Evaluating Strategies and Scenarios for Carbon Neutrality for the City of Palo Alto

Prepared for the City of Palo Alto
Christine Luong, Sustainability Manager

Stanford University
Public Policy Practicum - Winter 2022

Leila Doty, Matt Jacquez, Nidhi Mahale, Theresa Nelson, Taiwo Odunowo, Ben Paladino

Advisors: Dan Rich and Manami Suenaga

PUBLIC POLICY PROGRAM

TABLE OF CONTENTS

The City of Palo Alto has detailed in its Sustainability and Climate Action Plan (S/CAP) its strategy to reach an 80% reduction of greenhouse gas emissions by 2030, relative to 1990 levels. This comprehensive work is emblematic of the pioneering work that the City of Palo Alto is doing to be a leader in progress towards a carbon neutral future. In 2018, California Governor Jerry Brown signed Executive Order B-55-18 that sets a statewide target of reaching carbon neutrality by 2045. For the Winter Quarter Public Policy Practicum Project, the City has asked our team to evaluate the potential of Negative Emissions Technologies (NETs) and Palo Alto's Urban Forest as strategies to capture the remaining 20% of emissions, or 156,024 metric tons of CO2 post 80x30, needed to reach carbon neutrality by the state's target. Through the course of our research, we identified best practices in other governments, conducted stakeholder interviews, evaluated the state of the NET industry, and estimated the sequestration potential of improvements made to the Urban Forest and other natural sequestration opportunities.

In our analysis of Negative Emissions Technologies, we identified a number of companies developing Direct Air Capture technologies that could reduce net emissions by directly removing carbon from the atmosphere. We consulted with industry experts at Stanford University and many companies themselves. Ultimately, while these technologies promise a lot, we found none that are ready for commercialization within the City of Palo Alto at this time. Many of these technologies are still in the demonstration phase and could become scalable within the next decade. We suggest that the City lobby for more state and federal funding and tax incentives and develop a regional collaboration in this area to entice pilot projects to locate nearby.

In our evaluation of Palo Alto's urban canopy, we found that trees within City limits currently sequester approximately 18.5% of the City's remaining emissions after reaching the 80x30 target. However, space for increases in tree plantings within City jurisdiction is limited. We recommend the City emulate Seattle's Trees for Neighborhoods program and host a yearly tree-giveaway that would promote tree plantings on private property and increase plantings in other areas of the city, like the preserves and golf course. Right now, the protocols and methodology for including the current sequestration from the City's trees in the City's emissions inventories do not exist. We suggest the City lobby CARB to update its urban forestry project protocols for inclusion in offsets protocols.

This report provides significant information, resources for further research, and recommendations to sequester carbon both within and outside of the City of Palo Alto. However, right now, the City cannot rely on sequestration alone to reach carbon neutrality by 2045. We split our recommendations into two groups: what the City can do inside its boundaries and outside. Within the next decade, we recommend the City focus on improvements to the urban forest, invest in a biochar project and small algae farm within its boundaries. Regionally, the City should work to build a larger algae farm, retrofit emission sources with carbon capture technology, and build a direct air capture pilot project. We estimate that all of these steps together could help the City sequester up to 42% of the remaining emissions past the S/CAP.

While our analysis of the current state of sequestration options cannot reach full carbon neutrality for Palo Alto, each step towards this goal the City takes will be vitally important and enhances its leadership role in this area. Direct Air Capture and other NETs are likely to become more commercially viable over the next two decades, and in the meantime, Palo Alto can continue to set the example for municipalities around the world by taking steps to reduce their emissions further and moving forward with innovative ways to sequester carbon.

METHODOLOGY

To investigate the best carbon neutrality practices by public agencies and develop a recommendation for Palo Alto's own path towards carbon neutrality focused on the urban forest and carbon removal technologies, we adhered to the following approach:

1. Conduct basic background research. To understand Palo Alto's current climate strategy, we studied key documents including Palo Alto's Sustainability and Climate Action Plan (S/CAP), the AECOM Impact Analysis Memo, and the Achieving California Carbon Neutrality Report.

2. Research public agencies who are leading in carbon neutrality efforts. From an initial list of 12 governments taking aggressive actions to reduce carbon emissions, we conducted thorough case studies on six governments whose practices were particularly relevant to carbon sequestration and NETs. We then further narrowed promising case studies to the four governments engaging in the most relevant practices: Iceland; Boulder, CO; Seattle, WA; Copenhagen, Denmark.

3. Investigate the current state of carbon sequestration practices and Negative Emissions Technologies (NETs). We conducted online research on a wide range of natural carbon sequestration practices and carbon capture and storage technologies.

4. Identify and interview relevant stakeholders. To supplement the information we learned from our research, we conducted interviews with 6 members of local governments, 6 experts in academia, and 2 practitioners in industry.

5. Analyze findings and develop policy options for Palo Alto. We constructed two subjective linear models (SLMs) that compared nature-based and technology-based interventions on the basis of key criteria (amount of carbon sequestered, commercialization, land use, public health, resource conservation, lifecycle emissions, and equity). One model compares policy options within Palo Alto, and the second compares options outside of Palo Alto's city limits.

6. Present policy recommendation for Palo Alto. After analyzing the available policy options via the SLMs, we present a series of policy recommendations for Palo Alto to progress towards carbon neutrality.

ANALYSIS: CASE STUDIES

From an initial list of 12 promising governments identified by stakeholders and from the C40, Global Covenant of Mayors, and Carbon Neutral Cities Alliance partnerships, we conducted thorough case studies on six governments whose practices were particularly relevant to carbon sequestration and NETs. While these cities have aggressive goals, few, if any, have detailed measurable plans to get to 100% carbon neutrality. While no case study is a perfect model, we narrowed our focus to four governments engaging in the most relevant practices: Iceland; Boulder, Colorado; Seattle, Washington; Copenhagen, Denmark. We considered places that offered both best practices and relevance to Palo Alto's context, which is why there is a combination of national and international case studies. Below is a summary of our findings. For more information on the case studies, see Appendix A.

ICELAND

Iceland offers best practices in both forestry and NETs through their direct air capture[1] (DAC) plant. Iceland implemented a rigorous National Forestry Accounting Plan[2], where they calculated all of the trees currently on their land and those that they plan to plant in their territory over the next century including an aggressive afforestation goal: to plant 12.4 million seedlings per year for the next 100 years. Based on this forest reference level, they calculated that all of Iceland's trees will sequester at the forests' maximum capacity approximately 1,400,000 metric tons of carbon per year starting around 2085.

In the technology sector, Iceland became home to the world's largest direct air capture sequestration plant in 2021. The company Climeworks[3] operates this facility (See Appendix B for more information on Climeworks and their partner CarbFix[4]). This plant, called Orca[5], costs between $10 and $15 million in capital investments, is the size of two shipping containers[6], and will sequester 4,000 metric tons (or 2.6% of the CO2e reductions Palo Alto needs to achieve carbon neutrality) of carbon dioxide per year.

The extent to which Palo Alto can follow Iceland's best practices is limited given the much larger and unpopulated territory that Iceland has compared to the City, though Palo Alto could model the aggressive tactics and methodology that Iceland is employing to document, regulate, and augment their urban forest on a smaller scale. Additionally, Palo Alto can consider a partnership with Climeworks to enhance investments in cutting-edge direct air capture.

