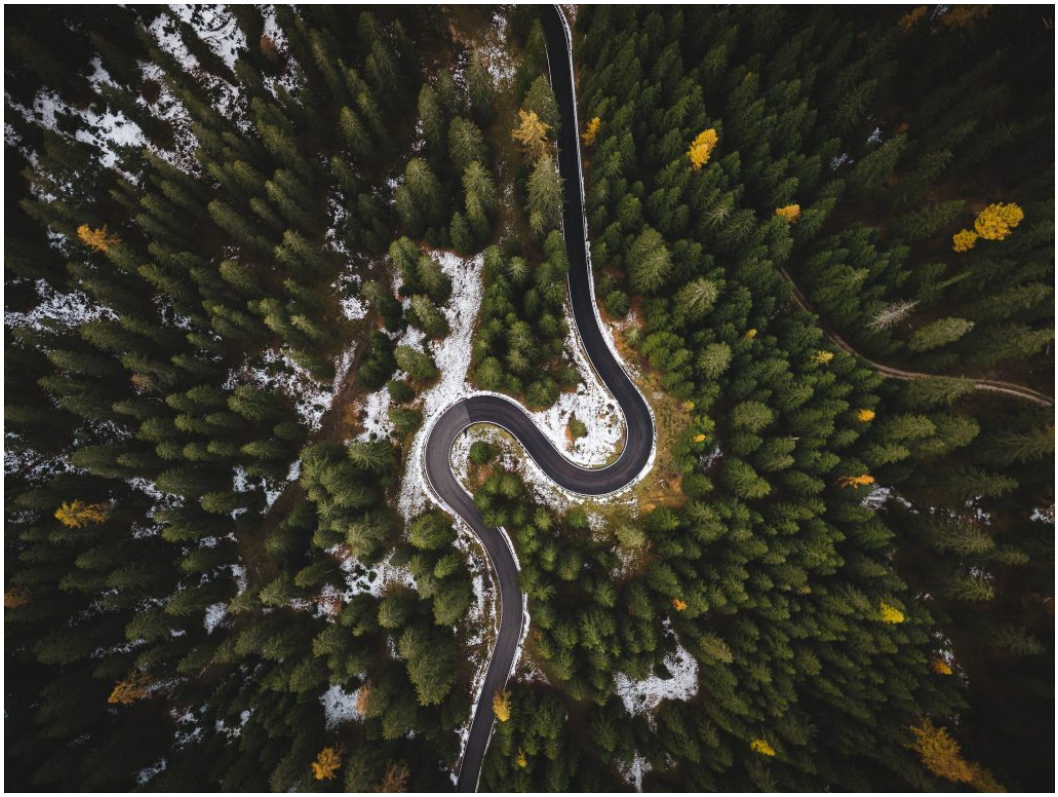

Photo credit: Joshua Welch

Last week saw two exciting reports released which examine how to remove carbon at scale.

*Getting to Neutral: Options for Negative Carbon Emissions in California* was led by a team from Lawrence Livermore National Labs (LNLL), and assesses pathways for California to remove 125 million tons of CO2 /year from the air by 2045, in order for California to meet its carbon neutrality goal.

*CarbonShot: Federal Policy Options for Carbon Removal in the United States* comes out of the World Resources Institute (WRI), and identifies federal policy options for investing in carbon removal over the next decade to enable at 2 gigatons (Gt)/year removal benchmark by 2050.

Yet while these reports offer advice on what technologies and practices can be used to reach these benchmarks, the "how to get there" roadmap in terms of policies, institutions, and cultural change still needs to be filled in — and it's a space that needs more creative ideas.

Here are a couple of takeaways from reading the reports together.

## *Waste biomass with carbon capture: key pillar, or speculative and supplemental?*

First, while they both encourage a "portfolio approach," utilizing multiple approaches and technologies, the portfolios these reports identify are actually strikingly different. The conclusions around what needs to happen next are fairly complimentary, but it's interesting that some of the most brilliant carbon removal analysts would diverge in their analysis of the roads to take there.

WRI's US report actually looks at four different scenarios, labeled "Natural Capture Only" (only techniques like afforestation and soil carbon sequestration; no investment in technological pathways); "All in on Direct Air Capture" (only investment in direct air capture); a "Technology Only" scenario that doesn't utilize natural capture; and an "All of the Above" scenario. Not surprisingly, it finds that the natural-capture-only scenario doesn't meet the 2GtCO2/year target, and the all-of-the-above portfolio is the most robust.

LLNL's California report rests its carbon removals on three pillars: 25 million tons (Mt) /year removals from natural and working lands, 16Mton/yr from direct air capture, and 84 Mton/yr from converting waste biomass to fuels and storing CO2. So while there is a modest contribution from direct air capture and natural solutions, the bulk of the work here is in transforming California's waste system — municipal, forestry, and agricultural waste — into fuel for bioenergy with carbon capture and storage.

