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Getting to ZERO—and Beyond

California's aspiration to become the first carbon-negative state appears to be achievable and affordable.

In response to mounting concerns about the consequences of unabated climate change, California established in 2018 an aspirational goal of achieving a completely carbon-neutral economy by 2045, and becoming carbon negative after that. The state has long championed climate-friendly policies such as using energy more efficiently, generating power from renewable sources, and putting cleaner cars on the road, among other emissions-reduction strategies. Unfortunately, California's own evaluations indicate that even when these are successful—after intensive electrification of the economy and a drastic shift away from fossil fuels—there will remain substantial greenhouse gas emissions. The residuals come from widespread small sources that are hard to control, and from larger sources that cannot be controlled in time.

California's case reflects the new climate math. Achieving carbon neutrality will mean adding negative terms to the equation—in other words, removing from the atmosphere amounts of carbon equal to the residual emissions. Scientists call these removals *negative emissions.* They include anything that permanently reduces the carbon dioxide concentration in the air, but do not include conventional reductions in emissions such as switching electricity generation to renewable sources.

No one has attempted to examine in any jurisdiction, including a state, exactly what the options are for achieving carbon neutrality with the help of negative emissions. Is it feasible? How much might negative emissions cost? What might the impacts be on other key issues, such as land use and jobs? Are there many technologies to do the job of removing carbon dioxide from the air, or just a few? Are there beneficial synergies? At Lawrence Livermore National Laboratory, we recently set out to address these questions by studying in depth all of California's real options for negative emissions.

The concept of negative emissions gained widespread attention in 2018 after the United Nations Intergovernmental Panel on Climate Change released its *Global Warming of 1.5°C* report. Our laboratory decided to take a detailed look at just what technologies to remove carbon dioxide from the air would really look like. Two of these have gotten a lot of attention recently in the popular press: reforestation and direct air capture. But there are several others, including increasing uptake and storage of carbon in soil; converting carbon dioxide into long-lived products such as carpet or building materials; and speeding up natural processes in the earth that absorb carbon dioxide (such as mineralization). An additional approach, and one that could prove to be critical, is to convert waste biomass, which would otherwise re-emit its carbon, into fuels using highly efficient processes that capture all the carbon dioxide produced during the fuel synthesis. By storing the captured carbon dioxide permanently underground in deep geologic formations, this approach would create carbon-negative fuels—that is to say, fuels whose production and use result in a net decrease of carbon dioxide in the air.

California's choices

California is perfectly positioned to take on carbon neutrality through negative emissions. Its proactive climate policies already call for reducing greenhouse gas emissions to 40% below 1990 levels by 2030, reducing them by 80% by 2050, and achieving zero-carbon emissions from retail electricity sales by 2045. These goals require average annual decreases of about 12 million tons for the next 30 years. To achieve this, the state has not shied away from adopting potent climate policies, and progress so far has already driven emissions below 1990 levels, despite huge increases in both economic activity and population since then.

But achieving these goals will not deal with the approximately 20% of residual emissions that are expected to still be around by mid-century, including emissions of nitrous oxide from numerous small sources such as fertilizer, emissions of methane from ruminants, and emissions of carbon dioxide from remaining fossil fuel uses such as home heating, jet fuel, cement, steel, and non-electrified road transport, among others—what was termed, in an article in the Fall 2019 *Issues*, "the hard stuff."

No one can predict the exact level of negative emissions that California will need to meet its carbon neutrality goal. However, the difference between the existing long-term goal of reducing emissions to 80% below 1990 levels by 2050 and the new carbon neutrality goal for 2045 amounts to just over 100 million tons of carbon dioxide per year. Thus, our group at Lawrence Livermore set out to determine whether the state could be removing 125 million tons of carbon dioxide from the air per year through negative emissions by 2045. This number represents a prudent risk mitigation level that would be supplemental to all the state's other mitigation efforts. We also evaluated whether larger amounts were possible, if desired.