BOULDER, COLORADO

Boulder is a strong example of how a city can incorporate carbon sequestration into their climate action plan[7] and assess emerging technologies. In 2017, the city launched soil carbon sequestration pilot projects[8] on 20,000 acres of previously purchased agricultural lands outside the boundaries of the city. Later in 2019, they founded Nature-Based Climate Initiatives (NCI)[9] and have produced an evolving framework and action pathways for city-based carbon drawdown opportunities, as well as a growing resource database. In that same year, Boulder worked with Stockholm, Helsinki and Minneapolis[10] to research biochar, which they found to be a cost effective, low risk sequestration option (explained in detail below in Biochar).

Palo Alto could consider working with NCI and attend its monthly working group sessions to incorporate the carbon management tool for urban lands[11] into the City's approach towards nature-based carbon sequestration. Since Boulder's soil carbon sequestration pilot project is still under way, the status of the project should be reviewed in a few years to assess the cost, feasibility, and effectiveness of a similar proposal for a potential nature based pilot project in Palo Alto. Lastly, Palo Alto should review Boulder's Cool Boulder Initiative when it is released in Spring 2022. Following these best practices, Palo Alto could consider shifting their focus towards heat management rather than carbon sequestration as a more effective means of reducing GHG emissions.

SEATTLE, WASHINGTON

Seattle is a climate-forward city that offers best practices in expanding a city's urban forest. To achieve the goals outlined in their Urban Forestry Management Plan[12], Seattle instituted a number of programs to expand its urban forest, including a successful initiative called Trees for Neighborhoods. Seattle residents can voluntarily participate in the Trees for Neighborhoods[13] program by requesting up to four trees per year (with a lifetime household maximum of six trees) that the city will provide free of charge. The trees can be planted both on public property (i.e, city streets) and on residents' private property (i.e., backyards). In addition to supplying the trees themselves through this initiative, Seattle provides training on proper planting and care, offers assistance applying for street tree planting permits, helps with planting, and conducts street tree evaluations every couple of years free of charge. Since Trees for Neighborhoods was first introduced in 2009, the program has helped Seattle residents plant over 12,300 trees.

To expand their urban forest, Palo Alto could implement a program like Seattle's Trees for Neighborhoods initiative. Palo Alto's urban canopy cover is currently at 37%, which is notably higher than the case studies we have investigated, with almost all available street tree planting spaces already being occupied. To continue meaningfully expanding Palo Alto's urban forest, tree planting on private property and nature preserves within Palo Alto's city limits offer the most promising areas of opportunity. If the City wishes to seriously pursue leveraging private property to expand the urban forest, a Trees for Neighborhoods type of program may be a successful approach.

COPENHAGEN, DENMARK

Copenhagen aims to be the first carbon neutral capital by 2025[14] (a 100% reduction in emissions using 2005 as the baseline year). One of their noteworthy efforts towards this goal is a plan to establish a carbon capture facility[15] by 2025 adjacent to the port of Copenhagen that will remove emissions from the Amager Resource Center (ARC). ARC processes the waste from the residents and businesses in the Copenhagen metro area, emitting 560,000 tons of CO2 annually. Designed by the Bjorke Ingels Group, the new carbon capture facility would capture 90% of ARC's annual CO2e emissions, or 500,000 tons per year (320% of the CO2e reductions Palo Alto needs to achieve carbon neutrality). The captured CO2 would be pumped aboard ships, sailed out to the North Sea, and stored in drained underground oil reservoirs. The cost to build and maintain the facility is high: Denmark is investing $2.4 million[16] into this project, and ARC and the Copenhagen Malmö Port are applying for $80 to $160 million in funding from the EU Innovation Fund, which would only finance up to 60% of the cost during the first ten years.

Copenhagen's efforts in carbon removal are at the cutting edge of public agencies taking action to mitigate climate change. However, establishing a carbon capture facility is likely not feasible in Palo Alto due to prohibitive costs and lack of available land.

ANALYSIS: NATURE-BASED SEQUESTRATION

Nature-based sequestration is a naturally-occurring process where natural elements remove carbon from the atmosphere, sometimes enhanced by technological capabilities. Some of the natural carbon sinks that exist are trees and other plants such as algae, soil, oceans, and wetlands. While nature-based solutions are a notable pillar[17] in achieving carbon neutrality, natural solutions alone are insufficient to reverse the emissions that are changing the climate. Below are findings from our nature-based carbon sequestration research. Each subsection showcases a variety of nature-based sequestration strategies, provides their cost estimates, assesses its feasibility to Palo Alto, and highlights key takeaways.

THE URBAN FOREST

Overview: Palo Alto is currently ahead of many cities in the care and scale of its urban forest. It has a comprehensive and accredited urban forestry department and boasts a city-wide 36.8% canopy cover with a 40% future goal, excluding nature preserves. Other cities that are working towards carbon neutrality only have targets to increase canopy cover to 20-30%. Municipal projects to invest in the urban forest include tree plantings and a comprehensive urban forest management strategy. Since the City of Palo Alto has already filled more than 90% of available street tree locations, their future investments in canopy cover will need to include plantings on private property, in parks, and/or in nature preserves.

We estimate that all the trees within Palo Alto – on the streets, in parks and preserves, and on private property – currently sequester approximately 28,875 metric tons of CO2 per year, or about 18.5% of the remaining CO2 reductions Palo Alto needs to achieve carbon neutrality past 80x30.
We identified two strategies to increase the canopy cover and the sequestration of the City's Urban Forest. Palo Alto should (1) prioritize planting trees on private land and (2) reforest the Preserves. Increasing trees on private property could take the form ofSeattle's Trees for Neighborhoods initiative (see Appendix D). Emulating this program to plant 1,000 new trees a year on private property would be enhanced by (1) purchasing and giving away trees with the greatest carbon sequestering potential, and (2) providing trees that are protected from removal, such as Coastal Live Oaks and Redwoods. Another option to expand the urban forest in Palo Alto is to reforest the Pearson-Arastradero Preserve and the Foothills Nature Preserve. These areas currently have lots of open grassland areas, but before logging and grazing by European settlers, they were conifer and oak forests. Reforesting these areas would not only increase sequestration but would be a highly visible endeavor to show the City's residents that the City is taking seriously the historical impacts we have had on the environment. (Details on these recommendations are in Appendix D)

Cost Estimates: We estimate that such a private tree giveaway program would cost the City around $250,000 a year to administer. Reforesting the grassy areas in the Preserves will cost the City upwards of $394,212. (see Appendix D)

Feasibility: Both initiatives are expensive, but actionable and highly visible to the community. They would each sequester only about 1% each of the remaining emissions past 80x30, but do not need to wait on technological improvements. However, a true accounting of carbon sequestered annually requires a detailed and up-to-date inventory of all the City's trees, which would likely be infeasible at this time. This is part of the reason that no urban canopy projects have counted towards emissions inventories in widely accepted protocols.

Key takeaways: If the City would like the trees they plant in giveaways and a Preserve reforestation initiative to sequester carbon at their full potential by their 2045 carbon neutrality goal, it is necessary to implement these programs quickly. Doing so would allow the trees the time to establish themselves and grow to full sequestering capacity. Much work and research is necessary to further refine the costs and benefits of these programs within Palo Alto. Currently, there is no widely accepted accounting protocol to include trees in carbon neutrality calculations, so the numbers we present are rough estimates. In the future, Palo Alto could lobby CARB for an update to its Urban Canopy Protocol that is more functional and accessible and provides a mechanism for accounting for natural canopy sequestration in emissions inventories.

