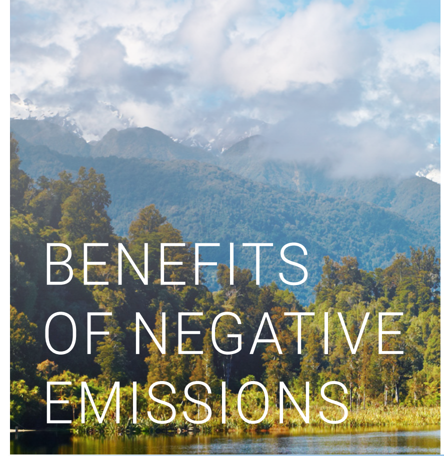
EXECUTIVE SUMMARY

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.

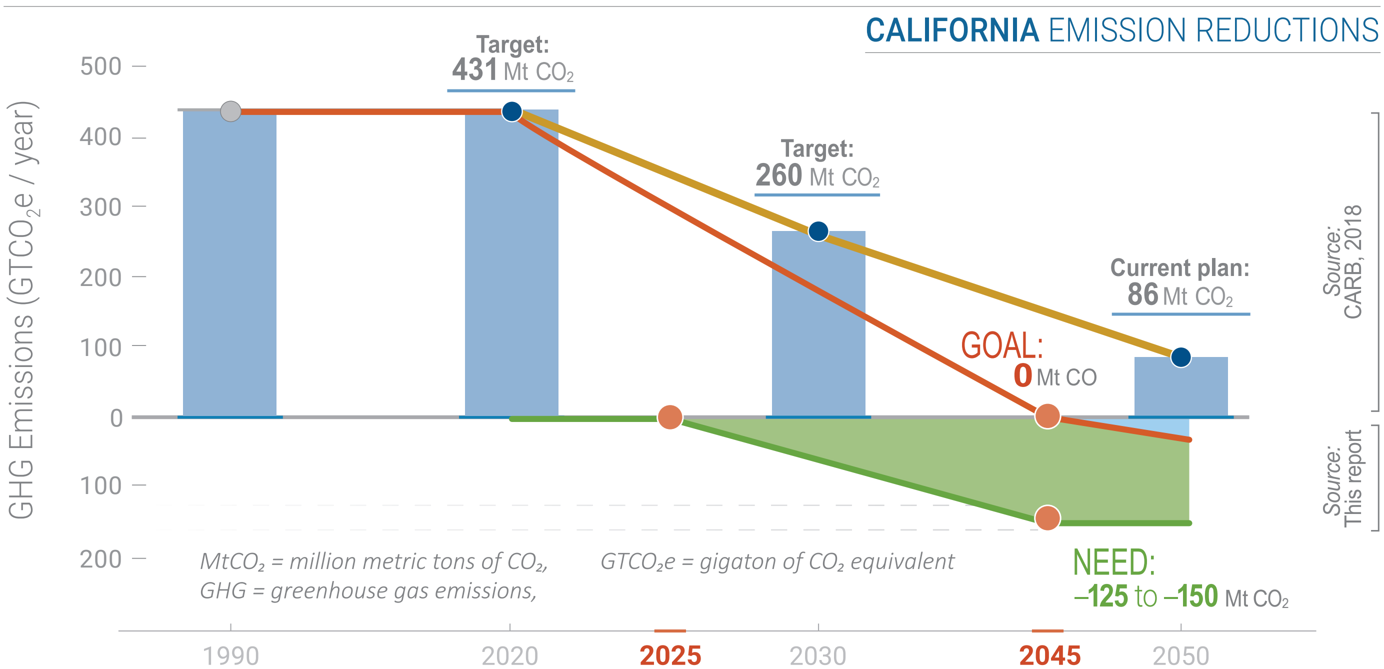


Figure ES-1. *Goals of California's emissions plan extrapolated to 2045 (CARB, 2017) with negative emissions estimates from this report.*

