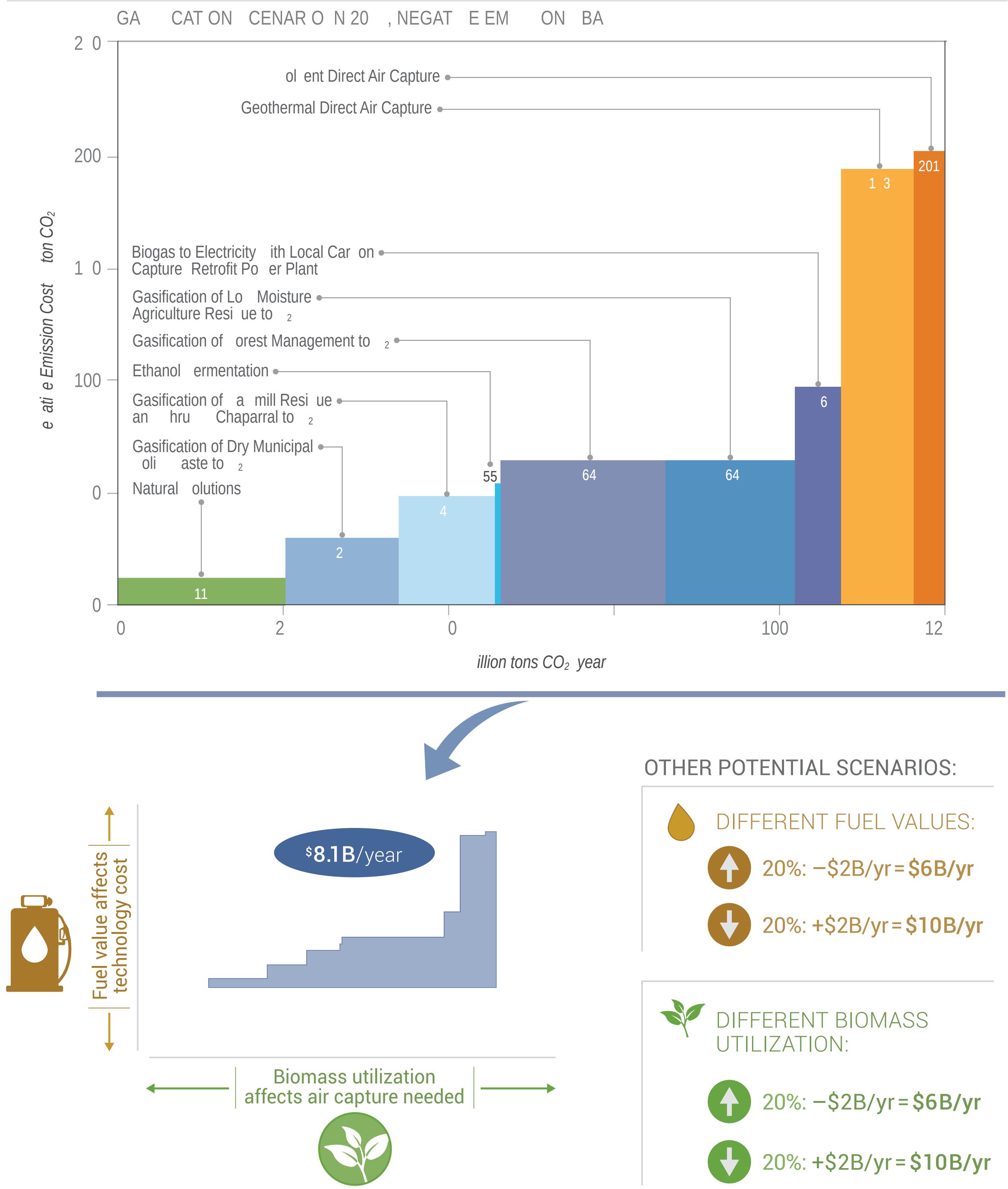


Figure ES-5. Cost of the negative emissions system. *(top) Average costs and cumulative quantities for the lowest-cost set of negative emissions pathways for California. All collection, transport, processing, and final storage costs for CO_2 are included, assuming full use of projected waste biomass resources in 2045. (bottom left) Total cost for the system is the area under the curve, which is \$8.1 billion in the case shown. Fuel value affects the cost of biomass conversion technologies (height of the bars), while biomass availability affects the quantities of CO_2 removed by conversion technologies (width of the bars). (bottom right) Changing the fuel selling price or biomass availability by 20% changes the total system cost as shown.*

California can Reach its 2045 Vision *and Lead the World in the Process*

Achieving 125 million metric tons of CO_2 per year of negative emissions for California will require that natural and working lands are managed in different ways. Biomass processing infrastructure will need to be planned, financed, and built around the state to produce carbon-negative fuels. Machines that remove CO_2 directly from the air will need to be built and powered. Geologists will need to identify the best sites to store CO_2 deep underground permanently and securely, and land and CO_2 will need to be transported and stored across many land and mineral ownership boundaries. Most of these steps come with potentially complex and time-consuming permitting processes.

But our analysis shows that most negative emissions options make, or are close to making, economic sense today. Figure ES-5 shows the progression of options, from inexpensive to most expensive. The total system cost depends strongly on the degree to which biomass is used. It also depends on the value of the fuels made from biomass – the more valuable they are, the less the resulting CO_2 costs. California's final plan will certainly be a mix of many technologies and approaches, but our work indicates that the overall cost is not a strong function of the actual technologies, and many approaches can be embraced.

The opportunity to act is unique. Pursuing negative emissions now enhances the security of California's own emissions outcome. The State is no stranger to innovation, and can pioneer climate solutions, technologies and policies that will undoubtedly need to spread globally to deal with the global climate crisis. California is ideally situated to lead in this task, with a long history of aggressive policies for efficiency, renewable energy and carbon reduction, along with geology and a workforce ideally suited to this task.

The stage is set. The actions needed today to help California be carbon neutral, and ultimately carbon negative, are available and affordable. And this plan does not need to wait for 2045. Progress can begin immediately, and the carbon reductions we envision can be achieved much sooner, accelerating a truly carbon-neutral economy for California, with a carbon negative economy in sight.