BIOCHAR

Overview: Biochar, more commonly known as charcoal, is a carbon-rich solid[18] produced from biomass using a thermochemical conversion process known as pyrolysis. When added to soil, biochar works as a "stock" to sequester carbon for hundreds of years, can simulate or reduce the decomposition rate of the natural organic matter in the soil, and can increase plant productivity.

> **Cost Estimates:** The carbon sequestration potential and financial cost of using biochar at large scales for carbon offsets are not entirely clear yet due to the nascent stage of the industry. However, a recent expert assessment[19] estimates that biochar could sequester 0.5–2 billion metric tons per year by 2050 at a cost of $30–120 per ton of CO2.
>
> **Feasibility:** While the carbon captured via biochar may be released[20] if the soils are not properly maintained, biochar is a commercially viable approach to carbon sequestration. To implement a biochar plant, Palo Alto would need to utilize existing waste management facilities and processes to collect and transport biomass from public waste.

Key takeaways: Given the soil in Palo Alto is not distrubed, biochar shows promise of several environmental benefits and carbon sequestration potential. Palo Alto could consider launching a pilot project modeling a recent case study in Stockholm, Sweden explained in detail in Appendix B.

BLUE CARBON

Overview: Blue carbon[21] is the naturally-occuring carbon sink that exists in the soils of tidal marshes, coastal wetlands, and seagrasses. The Lawrence-Livermore National Laboratory[22] considers blue carbon to be a fundamental part in achieving carbon neutrality in California. However, so far there are no standard methodologies that exist for receiving credit for coastal wetlands' sequestration, and real-time carbon flux data as tides add and release carbon in the soil is expensive and difficult to collect.[23] Standardized estimates of credits that blue carbon can offer are 5-10 years away. Rough estimates[24] are that tidal wetlands can sequester about 1.5 metric ton of carbon per acre per year. Palo Alto currently has approximately 400 acres of tidally-influenced wetlands within their borders, sequestering an estimated 600 metric tons of carbon per year (or 0.4% of the reductions needed to reach carbon neutrality).

> **Cost Estimates:** Specific cost estimates for Palo Alto are not available, but we estimate that it costs $52,500 per acre[25] of restored wetland.
>
> **Feasibility:** In order for baylands to reach their full sequestration potential, they must be restored and conserved, which is a feasible policy intervention now. Other incentives for the maintenance of coastal wetlands areas include conservation and preservation of ecosystems and co-benefits ranging from habitats for various species, fishing, nurseries, flood protection[26], nutrient sequestration, a reduction in pollutants[27], and recreational benefits.

Key takeaways: Pilot projects into wetland sequestration in the Bay Area are ongoing, and Palo Alto could consider a partnership with researchers to better understand the sequestration potential of their baylands and to begin to count these credits towards their carbon neutrality goal before official guidance and methodology exists. Further recommendations for the baylands are laid out in Appendix D.

ALGAE-BASED CARBON SEQUESTRATION

Overview: Algae is a natural carbon sink that can be up to 400 times more efficient[28] than a tree at removing CO2 from the atmosphere. Algae "absorbs" the carbon and uses it to reproduce. Algae can serve as a nutritional food source, create polymers to replace plastic, and produce biofuels.[29] Due to its wide range of uses, its fast reproduction rate, and its immense carbon capture capability, algae is becoming an increasingly viable carbon sequestration option.

Cost Estimates: Creating a 250 acre algae farm costs approximately $8,125,000, while a 10 acre algae farm would cost $325,000. Palo Alto could scale up or scale down depending on its budget and land availability. Partnering with another city to construct a Helios-NRG algae plant, which sequesters carbon emissions from power plants emitting flue gas, would cost around $2,499,030.

Feasibility: Palo Alto doesn't need naturally occurring algae to invest in this form of sequestration. Algae-cultivation is viable within Palo Alto, especially since the City has enough land to construct a small algae farm on. Palo Alto can also pump captured carbon sourced from other carbon sequestration methods into the algae farm. Conversely, since the Helios-NRG plant has been designed to pair with a flue-gas emitting power plant, Palo Alto may need to partner with a city that has such a plant in order to implement that option.

Key takeaways: Algae could be a key tool for efficient carbon sequestration. Since it has a wide array of uses, algae cultivation in Palo Alto could not only aid sequestration efforts, but also provide the City with a new sustainable and versatile resource. Palo Alto can model algae sequestration projects[30] sponsored and funded by the U.S. Department of Energy and the National Energy Technology Laboratory or the algae cultivation efforts by Qualitas[31] in Texas and New Mexico.

ANALYSIS: NEGATIVE EMISSIONS TECHNOLOGIES (NETS) RESEARCH

NETs capture and store CO2 from either concentrated sources such as waste and agriculture or DAC. NETs can further utilize or repurpose captured CO2 to generate new products. From our research, the most feasible forms of carbon capture and storage (CCS) to sequester Palo Alto's carbon emissions are solvent and mineralization. The subsections below give an overview of each type and its cost estimates, feasibility to Palo Alto, and key takeaways. For more information about companies and researchers who are working in these fields, see Appendix B. For more information about technologies that are promising, but are not currently available, see Appendix C.

SOLVENT CARBON CAPTURE TECHNOLOGIES

Overview: When a CO2 gas stream[32] is exposed to a liquid medium, the CO2 is absorbed by either a physical or chemical mechanism. The absorption liquid is then regenerated using high temperatures or reduced pressures to break the absorbent-CO2 bond, yielding a pure stream of CO2 that can be further processed.

Cost Estimates: From a Department of Energy analysis, after capital costs of $400–$500 million per unit, commercial technology can capture carbon at roughly $58.30 per metric ton of CO2.[33] However, a new solvent[34] captures carbon dioxide from power plants for as little as $47.10 per metric ton, marking a significant milestone in the journey to lower the cost of carbon capture. The costs are likely to continue decreasing per unit as more commercial development is underway.

Feasibility: While solvent carbon capture is the most commercially available technology and the per unit cost is more affordable, it requires high capital investments and high amounts of land for large scale facilities to capture carbon. Then, we have to do something with the CO2, whether through geological injection or using it industrially.

Key takeaways: Several case studies in Appendix B show the promise and potential applications for commercialization regionally in the Bay Area. While only a small number of companies provide these services and both the capital and per unit costs are still extremely high, the technology exists to consider launching a solvent carbon capture pilot project.

MINERALIZATION CARBON CAPTURE TECHNOLOGIES

Overview: Carbon dioxide naturally reacts to certain rocks to create a solid mineral,[35] such as a carbonate, where it cannot escape back into the atmosphere. There are two technological methods for getting carbon dioxide to react with other minerals and form a rock: direct injection into underground rock formations (which companies like CarbFix[36] are using) or using crushed rock on the surface to interact with the atmosphere. Once produced, it is possible to use carbonate in construction materials.[37] Because of its permanence, many companies that capture carbon use mineralization to store it; however, the ecological consequences of direct injection are not certain at this time.

Cost Estimates: The price of mineralization storage varies depending on the conditions of the sinks that are already in existence.