*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

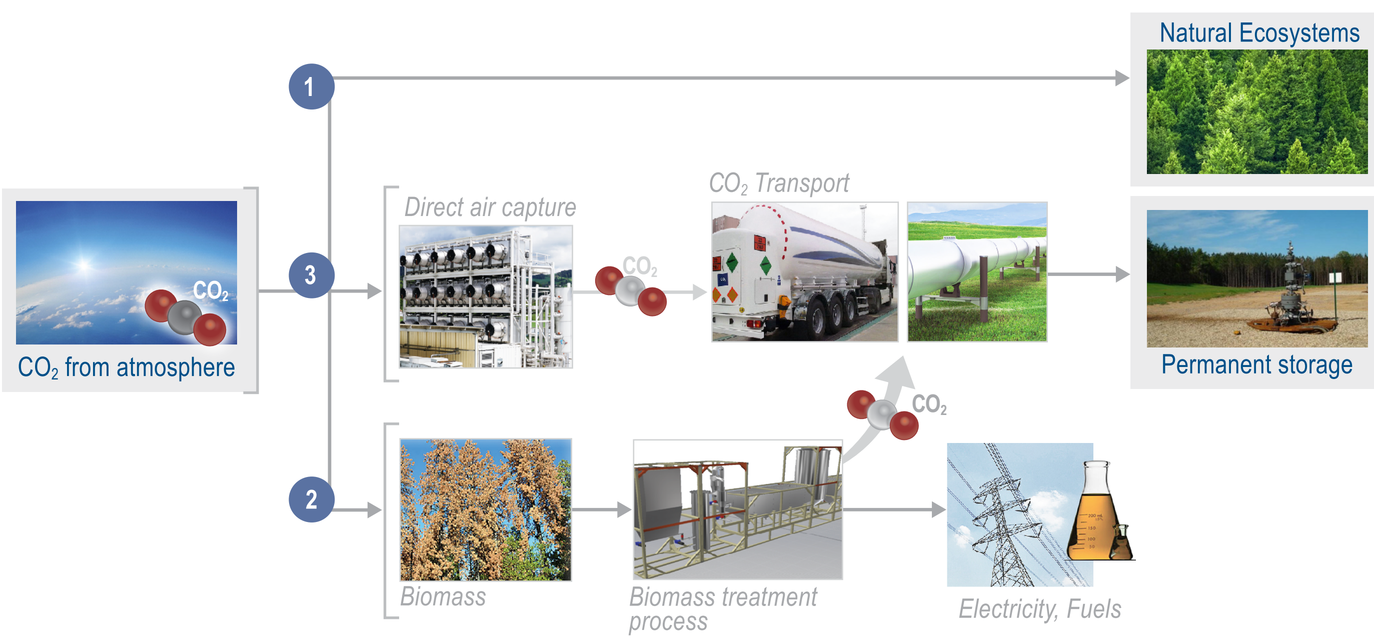


Figure ES-2. *The three main pathways to negative emissions (removing CO_2 from the atmosphere) for California are restoring natural ecosystems, converting waste biomass to fuels while capturing the CO_2 generating during processing, and direct air capture machines.*