That's interesting, because the WRI US report almost dismisses BECCS. Its "staple pathways" are afforestation and direct air capture, with direct air capture potentially doing most of the heavy lift; soil carbon strategies are labeled a "no regrets" measure, and carbon mineralization and accelerated development of enhanced root crops are also categorized as "speculative bets" worthy of funding. The report categorizes BECCS, wood waste preservation, and extended timber rotations as "supplemental pathways" that are not prioritized for funding, and may deliver a negligible amount of carbon removals, or "are unlikely to be the difference makers on their own." Yet these are the techniques that LLNL's California analysis hinges upon.

## *Why do the reports have such a different take on bioenergy and biomass waste?*

Perhaps it's as simple as the different scale of analysis — California is a place which is abundant in biomass waste, and which already has put waste streams on the agenda, with legislation like SB 1383, which aims to reduce 75% of organic waste deposited in landfills by 2025. Perhaps a systematic transformation of the waste sector looks more politically and technically possible from Sacramento than from Washington. The WRI report notes that BECCS is likely to be constrained by available waste and by-product feedstocks, as well as competing uses for them; it also does not consider municipal solid waste, which includes food waste that would ideally be avoided, and paper that could be recycled.

Or perhaps the methodology of the California report ruled out other options. It limits the scope to removals to those that could take place inside of California, and features detailed calculations of the energy needed to run direct air capture, as well as spatially explicit analysis — most of the direct air capture capacity is from geothermal energy around the Salton Sea, and then that CO2 needs to be transported to the Central Valley for storage. Doable, but probably not easy given the challenges building new infrastructure and competition for other uses of energy. Once direct air capture gets mapped down to the ground level, constraints may appear, and hence the limited amount of direct air capture in the LLNL report strikes me as realistic for California.

The WRI report, being at the US scale, needs to appeal to a different set of bipartisan actors, including legislators representing districts with a heavy fossil fuel presence. The WRI report sensibly features a strong storyline about innovation in creating a direct air capture industry, which should be more of a bipartisan sell. The high scenario (for 1.4 Gt CO2/year removals via direct air capture) would be a $1.3 trillion capital investment, using 2,825 terawatt-hours each year, or about 76% of 2018 electricity generation. A "$1.2 trillion public works-style investment" between 2040 and 2050 is alluded to but not developed — is that the Green New Deal? (And is that more or less realistic than transforming the waste system to fully utilize all biomass waste?)

## *What would an actual roadmap for gigaton-scale removals look like?*

Which brings me to the second key takeaway — both of these reports are more a collection of milestones than a true roadmap for getting to scale.

LLNL's California report explicitly doesn't address policy, while the WRI report focuses upon the steps that need to be taken in the next ten years: it is a roadmap for "kickstarting" carbon removal, not seeing it all the way to scale. This puts it in the company of two other road-map style reports from 2019, *Capturing Leadership: Policies for the US to Advance Direct Air Capture Technology* by the Rhodium Group, and *Clearing the Air: A Federal RD&D Initiative and Management Plan for Carbon Dioxide Removal Technologies* from the Energy Futures Initiative. Both reports focused on the role of federal policy in near-term innovation over the next decade (not to mention the 2018 National Academies research agenda report on carbon dioxide removal and reliable sequestration, which made detailed recommendations for federal research priorities).

This focus on how to invest in the next decade is understandable: it makes sense to focus on actionable, near-term items.

Yet all of these reports leave us with something of a foggy gap: how to move from these demonstration projects and "learning by doing" private sector incentives, funded in the next decade, to this 100-millon-ton or gigaton scale?

Generally, the instrument of the carbon price, whether through a tax or market mechanism, is imagined to be the magic wand that once waved will create that road.

But it still feels a bit too politically and socially vague. How does the private sector decide to develop an industry based around waste removal? Notably, many waste treatment processes are in the public sector (like wastewater), or they don't actually achieve their sustainability goals (like recycling).

It's politically expedient to rely on a carbon price manifesting an enormous private industry for capturing gaseous waste— a gaseous waste removal sector with infrastructure that may be on the scale of the existing fossil fuel industry. But it can also read as a bit obfuscatory, or even delusional, to expect this to be a private industry with tremendous market opportunities absent signals that policy will actually move in that direction. Analysts often

make analogies to the rapid scale-up of new energy technologies like solar PV or wind, yet energy technologies deliver a usable commodity — energy — while direct air capture simply removes a public hazard from the commons.

Perhaps we are going about the roadmapping in the wrong manner. There have been a host of reports that assess negative emissions technologies, and try to add up their potentials into a portfolio, reminiscent of both the wedges for climate stabilization as well as language from investment and risk management. These reports bring up the question if the selection of technologies / portfolio composition question is really the right starting point. The California report foregrounds waste management — perhaps that is the right starting frame. One could imagine land management or energy systems as other relevant entrance points. It would be fruitful for the next generation of carbon removal roadmaps to experiment with systemic views.

A final optimistic takeaway: the authors estimate the system cost for removing California's residual emissions of 125 million tons to be between $8.1 and $13.9 billion dollars a year, depending on the scenario, with the lower one just about 6% of CA government spending. This seems like a tremendous bargain!