- Storage in reservoirs costs between $7-13 per metric ton of carbon sequestered, but can cost up to $20-80 per ton if these facilities need to be managed for water and pressure.
- Mineralization deep underground through injection costs about $30-$50 per metric ton[38]

Feasibility: In the San Francisco Bay Area, there is sufficient surface basaltic rock for surface carbon mineralization[39] to be feasible and effective. However, there is not a readily standardized methodology for carbon capture at the moment. (For more information, see Appendix C)

Key takeaways: Many direct air capture technologies are relying on mineralization to permanently store the carbon that has been captured through solvent means. If the City wants to use mineralization as a way of capturing carbon in the future, they should continue to monitor the state of these technologies since it is feasible and scientifically understood, but not commercialized.

POLICY OPTIONS

The following tables present policy options that Palo Alto can implement to reduce emissions toward its goal of carbon neutrality, organized by Natural Sequestration or NETs. General trade-offs to consider are that policy options within Palo Alto's boundaries require time to reach their full sequestration potential. Early initial investments are needed to reap the benefits of these solutions in the long run. Options outside of Palo Alto are more expensive and require large-scale facilities to sequester carbon emissions.

NATURE-BASED SEQUESTRATION OPTIONS				
Companies / Projects	**Overview**	**Region**	**Amount of Carbon Sequestered**	**Cost Breakdown**
Urban Canopy Option #1	Begin a private tree giveaway program modeled after Seattle's Trees to Neighborhoods program to increase canopy cover targets on private property. Assuming the program runs for 5 years.	Within Palo Alto	1,111.97 tons CO2 per year by 2045	$1,250,000 Cost per ton unknown
Urban Canopy Option #2	Reforest the Pearson-Arastradero Preserve and Foothills Nature Preserve.	Within Palo Alto	1,533.7 tons CO2 per year by 2045	$394,212 $257/ton removed
Stockholm Biochar Project	Stockholm opened the first large-scale biochar plant, fueled by garden waste from city residents. It was designed to be replicated in similar cities with waste management facilities that collect and transport biomass. Palo Alto can launch a pilot project and open a biochar plant within its borders utilizing Stockholm's replication manual[40] and checklist.[41]	Within Palo Alto	8,333 tons of CO2 per year.	After 8 years from 2020-2028 and an initial cost of $972,240, Stockholm expects to see revenue increase. Further pricing details are not available, but the costs will likely be lower in Palo Alto due to lower scale.
Blue Carbon	Palo Alto could augment their current tidally-influenced wetlands by restoring an additional 50 acres of wetlands. Areas that could be restored include the Renzel Wetlands, the Remanent Marsh, and part of the Flood Basin. However, more research is needed to increase tidal connection in these areas, and the methodology for claiming carbon credits for this restoration is 5-10 years away. Further recommendations for the baylands that do not directly translate to carbon credits are laid out in Appendix D.	Within Palo Alto	A rough estimate is that an additional 50 acres of wetlands will sequester 75 metric tons of carbon per year (1.5 metric tons of carbon sequestered per acre per year).	$2,625,000 $35,000/ ton removed

NATURE-BASED SEQUESTRATION OPTIONS				
Companies / Projects	Overview	Region	Amount of Carbon Sequestered	Cost Breakdown
Helios-NRG[42]	Helios-NRG developed novel algae technology[43] to capture CO2 from carbon-based power plants and convert it to valuable products that generate revenue. This option[44] is only feasible in areas that have a power plant that emits flue gas. For implementation by Palo Alto, could partner with a plant to build an algae-capture infrastructure there.	Outside Palo Alto	Sequesters 70-90% of carbon emitted from a power plant, which ranges from 230,588 - 296,470 metric tons of CO2 per year.	$2,499,030 $8.42/ton removed, lifecycle costs & emissions unknown
Qualitas Algae Cultivation[45]	Qualitas has been practicing algae cultivation through its algae farms in New Mexico and Texas. The algae feeds off of captured carbon. Palo Alto could create a similar cultivation farm within or outside of the City. The more carbon there is to feed the algae, the more algae can be grown. Algae can feed off of carbon captured directly from the air,[46] or they can be "fed" carbon solvents if they are captured from a nearby factory's emissions. Once algae is grown it can then be repurposed as a food source[47] or as biofuel.[48]	Within or Outside of Palo Alto	Within Palo Alto, we recommend a 10 acre farm, which will capture approximately 392 metric tons of carbon per year. Outside of Palo Alto we recommend a 250 acre farm, which will capture approximately 9,788 metric tons of carbon per year	$2,625,000 $271/ton removed lifecycle costs & emisions unknown

NEGATIVE EMISSIONS TECHNOLOGY / OFFSET OPTIONS				
Companies / Projects	**Overview**	**Region**	**Amount of Carbon Sequestered**	**Cost Breakdown**
Climeworks DAC facility[49]	Palo Alto could build a Climeworks Direct Air Capture facility. Palo Alto could count a percentage of the carbon captured towards an offset of their carbon footprint, depending on how much of the costs they contributed to the creation and operation of the facility.	Outside Palo Alto	The largest facility in existence captures 4,000 metric tons of carbon per year.	The largest facility in existence costs $10-15 million in capital investments, plus $600-800 per ton of carbon captured once in operation. The total lifetime cost of the project is unknown.
European CO2 Test Centre Mongstad[50]	TCM is one of the world's largest solvent CCS located in Norway. The project tests, verifies and implements new technologies related to cost-efficient and industrial scale CO2 capture. It also provides advisory services to carbon capture projects. This is an existing project Palo Alto could buy into or replicate. For further guidance, the city could partner with TCM for consultation on constructing a new solvent plant.	Within Palo Alto	100,000 metric tons per year	The total cost of the project is $1.02 billion. Estimated $28–40 per metric ton of CO2, plus $2.8-4 million per year over an eight year period in capital investments. Capital investment costs are unknown.
Boundary Dam Project[51]	TCM is one of the world's largest solvent CCS located in Norway. The project tests, verifies and implements new technologies related to cost-efficient and industrial scale CO2 capture. It also provides advisory services to carbon capture projects. This is an existing project Palo Alto could buy into or replicate. For further guidance, the city could partner with TCM for consultation on constructing a new solvent plant.	Within Palo Alto	100,000 metric tons per year	The total cost of the project is $1.02 billion. Estimated $28–40 per metric ton of CO2, plus $2.8-4 million per year over an eight year period in capital investments. Capital investment costs are unknown.