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

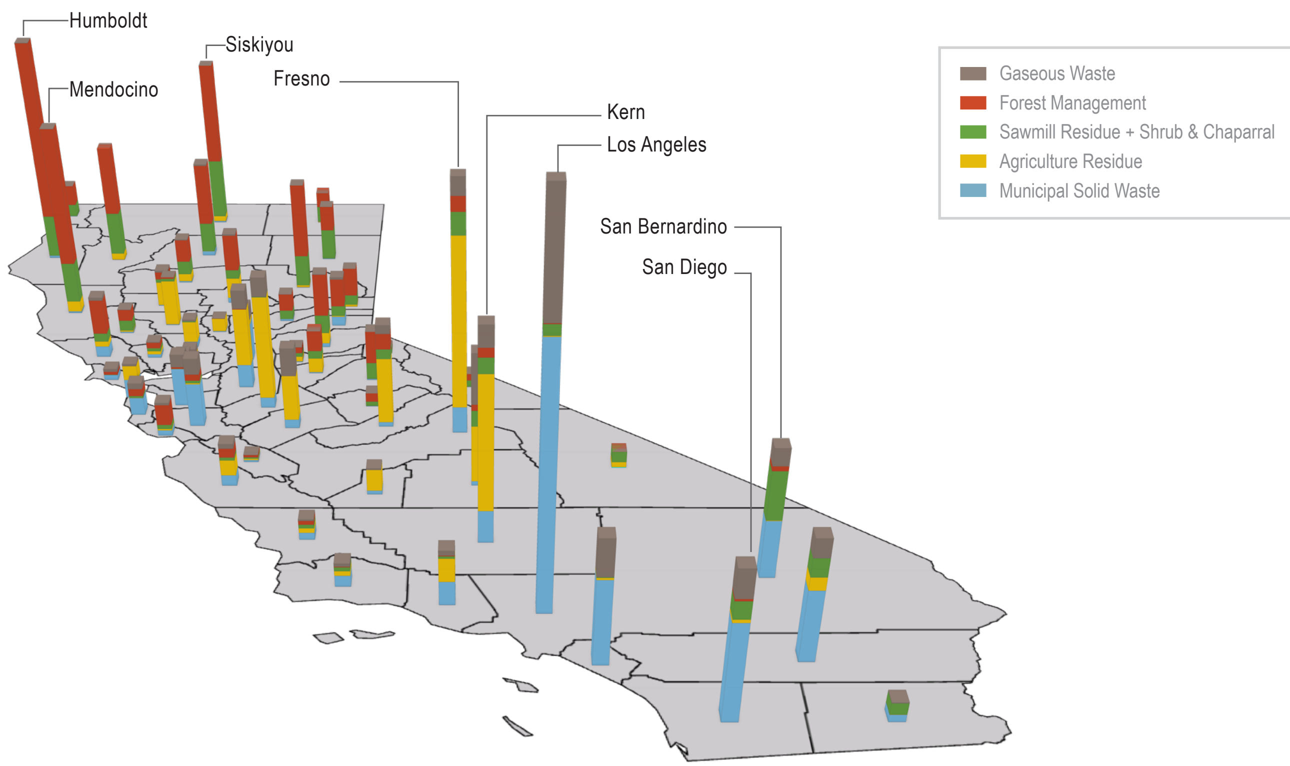


Figure ES-3. All of California can participate in collecting the biomass needed for negative emissions. *Our study assumed contributions across counties and resource types. In sum, 56 million bone-dry tons of waste biomass will be available in 2045, at a typical carbon content of 50%. Gaseous waste comes 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

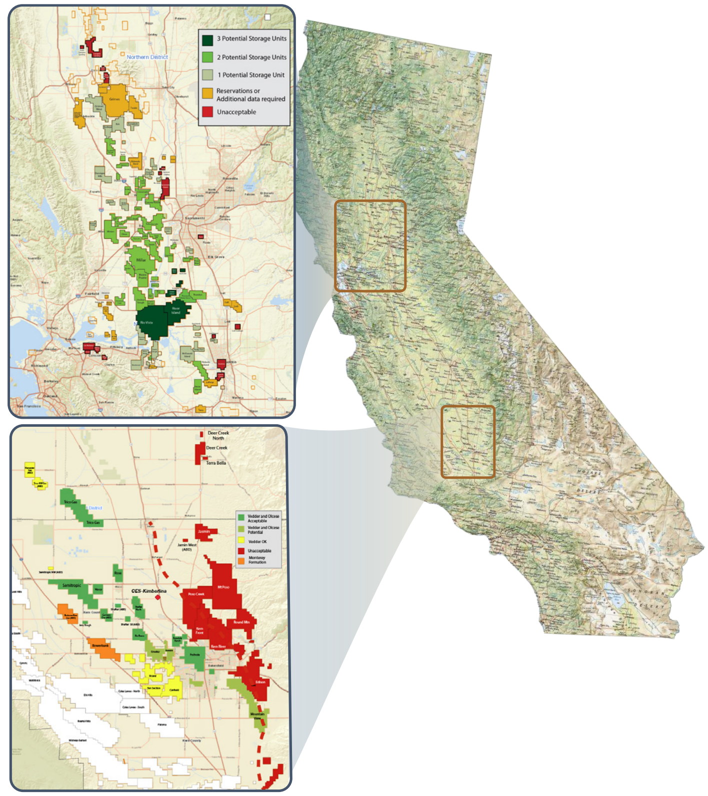


Figure ES-4. Two prospective areas for underground geologic storage. *Oil and gas fields are highlighted. Color indicates the degree of conformance with existing State and Federal standards for geologic CO_2 storage, as well as additional safety constraints. White fields have not been evaluated.*

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.

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.

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.