With funding from the ClimateWorks Foundation and the Livermore Lab Foundation, we released a report in January 2020 in which we analyzed all the technology pathways for which there was enough data to reasonably estimate cost and capacity numbers. We examined the limits to each approach, in terms of land, energy, and time. We drew up a series of scenarios that used all the available technologies. We subjected the report to strenuous outside review. And as a bottom line, we discovered that not only is there a host of ways through which California could meet its 2045 carbon neutrality goal, but that it would be a lot less costly than previously imagined. Maybe the hard stuff won't be so hard after all.

Our analysis envisions a three-pronged strategy. We would aggressively deploy natural solutions (storing carbon in living systems through management and restoration of natural and working lands), use all the state's waste biomass, and then cross the finish line of 125 million tons per year by using as much direct air capture as needed. We found that the state could make this emissions math work for a total of less than $10 billion per year, or an average of about $60 per ton of carbon dioxide. This result relies only on technologies that are available and ready to be scaled up today, and comes with numerous benefits including clean water from proper ecosystem management, clean air from reducing burning of biomass and vehicle fossil fuel use, and the opportunity to evolve a host of new jobs in the state's Central Valley and rural counties.

Our analysis focused on *costs* and *deployment limits*. For costs, we used a full-system approach, including all processing, transportation, and storage costs. For limits, we focused on the necessary enablers for each class of negative emissions technology:

- *Natural solutions.* These are limited by acreage of natural and working lands that are included in management or restoration efforts, and rate of carbon uptake in those ecosystems.
- *Waste biomass fuel plus carbon dioxide storage solutions*. These are limited by the available amount of waste biomass that can be responsibly and realistically sourced without violating ecological, environmental, logistical, and economic constraints (for example, we did not consider any increase in the logging of mature trees, any bioenergy crops specifically for negative emissions, or transportation of waste forest biomass from steep or remote places).
- *Direct air capture solutions*. These are limited by the amount of carbon-free energy that can be produced without a major land-use footprint.

These limitations were intended to reflect quality-of-life values widely shared by California's citizens, and to ensure that our estimates were realistic and robust. Land use change is a major concern to Californians, so committing acreage to any of the three classes of technologies has to be done in ways that minimize those impacts. We also limited ourselves to solutions that could be accomplished within the state's own borders.

Natural solutions

When we evaluated natural solutions, such as reforestation and ecosystem restoration, we found that an optimistic and aggressive solution set would account for about 25 million tons per year of carbon dioxide reduction. The state's existing plan would yield a reduction of only about 3 million tons per year, but that is based solely on limited existing jurisdictions and programs; the actual potential is much higher. The largest of these solutions are inexpensive at less than $1 per ton of carbon removed, and the whole portfolio averages about $11 per ton removed. Considering all the other benefits that natural solutions will provide, maximizing implementation of solutions in this category is clearly desirable. However, natural systems are prone to environmental stress and disasters (such as fire), and the permanence of a portion of the stored carbon may be uncertain.

Waste biomass fuel plus carbon dioxide storage

To better understand the economic activities that would result in removing carbon dioxide from the air, climate modelers created a catch-all category of technologies called bioenergy with carbon capture and storage (BECCS), which they can include in computer models. Because BECCS does not exist in the real world beyond pilot and demonstration activities, we like to call this the first energy technology ever invented by a computer. The questions we asked about this nearly imaginary technology are: what are the practical ways biomass can be used to remove carbon dioxide from the atmosphere without creating environmental problems, and which of them can be implemented in real life?

Our study indicates that there are several useful—and profitable—biomass-based approaches that produce a fuel and permanently store about half the carbon dioxide that is normally released during biofuel production. The intense wildfires in California over the past few years have added another variable to the equation: if the state follows its plan to clear flammable brush and undergrowth from 1 million acres of at-risk forests, woodland, and shrubland every year, what will happen to the approximately 15 million tons of biomass that will be generated annually? Its current fate is to be burned during low-risk fire season, or to be piled up to decay in place. We determined that it could be used to both create biofuel and carbon dioxide, and that storing the carbon dioxide would remove between 15 million and 25 million tons of carbon dioxide from the air per year. This was an eye-opening conclusion and led to a series of discussions in California about the value of incorporating waste forest biomass into a negative emissions strategy for the state.