NATURE-BASED SEQUESTRATION OPTIONS				
Companies / Projects	**Overview**	**Region**	**Amount of Carbon Sequestered**	**Cost Breakdown**
Gorgon, Australia Plant[52]	This is the world's largest solvent CCS operation. This is an existing project Palo Alto could buy into or replicate. Capital costs could potentially be lowered by reducing the plant's scale.	Outside Palo Alto	3 to 4 million metric tons of CO2 per year	The total cost of the project is roughly $2.2 billion, plus $26 per metric ton. Capital investment costs are unavailable.
Quest, Canada CCS Facility[53]	The facility stores CO2 below the surface after solvent capture. Long term impacts of geologic sequestration are still being investigated. This is an existing project Palo Alto could buy into or replicate.	Outside Palo Alto	More than 1 million metric tons of CO2 per year	The initial capital investment is $790 million, and the unit cost is $76.86 per metric ton. The total lifetime cost is unknown (unclear timeline).
Svante[54]	Palo Alto can partner with any producer of cement, steel, ammonia, aluminum, methanol and hydrogen to help bring a pilot Svante 400 Model to capture 30 kg of carbon emitted in the industrial production per day.	Outside Palo Alto	10,950 metric tons of CO2 per year	The initial capital investment is $12.3 million. Cost per metric ton and the total lifetime costs are not available.
Charm Industrial Carbon Offsets[55]	Charm takes carbon from plants, converts it to liquid and injects it deep underground, permanently removing it from the atmosphere. Palo Alto could purchase offsets from this company to reduce net emissions.	Within Palo Alto	400 metric tons of CO2 year. However, production can be scaled up.	$240,000 per year to offset and sequester 400 tons of carbon (or $600 per ton of carbon).
Climeworks Offsets[3]	Sold on a monthly basis, Palo Alto could purchase offsets from Climeworks that will be captured in an already-created Climeworks facility. 5,000 metric tons of offsets is the typical amount purchased by partner industries to match Climework's current capacity, but in the future production can be scaled up to sequester more tonnage.	Outside Palo Alto	5000 metric tons over 23 years (217 mt/year)	$6,000,000 total for 5,000 metric tons of offest (or $120 for every 0.1 metric tons of carbon).

To compare the policy options available to Palo Alto, we constructed a Subjective Linear Model (SLM). The SLM evaluates each policy option on the basis of seven weighted criteria: amount of carbon sequestered (30%), commercialization (25%), land use (25%), public health (5%), resource conservation (5%), lifecycle emissions (5%), and equity (5%). One model compared policy options within Palo Alto, while the other compared options outside of the City. For more information on how we compiled and conducted this modeling, see Appendix E. Ultimately, we arrived at our recommendations based on what options scored the highest on the SLM. In the recommendations below, policy options are ordered based on their SLM ranking.

To reach carbon neutrality by 2045, the City must sequester or remove the remaining 20% emissions beyond Palo Alto's 80 x 30 plan, or 156,000 metric tons of carbon per year. The City's urban forest currently sequesters 17,934.5 metric tons of carbon per year, or 18.5% of the remaining emissions needed to achieve carbon neutrality. The City's baylands currently sequester 600 metric tons of carbon per year, or 0.4% of the remaining emissions. These current sequestration numbers are unaccounted for in the City's current emissions reductions calculations because of a lack of official guidance on carbon accounting methodology. To be clear, the City of Palo Alto will not be able to achieve carbon neutrality by 2045 with the natural and technological options that are currently available . However, the City can combine recommended options as their capacity allows them to progress toward the remaining 20% of reductions needed to be carbon neutral.

RECOMMENDATIONS WITHIN PALO ALTO

We recommend that Palo Alto prioritize policy interventions within its city borders because jurisdiction is clear and guidance for receiving carbon credits within the City are better defined. Feasible policy options within the City are limited to natural sequestration methods due to the current state of commercialization for NETs and the amount of land that they require. We recommend the following:

1. Qualitas Algae Farm: Palo Alto should establish a 10 acre Qualitas algae cultivation farm within the City limits, and if space allows this intervention can be scaled up. While a 10 acre farm does not sequester enormous amounts of carbon, this option scored highest in the SLM because it is highly commercialized, it has strong benefits for public health (especially when considering algae's value as a nutrient-rich food-source), and it requires relatively low emissions and resources to sustain.

- Total cost: $325,000
- Total sequestration: 392 metric tons of carbon per year (0.25% of reductions needed)

2. Urban Forest: The city should prioritize additional tree planting to expand their canopy cover from 36.8% to 40% using a private tree giveaway program (modeled after Seattle's program; for more information, see Appendix D). Additionally, the City should reforest all grassy areas of the Preserves. This option scored second highest on the SLM because it is highly commercialized and offers strong co-benefits for public health, resource conservation, equity, and lifecycle emissions.

- Total cost: $1,644,212 ($250,000 per year to run a private tree program for 5 years, plus $394,212 to reforest the Preserves)
- Total sequestration: 2,645.67 metric tons of carbon per year (1.7% of reductions needed)

3. Blue Carbon: Palo Alto should enhance their blue carbon capacity by restoring an additional 50 acres of tidally-influenced area. This option scored high in the SLM because of the very strong co-benefits that it offers to the City, including low lifetime emissions, high contributions to public health, and a very strong contribution to resource conservation. Further recommendations for the baylands that do not directly lead to carbon credits are laid out in Appendix D.

- Total cost: $2,625,000 ($52,500 per acre)
- Total sequestration: Rough estimates suggest 75 metric tons of carbon per year (0.05% of reductions needed), but official guidance is 5-10 years away.

4. Biochar Pilot Project: Palo Alto should launch a pilot project replicating the Stockholm Biochar Project within the City. Stockholm's replication manual and checklist provide foundational information for moving forward. The pilot would engage the public directly and would not require the City to generate new plants. Rather, the City can utilize established waste management facilities and processes to transport and collect biomass. Once generated, the biochar would be spread throughout the city and help restore degraded soils.

- Total cost: $972,240 initial investment but will eventually experience a return via revenue generation. Note: The projections are overestimates based on higher amounts of biomass generated in Stockholm. The City has not published specific pricing data to allow us to reach a more accurate estimate for Palo Alto.
- Total sequestration: 8,333 metric tons of carbon per year

Implementing all four of these nature-based options within Palo Alto would sequester 11,445 metric tons of carbon per year, or **7% of the total reductions needed** to get the City of Palo Alto to carbon neutrality.

	Recommendation	**Cost Estimate**	**Sequestration**
Qualitas Algae Farm	Create 10 acres of algae farms within the City	$325,000	392 **mt/year (0.25% of total**)
Urban Forest Improvements	Expand urban forest canopy cover in city area by aggressively planting trees on both private property and on nature preserves		2,645 mt/year (1.7%)
Blue Carbon	Enhance blue carbon capacity by restoring an additional 50 acres of tidally-influenced area		75 **mt/year (0.05%)**
Biochar Pilot Project	Replicate the Stockholm Biochar Project in Palo Alto	$972,240	8,333 mt/year (5.3%)
Total			**11,445 mt/year (7.33%)**

RECOMMENDATIONS OUTSIDE PALO ALTO

Outside of Palo Alto's borders, we are able to compare both nature-based and technological sequestration options, given less restrictions on land use and the greater availability of industrial plants and other infrastructure needed for many commercialized NETs. Our recommendations single out a combination of these options that can help the City work towards carbon neutrality.

1. Svante: Palo Alto should partner with regional producers of cement, steel, ammonia, aluminum, methanol, or hydrogen to bring a pilot Svante 400 Model to a Bay Area plant. Palo Alto will likely receive carbon credits proportional to the funding they provide for the project. This project scored among the highest in our SLM because it is highly commercialized and it has minimal demands for land. This technology does not require more land than is already developed in an existing plant.

- Total cost: $12.3 million of capital investment; price per ton of carbon removed is the cost associated with production.
- Total sequestration: 10,950 metric tons of carbon per year (7% of reductions needed)

2. Svante: Palo Alto could create a 250 acre Qualitas algae cultivation farm outside of the City. This option scored high in the SLM because it is very commercialized, can be paired with other carbon capture technologies, has strong benefits for public health (especially when algae is used as a food-source), and it requires relatively low emissions and resources to sustain.