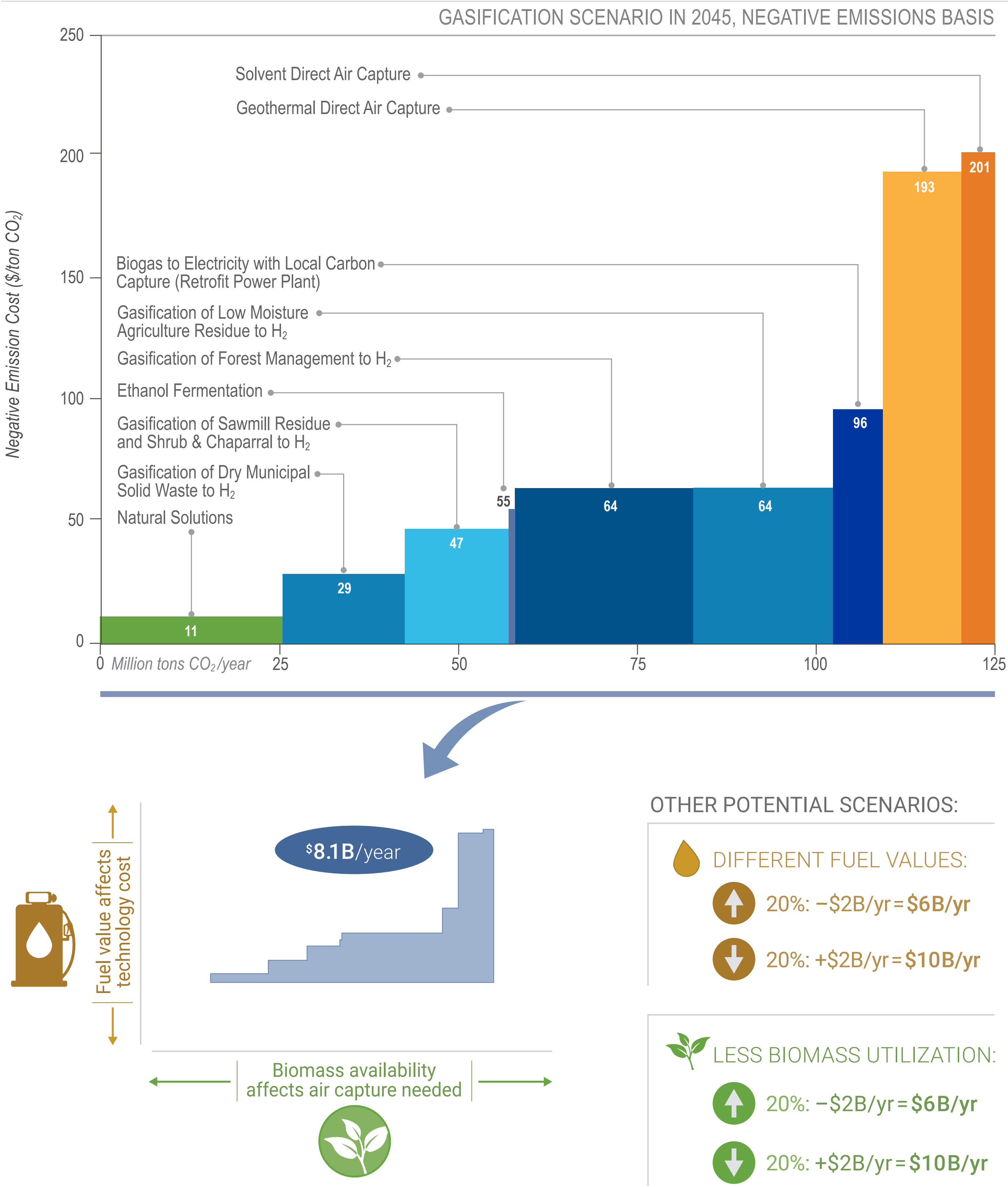


Figure ES-5. Cost of the negative emissions system. *(a) Average costs and cumulative quantities for the lowest-cost set of negative emissions pathways for California. All collection, transport, processing, and final storage costs for CO_2 are included, assuming full use of projected waste biomass resources in 2045. (b) 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). (c) Changing the fuel selling price or biomass availability by 20% changes the total system cost as shown.*

Getting to Neutral: Options for Negative Carbon Emissions in California

Sarah E. Baker, George Peridas, Joshuah K. Stolaroff, Hannah M. Goldstein, Simon H. Pang, 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

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