Not only is there a host of ways through which California could meet its 2045 carbon neutrality goal, but it would be a lot less costly than previously imagined.

In total, we estimate that California disposes of a stunning 56 million tons of biomass waste (half the weight of which is carbon) each year, in such diverse forms as trash, sewage, farm waste (such as almond shells), and left-behind materials from commercial logging and thinning conducted as part of the state's efforts to reduce fire risk. Avoiding the decay or combustion of this biomass not only offers a significant opportunity for a carbon benefit but would also reduce air pollution.

We evaluated more than 50 pathways to turn waste biomass into fuel, and found that turning it into hydrogen through a process called gasification is the most promising. Gasification separates all the carbon as carbon dioxide, leaving the hydrogen (the other main component of most forms of biomass), which can then be used as a clean-burning fuel. Hydrogen is also a valuable chemical feedstock. Gasification to produce hydrogen from coal is a commonly used process today, such as in Sasol's synthetic fuels plants in South Africa and in chemical production plants in China, so the technological foundations are already developed.

In current applications of gasification, the carbon dioxide is separated as a waste and released into the air. For negative emissions applications, the carbon dioxide would instead be captured, compressed, and stored deep underground in California's abundant sedimentary rocks. Gasification could produce 4 million tons of hydrogen per year, which we assumed would be sold at the current wholesale price of $2 per kilogram. This revenue would offset about two-thirds of the costs of disposing of the carbon dioxide generated. This results in a cradle-to-grave carbon dioxide cost of about $60 per ton, with a statewide capacity to remove more than 80 million tons per year from the atmosphere. The gasification plants would also result in a dramatic improvement over the air pollution impacts of current biomass burning for electric power or disposal.

Other options for biomass use, such as making liquid fuels or even electricity, both with carbon dioxide capture and storage, are not far behind in terms of cost. Biomass provides a robust and fungible source of carbon from the atmosphere. Previous analysis of biomass as an energy source suggested that the logistics and economics of transporting it may be a prohibitive factor. Contrary to that, we found that because of the high carbon density in all biomass forms, it is quite economical to transport it to processing sites when considering costs in terms of carbon dioxide. Biomass may be a poor energy source, but it is a great carbon source. This is an encouraging finding.

Direct air capture

The final piece of the California carbon neutrality puzzle is to build machines that directly remove carbon dioxide from the air. We found that, as with natural and biomass solutions, land use is a critical limit on direct air capture. For each million tons of carbon removed using direct air capture per year, at least 250 megawatts of power is needed to run the equipment. If only solar power is used, that would require covering an area roughly 20 square kilometers in size with solar panels; this is in addition to the land required for the direct air capture equipment itself. This large land requirement for renewable power led us instead to consider powering direct air capture systems only with more concentrated and local energy sources. We evaluated the power available in the Salton Sea area from geothermal energy (providing another limit of 11 million tons per year from that source) plus locally derived natural gas (with full capture and storage of the carbon dioxide it would emit). These direct air capture approaches require footprints that are about 90% smaller than a solar-powered approach.

Today, direct air capture is expected to start at a cost of more than $250 per ton of carbon reductions for the first few plants in 2025. With natural solutions at $11 per ton and biomass solutions at $60 per ton, we expect that the state will use as much of those cheaper options as possible before relying on direct air capture. However, we could account for only about 109 million tons of carbon reductions per year from the natural and waste biomass solutions, and that assumes that all the state's capacity is used and that hydrogen is the only fuel created—which is unlikely. This keeps the door open for direct air capture at modest amounts from 16 million to 50 million tons per year, depending on the amount of biomass utilization, to reach our 125 million ton target.