- Total cost: $8,125,000
- Total sequestration: 9,788 metric tons of carbon per year (6% of reductions needed)

3. Climeworks: Palo Alto should partner with Climeworks to build a direct air capture facility in the Bay Area. We recommend partnering with local actors to obtain funding, and Palo Alto would likely receive carbon credits proportional to the funding they provide for the project. This option scored among the highest in our SLM because it is highly commercialized, requires no lifecycle emissions since it can be powered by renewable energy, and has a relatively small physical footprint.

- Total cost: $10-15 million of capital investment, plus $600-800 per ton of carbon captured once in operation.
- Total sequestration: 4,000 metric tons of carbon per year (3% of reductions needed

Implementing these three options outside of Palo Alto would sequester 24,738 metric tons of carbon per year, or 16% of the total reductions needed to get the City of Palo Alto to carbon neutrality. Excluding urban canopy sequestration, when combined with the recommended interventions within Palo Alto, **all recommended policies would sequester 23% of the City's remaining emissions reductions goal**. Adding to this the 19% of reductions that we estimate the Urban Forest and Blue Carbon is currently sequestering, **the combined interventions would remove approximately 65,520 tons of CO2 or 42% of the 20% reduction needed to get the City to Carbon neutrality.**

	Recommendation	Cost Estimate	Sequestration
Svante	Partner with regional producers of cement, steel, ammonia, aluminum, methanol, or hydrogen to bring a pilot Svante 400 Model to a Bay Area plant	$12.3 million	10,950 **mt/year (7% of reductions needed for carbon neutrality)**
Qualitas Algae Farm	Create 250 acres of algae farms	$8 million	9,788 **mt/year (6%)**
Climeworks DAC facility	Partner with Climeworks to build a direct air capture facility built in the Bay Area	$10-15 million of capital investments, plus $600-800 per ton of carbon captured once in operation	4,000 mt/year (3%)
Total		$30.3 million, plus $600-800 per ton of carbon captured by Climeworks	24,738 mt/year (15.8%)

ADDITIONAL RECOMMENDED STRATEGIES

There are other actions that the City should take now that will enhance the City's ability to be a leader in carbon neutrality efforts.

1. Incentives: Take advantage of incentives to bring NETs to Palo Alto as they become commercially viable.
    - The Department of Energy has greatly expanded the research funding available for the development and demonstration of DAC technology. These demonstration projects often involve universities, private companies, regulators and local municipalities as key stakeholders, and they rely on funding from both the federal and state government. These projects are often eligible for the 45Q federal tax credit which can pay up to $50 per tCO2 captured and stored. Projects can also receive credits from California's cap & trade system.
2. Advocate to CARB[56] for detailed guidelines to measure carbon sequestration credits from trees and blue carbon into emissions inventories.
3. Regularly assess emerging technologies as commercialization and costs change (especially of the promising technologies listed in Appendix C, and see if pilot programs can be launched.
    - While NET options such as the Quest, Canada CCS Facility and Boundary Dam Project would bring Palo Alto to 100% carbon neutrality, we do not recommend that Palo Alto replicate or buy into existing CCS facilities like these at this time. They generally require large scale plants with extremely high capital costs despite lower unit costs. Furthermore, many of these projects and companies are new or under development, and their long term impacts require more research.
4. Partner with Boulder's Nature-Based Climate Initiatives (NCI) to quantify how much CO2 the City can sequester carbon with natural solutions and attend working groups to inform pilot projects.
5. Strengthen and leverage the City's relationship with Stanford University and other local research groups.

- Stanford Center for Carbon Storage
  - Jennifer Wilcox, Energy Resources Engineering Assistant
- Stanford School of Earth, Energy, and Environmental Science
- Local blue carbon research groups
  - Paytan Biochemistry Lab[57]
  - San Francisco Esterine Research Institute[58]
- To launch a biochar pilot project, Carbon Capture and Storage research group and NGOs such as USDN,[59] The Trust for Public Land,[60] and the CA Carbon Cycle Institute[61] to evaluate similar pilot options

6. Prioritize reducing carbon emissions.

We'd like to reiterate the importance of this final recommendation: emissions reductions are the most effective way for Palo Alto to achieve carbon neutrality in time for the State's 2045 deadline. The more emissions reductions Palo Alto can achieve over the next couple decades, the less the City will need to rely on carbon sequestration methods. Carbon sequestration is expensive, arduous, and time intensive. Even with immense investment into some of the most effective solutions we have found, Palo Alto will not be able to reach its complete neutrality goal with the options that are available to them today. If the City implements our recommendations, it will only get to 42% of the reductions needed to achieve carbon neutrality (8.4% of the City's total emissions). However, the City's interest in developing a carbon neutrality strategy is an important first step, and we commend the City of Palo Alto on its continued commitment to carbon neutrality, emissions reductions, and sustainability.

The Public Policy team was supported and aided by several individuals and entities throughout the practicum. First and foremost, we would like to thank Dan Rich, our instructor, for his tireless support, feedback, and guidance that helped make this memorandum successful. We would like to acknowledge Manami Suenaga, our Teaching Assistant, for her insights and feedback, and for working with us throughout this process. We would like to extend our gratitude to the generous individuals who took the time to speak to us and answer our questions to help inform our research:

Christine Luong, *City of Palo Alto, Sustainability Manager*
Jonathan Abendschein, *City of Palo Alto, Assistant Director, Resource Management, Utilities Department*
Peter Gollinger, *City of Palo Alto, Urban Forestry Manager*
Jim Stack, *City of Palo Alto, Senior Resource Planner, Utilities Department*
Natalie Khtikian, *Climeworks Market Manager, North America*
Lynn Orr, *Stanford University, Emeritus faculty, Department of Energy Resources Engineering, Academic Council*
Lincoln Bleveans, *Stanford University, Executive Director, Sustainability & Energy Management*
Jana Dilley, *City of Seattle, Pollution Prevention, Community Engagement Manager, Seattle Public Utilities*
Jake Brenner, *Ithaca College, Associate Professor and Chair, Environmental Studies and Science*
Jacques de Chalendar, *Stanford University, Adjunct Professor, Department of Energy Resources Engineering*
Daren Anderson, *City of Palo Alto, Assistant Director Open Space, Parks, Golf, and Animal Services*
Brett KenCairn, *City of Boulder, Director of the Urban Drawdown Initiative, Colorado's Senior Policy Advisor for Climate and Resilience*
Aurora Winslade, *Stanford University, Director of Sustainability, Leading Organizational Change Faculty*
Adina Paytan, *University of California Santa Cruz, Paytan Biochemistry Lab*
Peter Reinhardt, *Charm Industrial, Chief Executive Officer*
Lou Stubecki, *City of Seattle, Program Manager for Seattle Trees For Neighborhoods*

1. Lebling, Katie, et al. "Direct Air Capture: Resource Considerations and Costs for Carbon Removal," *World Resources Institute.*
https://www.wri.org/insights/direct-air-capture-resource-considerations-and-costs-carbon-removal
2. "National Forest Accounting Plan, Forest Reference Level 2021-2025: Iceland," *Icelandic Forest Service*. https://www.skogur.is/static/files/utgafa/nfap_iceland_october_2020.pdf
3. Climeworks. https://climeworks.com/
4. Carbfix. https://www.carbfix.com/
5. Panko, Ben. "World's Largest Carbon Capture Plant Opens in Iceland," *Smithsonian Magazine.*
https://www.smithsonianmag.com/smart-news/worlds-largest-carbon-capture-plant-opens-iceland-180978620/
6. Judge, Peter. "Climeworks opens the world's largest carbon-capture facility in Iceland," *Data Center Dynamics.*
https://www.datacenterdynamics.com/en/news/climeworks-opens-the-worlds-largest-carbon-capture-facility-in-iceland/
7. "Study Session for June 8, 2021: Update on Climate Action Plan," *City of Boulder.*
https://bouldercolorado.gov/media/3302/download?inline
8. Easter, Mark, et al. "Carbon Sequestration Pilot Project Feasibility Study," C*olorado State University.*
https://assets.bouldercounty.org/wp-content/uploads/2018/03/Carbon-Sequestration-Pilot-Feasibility-Study.pdf
9. "About Nature-Based Climate Initiatives," *Nature-Based Climates Initiatives.* https://nci.earth/
10. "Carbon Lane - Executive Summary," *EIT Climate-KIC.*
https://www.aalto.fi/sites/g/files/flghsv161/files/2020-02/Carbon%20Lane%20Executive%20Summary.pdf
11. "Carbon Management Tool for Urban Lands," *Nature-Based Climates Initiatives.*
https://nci.earth/resource-database/carbon-management-tool-urban-lands
12. "Urban Forest Management Plan," *City of Seattle.* https://www.seattle.gov/trees/management
13. "Trees for Neighborhoods," *City of Seattle.*
https://www.seattle.gov/trees/planting-and-care/trees-for-neighborhoods
14. "Copenhagen, Denmark," *Carbon Neutral Cities Alliance.*
https://carbonneutralcities.org/cities/copenhagen/#:~:text=Copenhagen%20has%20major%20climate%20ambitions%2C%20and%20aims%20to%20be%20the,the%20reduction%20of%20CO2%20emissions.
15. "Copenhagen Port Participates in Carbon Capture and Storage Project," *The Maritime Executive.*
https://www.maritime-executive.com/article/copenhagen-port-participates-in-carbon-capture-and-storage-project
16. "Denmark Invests in Carbon Capture as It Phases Out Offshore Drilling," *Yale Environment 360.*
https://e360.yale.edu/digest/denmark-invests-in-carbon-capture-as-it-phases-out-offshore-drilling
17. Baker, Sarah, et al. "Getting to Neutral: Options for Negative Carbon Emissions in California," *Lawrence Livermore National Laboratory.*
https://www-gs.llnl.gov/content/assets/docs/energy/Getting_to_Neutral.pdf
18. Paustian, Keith, et al. "Soil C Sequestration as a Biological Negative Emission Strategy" *Frontiers in Climate*, https://www.frontiersin.org/articles/10.3389/fclim.2019.00008/full
19. "Soil Carbon & Biochar," *The Institute for Carbon Removal Law and Policy*. https://www.american.edu/sis/centers/carbon-removal/upload/icrlp_fact_sheet_soil_carbon_biochar_181006.pdf
20. "Biochar Carbon Removal Fact Sheet," *The Institute for Carbon Removal Law and Policy*.
https://www.american.edu/sis/centers/carbon-removal/fact-sheet-biochar.cfm

21. "About Blue Carbon," *The Blue Carbon Initiative.* https://www.thebluecarboninitiative.org/about-blue-carbon#ecosystems
22. Baker, Sarah, et al. "Getting to Neutral: Options for Negative Carbon Emissions in California," *Lawrence Livermore National Laboratory*, LLNL-TR-796100, https://www-gs.llnl.gov/content/assets/docs/energy/Getting_to_Neutral.pdf
23. "Final Evaluation Findings San Francisco Bay National Estuarine Research Reserve," *Office for Coastal Management, National Ocean Service, National Oceanic and Atmospheric Administration, and United States Department of Commerce*, https://coast.noaa.gov/data/czm/media/SanFrancisco-BayNERR.pdf
24. "Coastal 'Blue Carbon': An Important Tool for Combating Climate Change," *The Pew Charitable Trusts*. https://www.pewtrusts.org/en/research-and-analysis/issue-briefs/2021/09/coastal-blue-carbon-an-important-tool-for-combating-climate-change
25. Duggan, Tara. "$63 million wetland restoration could be a blueprint for how California adapts to climate change. But it's taking forever" *San Francisco Chronicle*, https://www.sfchronicle.com/climate/article/This-delta-wetland-restoration-will-help-16680372.php
26. "Green Infrastructure and Ecosystem Services Assessment," *The Conservation Fund*. https://www.conservationfund.org/images/projects/files/Houston_Galveston_Report.pdf
27. "Coastal 'Blue Carbon': An Important Tool for Combating Climate Change," *The Pew Charitable Trusts*. https://www.pewtrusts.org/en/research-and-analysis/issue-briefs/2021/09/coastal-blue-carbon-an-important-tool-for-combating-climate-change
28. Lamm, Ben. "Algae might be a secret weapon to combatting climate change," *Quartz*, https://qz.com/1718988/algae-might-be-a-secret-weapon-to-combatting-climate-change/#:~:text=Algae%20as%20carbon%20sequestration&text=Trees%20and%20algae%20sequester%20carbon,the%20form%20of%20more%20algae.
29. Loeschen, Daniel. "Biofuels," *Mixer Direct*, https://www.mixerdirect.com/blogs/mixer-direct-blog/biofuels
30. "NETL'S Fossil Energy and Carbon Management R&D Awards," *National Energy Technology Laboratory*, https://netl.doe.gov/node/2476?list=Carbon%20Utilization
31. Nordrum, Amy. "New Tech Could Turn Algae Into the Climate's Slimy Savior," *IEEE Spectrum*, https://spectrum.ieee.org/new-tech-could-turn-algae-into-the-climates-slimy-savior
32. Borhani, Tohid N., and Meihong Wang. "Role of solvents in CO2 capture processes: The review of selection and design methods." *Renewable and Sustainable Energy Reviews*, https://www.sciencedirect.com/science/article/pii/S1364032119305076
33. James, Robert et al. "Cost and Performance Baseline For Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity," *US Department of Energy National Energy Technology Laboratory (NETL)*, http://netl.doe.gov/projects/files/CostAndPerformanceBaselineForFossilEnergyPlantsVol1BitumCoalAndNGtoElectBBRRev4-1_092419.pdf
34. DOE/Pacific Northwest National Laboratory. "Cheaper carbon capture is on the way: Solvent breaks barriers, captures carbon for less than industrial counterparts." *ScienceDaily*, https://www.sciencedaily.com/releases/2021/03/210311152719.htm
35. "Making Minerals - How Growing Rocks Can Help Reduce Carbon Emissions", U*nited States Geological Surve*y, https://www.usgs.gov/news/featured-story/making-minerals-how-growing-rocks-can-help-reduce-carbon-emissions
36. "We Turn CO2 Into Stone", *Carbfix*, https://www.carbfix.com/
37. "Gaseous Carbon Waste Streams Utilization: Status and Research Needs National Academies of Sciences", *Engineering, and Medicine, The National Academies* Press, https://doi.org/10.17226/25232
38. Utonih, Selma-Penna and Viviana León R., Vhelma , "Economic Assessment of the CarbFix CCS Method", *Iceland School of Energy*, https://www.or.is/documents/871/03_selma_whelma_economic_assesment_carbfix_uksWaTZ.pdf