However, we did not consider it appropriate to simply use current numbers for air capture costs, because there will be reductions through learning in building out even this modest capacity. Accordingly, we built a model for the cost reductions through learning, based on the expansion in number of units. We used an average learning rate of about a 12% price decrease for each doubling of air capture technology production, which is typical of modern technology learning.

But the actual amount of learning will depend greatly on the total number of units built, and this caused the biggest discussion among our reviewers. We adopted assumptions of earlier analyses and started out suggesting that as much as 1 billion tons of direct air capture capacity could be in place worldwide in 2045, resulting in learning that cut the costs to as low as $100 per ton. But our reviewers criticized this as being far too optimistic, and also out of California's control. We ultimately chose to analyze a much more moderate number of about 50 million tons of worldwide capacity in 2045, about half of which would be in California. This resulted in post-learning costs of about $150 to $190 per ton including transportation and geologic storage (about $10 to $20 per ton).

Some observers might suggest that nuclear power would be an excellent means to run direct air capture facilities. We did not consider this option, partly because many Californians oppose nukes, but mostly because of costs. Geothermal- and natural gas-powered options are considerably cheaper than a new nuclear plant, and easier to license and site. Although using one of the existing nuclear reactors might in principle sound attractive, it is heat, not electricity, that is primarily needed for direct air capture. Using waste heat from the San Onofre reactor could lead to the capture of 9 million tons of carbon dioxide per year, but direct use of steam would also require more than 20 square kilometers of collectors adjacent to the plant, which we considered impractical.

Where will the carbon dioxide go?

The biomass and direct air capture portions of our portfolio would remove 100 million tons of carbon dioxide from the air per year. What could be done to permanently keep it out? The only answer available to California at that scale is geologic storage: sending the carbon back where it came from. This places carbon dioxide deep underground, in sandstones more than 3,000 feet below the surface that are capped by impermeable shales. There the carbon dioxide would be in a liquid form very similar to oil and can be expected to stay underground with about the same assuredness as oil at that depth. It would be extremely unlikely to come out on its own over millions of years, but not impossible if a very poor site is chosen, though that is something that recent, stringent state and federal regulations would not allow.

California is blessed with ample safe storage capacity. We identified 17 billion tons of storage capacity in and around the main oil- and gas-producing regions of Kern county and the Sacramento-San Joaquin Delta region alone. This amounts to 170 years of capacity at our projected need—and that is a minimum estimate, as there are more areas to be assessed. We have so far evaluated only sites with readily available data from oil and gas exploration.

This form of storage also has a clear accounting advantage, in that the pipe carrying the carbon dioxide into the ground has a flow meter on it, making it very easy to establish how much was placed there. With adequate monitoring, confirmation of storage is straightforward. Best practices for that monitoring of injected carbon dioxide are now well established through numerous research and deployment programs in many countries. In the United States, 14 million tons of carbon dioxide has been placed underground by the Department of Energy in experimental programs designed to evaluate monitoring and safety. No leaks or hazards have been detected. Safety has also been demonstrated in the commercial sector, where close to 100 million tons of captured carbon dioxide per year is carried by more than 4,500 miles of dedicated pipelines and injected into geologic formations as part of oilfield operations.

What will it all cost?

Overall, our best estimate is that it will cost about $8 billion per year, including capital and operating costs, to achieve our goal of 125 million tons of negative emissions per year. This is about one-third of one percent of California's current gross domestic product (the total value of all goods and services produced in the state each year), although it comes on top of whatever costs are required to achieve the 80% reductions already mandated by the state.

To test our results, we compared various technological mixes to see where the main uncertainties lay. These sensitivity scenarios painted a similarly affordable picture. All the alternative mixes varied the cost between $6 billion and $15 billion, mainly depending on the amount of biomass available and therefore the amount of expensive direct air capture used. Changing biomass availability by 20% in either direction changes the total by $2 billion per year. Interestingly, so does changing the value of the fuels produced. More valuable fuels make the carbon cost drop because the same facility produces more valuable products, and has to assign less cost to the carbon dioxide.

Who else can do this?

We believe that with varying mixes of technologies, this California-specific analysis would likely yield similar results for other jurisdictions, including Texas, Wyoming, and the entire Gulf Coast. Gulf Coast states could capture their industrial carbon emissions and store them in the region's vast geologic reservoirs, while Wyoming has almost unlimited space for direct air capture systems. The Midwest has significant biomass resources, but may have to transport carbon dioxide longer distances to good storage sites. Pipelines are an obvious answer, although they can provoke local opposition. Another alternative is transporting the carbon dioxide on tanker ships on the Mississippi River and its tributaries. Europe is currently designing a test project called Northern Lights to ship carbon dioxide by sea from industrial sites to permanent storage under the North Sea. The United States could to the same, shipping carbon dioxide to the Gulf Coast.

The populated Northeast is likely to use its biogenic trash feedstocks to achieve negative emissions, with direct air capture occupying the same cleanup spot as in California. Eastern states in general have much larger capacity for natural solutions, which is going on today as marginal farmland is allowed to return to forest. This reduces the need for pipelines and nearby geologic storage.

Clearly the rate at which the nation deploys direct air capture technology will be an incredibly important factor in how much it will cost to move to carbon neutrality. Direct air capture will always be the swing technology—expensive, at least early on, but with relatively few limits on capacity. Particularly in the United States where natural gas is abundant, regions with relatively little waste biomass or ecosystems to be restored can rely on air capture to meet their aspirations. Ensuring early deployments will be critical, but so will large-scale use of the technology. The mechanisms to pay for those deployments in early days while air capture is still expensive are not yet fully identified. And the technology remains controversial, as indicated by disagreement among presidential candidates over whether it should be part of a national strategy.

An important aspect of the overall monetary picture of negative emissions is whether the geographic region being analyzed has common economic interests and can bring to bear a sufficient diversity of negative emission resources. The amount of money being transferred is a crucial issue for the policy goals of the region. In California, almost all the money would stay in the state. It would constitute a major transfer of funds from coastal regions, where the majority of the population is, to rural regions, where the waste biomass and geologic storage are. This would provide the state and local governments a new tool to achieve their goals in employment, ecosystem restoration, and local economic development or revitalization in communities that are currently struggling to make ends meet. Other jurisdictions will have to consider the same political math. We believe this will encourage multistate compacts. Although the costs for these methods of carbon dioxide removal are small compared with the damage expected with climate change, it is likely that the expenditures will be more acceptable if they stay inside a somewhat politically cohesive group boundary.

Who will pay?

In the end, this is the most important question that technologists, advocates, and policy-makers alike must address. It is one thing to imagine implementing state or local levies to pay for carbon dioxide removal in the same way that they are used to pay for trash removal, as some researchers have suggested. But no such system exists today, so how do we get started? What can we do today, not in 2045?

Fortunately, California has a long and successful track record in designing policies to spur deployment of climate mitigation technologies and practices. The most relevant of those to negative emissions at the moment is the Low Carbon Fuel Standard (LCFS). Its goal is to progressively reduce the full life-cycle carbon intensity of the state's transportation fuels. This value in 2011 was about 12,000 grams, or 26 pounds, of carbon dioxide per gallon of gasoline. The target for 2020 is 7.5% below that baseline, and that level is set to decrease by 1.25% per year until the current goal of 20% reduction is reached in 2030.

Fuel refiners, importers, and wholesalers in California must meet this standard either by reducing the carbon intensity of their fuel (such as mixing in biofuel or finding ways to emit less carbon during fuel production and processing) or by buying credits generated by someone else's actions. These credits are metered in terms of tons of carbon dioxide avoided, and are priced in terms of dollars per ton of carbon dioxide. Today those credits sell for a little over $200 per ton of carbon dioxide. The government does not participate in this market; it is handled between private parties but recorded by the state.

The price impact to the end consumer of the LCFS's 2030 target would amount to about $0.36 per gallon of gasoline at today's LCFS prices. This price could drop as more biofuel supplies, electrified transport, and other means of reducing carbon intensity come online. Another way to minimize costs for consumers would be to cap the price of credits that companies pay to offset their emissions. The California Air Resources Board recently proposed changes to the LCFS that would act as a price ceiling for credits near the $200 per ton level.

Our best estimate is that it will cost about $8 billion per year, including capital and operating costs, to achieve our goal of 125 million tons of negative emissions per year.

Despite active opposition and litigation in its early days, the LCFS program is now widely supported, and viewed as an instrumental driver for investment in pathways that lower the carbon intensity of transportation in California. It is widely expected to be extended beyond its current 2030 sunset date.

The state is about to test a new, and potentially large, source of LCFS credits. Geologic storage of carbon dioxide was added as a compliance option in January 2019—meaning carbon dioxide capture and storage can be used to reduce the carbon intensity of fuels. Many regulated parties and independent project developers are now considering capturing and storing carbon dioxide from existing transportation-fuel sources such as ethanol facilities and refineries. The LCFS geologic storage rules are the strictest in the world, meant to ensure safe storage, transparency, and accountability. Projects can be located anywhere in the world, as long as the affected fuel is ultimately sold in California. The storage rules also apply to direct air capture anywhere, without the requirement for any linkage to California, presumably because using this method to remove carbon dioxide from the atmosphere at any location would ultimately have a climate effect comparable to removing the same amount emitted by a California tailpipe.

Remaining challenges

The majority of the carbon dioxide removal systems we considered for California, including all the biomass-to-fuel with carbon-dioxide-storage systems and all the direct air capture systems, are eligible to apply for LCFS credits. With an estimated average cost of $60 per ton for carbon dioxide for converting waste biomass to carbon-negative fuels, economic viability seems likely if financing and licensing can be obtained. And businesses are responding, with a number of plans for biomass processing and geologic storage being considered. Owners of existing fossil facilities, such as hydrogen production from natural gas, are also considering capturing some of their emissions and reducing their carbon intensity by this means. These new projects will address California's only growing segment of greenhouse gas emissions: transportation.

Is the LCFS a ticket to negative emissions growth in California? Can biomass processing to fuel quickly grow to the levels we imagine? The LCFS program does indeed appear to be the right framework and provide current price levels consistent with the technology needs, although some refinement of the program may be necessary to make negative emission technologies financeable. In addition, having a reliable supply of waste biomass is key to the financing of conversion facilities. Because economic biomass plants rely on a sizeable and steady feedstock, providing long-term contracts for biomass supply is an important enabler. This may require some form of public-private partnership that would undertake or facilitate the aggregation of feedstock from many disparate sources and its steady distribution to the conversion plants.

Finally, although regulatory authorities for permitting such plants appear to be in place, they are scattered among various local, state, and federal agencies. Navigating this regulatory maze within a timeline that allows for project development and financing will initially be both novel and daunting. We perceive a high degree of regulatory risk and the potential for projects to suffer death by a thousand cuts—factors that we cannot easily accommodate in our cost estimates. But Californians have shown themselves willing to do what is necessary to make progress on addressing climate change, and so we expect that none of the likely hurdles is insurmountable, though all are important to resolve and clarify.

Negative emissions technologies are just in their infancy, rather like the early days of renewables. But their promise is bright. California and the nation still have to stop emitting greenhouse gases from most major sources, and will have to build a sizeable new negative-emissions industry, but this is achievable and well within the bounds of what we have done in the past. We believe that negative emissions can provide the world a much-needed fighting chance to avoid changes in climate that threaten everyone's well-being. California—the fifth largest economy in the world—has the opportunity to show how it can be done.

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Recommended reading

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