39. Kelemen, Peter B. et al, "Engineered carbon mineralization in ultramafic rocks for CO2 removal from air: Review and new insights", *Chemical Geology*, https://www.sciencedirect.com/science/article/pii/S0009254120301674
40. "Bringing Biochar To Your City: Lessons From The Stockholm Biochar Project", Bloomberg Philanthropies, https://nordregio.org/wp-content/uploads/2018/05/Replicating-in-Stockholm-booklet-manual.pdf
41. "Keys To Success When Replicating The Biochar Project", *Bloomberg Philanthropies*, https://nordregio.org/wp-content/uploads/2018/05/Replicating-in-Stockholm-checklist.pdf
42. "About Us", *Helios-NRG, LLC*, https://helios-nrg.com/
43. "Algae Biotech", *Helios-NRG, LLC*, https://helios-nrg.com/algae-biotech
44. "Novel Algae Technology for CO2 Utilization (SC0017077)", *Helios-NRG*, https://img1.wsimg.com/blobby/go/1e29b6dd-3b53-48b4-9973-978dc04918d7/downloads/DE-SC0017077%20Ph2-%20CCUSOGT%20Poster-Phase%202%20-Fina.pdf?ver=1645112581576
45. "Growing algae more sustainably for biofuel production", *Colorado State University*, https://engr.source.colostate.edu/growing-algae-more-sustainably-for-biofuel-production/
46. "Air Carbon for Algae Production – AirCAP", *U.S. Department of Energy*, https://www.energy.gov/sites/default/files/2021-04/beto-36-peer-review-2021-algae-benemann.pdf
47. L. Wells, Mark et al., "Algae as nutritional and functional food sources: revisiting our understanding", *The Journal of Applied Phycology*, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5387034/
48. "Biofuels: The Promise of Algae", *Biotechnology Innovation Organization*, https://archive.bio.org/articles/biofuels-promise-algae#:~:text=Algae%20are%20renewable%20resources%20for,used%20for%20growing%20food%20sources.
49."Achieve Net Zero Targets with Climeworks Direct Air Capture." *Climeworks*, climeworks.com
50."Technology Centre Mongstad | Carbon Technology Testing." *TCM*, tcmda.com
51."Boundary Dam Carbon Capture Project." *SaskPower*, www.saskpower.com/Our-Power-Future/Infrastructure-Projects/Carbon-Capture-and-Storage/Boundary-Dam-Carbon-Capture-Project.
52. Chevron Policy, Government and Public Affairs. "Gorgon Project." *Chevron.Com*, https://australia.chevron.com/our-businesses/gorgon-project.
53. "Quest Carbon Capture And Storage." *Shell*, www.shell.ca/en_ca/about-us/projects-and-sites/quest-carbon-capture-and-storage-project.html.
54. "Svante | Capturing Carbon, Today." *Svante*, svanteinc.com.
55. "Charm | Carbon Removal Technology." *Charm*, charmindustrial.com.
56. "California Air Resources Board," *CA.gov*, https://ww2.arb.ca.gov
57. "Paytan Biochemistry Lab," *UCSC.edu*, https://paytanlab.ucsc.edu.
58. "Coastal Training Program," *San Francisco State University: San Francisco Bay National Estuarine Research Reserve*, https://sfbaynerr.sfsu.edu/what-we-do/training
59. "About, " *Urban Sustainability Directors Network*, https://www.usdn.org/about.html
60. "Home," *Trust for Public Land*, https://www.tpl.org.
61. "Home Page," *Carbon Cycle* Institute. https://www.carboncycle.org.

We initially looked at nine places as potential case studies, listed below. The places we chose not to consider further after initial research have an asterisk.

- Vancouver, British Columbia, Canada*
- Ithaca, New York, USA*
- Boulder, Colorado, USA
- Berkeley, California, USA*
- Cupertino, California, USA*
- Seattle, Washington, USA
- Amsterdam, Netherlands*
- Copenhagen, Denmark
- Iceland

While our initial lists of cities included places in California and places that were comparable to Palo Alto, we did not further research the indicated cities because they did not offer best practices for achieving carbon neutrality relevant to our focus on the urban canopy and carbon sequestration. For example, Berkeley has a sustainability target to reduce greenhouse gas emissions by 80% below 2000 levels by 2050. However, the City's plans do not include carbon sequestration and NETs. Other cities we looked at, such as Amsterdam, have had some success in their carbon-neutral plan; however, their strategy does not apply to Palo Alto since they are currently phasing out natural gas and growing its use of renewable energy, a step that Palo Alto has already taken. More information of the case studies we did pursue further is expanded below.

Iceland Case Study

Fast Facts		
	Palo Alto	**Iceland**
Population	66,573 (2019)	366,425 (2019)
Area (mi. sq.)	26 mi. sq.	Almost 40,000 mi. sq.
Population Density (population/mi²)	2,560.5 people/mi²	9 people/mi²
Ecology	Bay wetlands, foothills, grasslands, woodlands, forests	Tundra and subpolar oceanic biomes
Climate Goals	80% emissions reductions from 1990 levels by 2030; hoping for carbon neutrality soon	55% GHG emissions reduction from 1990 levels by 2030; carbon neutral by 2040; fossil-fuel-free by 2050
Language	English	Icelandic; while there are some materials printed and made available in English, many with more details are only available in Icelandic (for example, the 2020 Climate Action Plan in full is only available in Icelandic, with a much shorter summary document available in English).

Iceland is a country leading efforts to combat climate change. The Icelandic government articulates the need for such aggressive interventions because the country has one of the highest rates of GHG per capita, and the effects of climate change are actively playing out in the island nation's environment: glaciers are melting, marine ecosystems are being disturbed by acidification of the sea, and there are increased cases of heavy precipitation. landslides, and volcanic eruptions.

Iceland's Climate Action Plan, the main framework for achieving goals in compliance with the Paris Agreement and with reaching carbon neutrality, was first released in September of 2018. In this document, the Ministry for the Environment and Natural Resources laid out 33 action steps. Two years later in June 2020, the Ministry released an update to this plan, adding 15 additional steps to be taken, and highlighting the 28 of 48 action items that had been set into motion at the time of review. The government anticipates spending a minimum of ISK 46 billion (USD $358,410,656) on key climate action from 2020-2024.

Part of the Climate Action Plan is to "reduce emissions and increase carbon sequestration through improved land use, land use change, and forestry." In preparing the carbon sequestration strategy, Iceland also emphasizes "achieving other environmental goals than those related to climate. Namely, combating soil erosion and revegetating denuded lands, and restoring and adhering to principles of biological diversity – thus aiming its actions towards tackling three major global environmental challenges simultaneously."

As part of their goal to "enhance action in forestry," the Skógraektin Icelandic Forest Service conducted a complete review of the trees in the country. In their Forest Accounting Plan, they proposed a forest reference level (FRL) for managed forest land for the period 2021-2025," comparing afforestation rates following the implementation of different policies with a business-as-usual projection. Through this thorough review, that required taking samples of the most common trees found in Iceland's forests and "mak[ing] curves that estimate between age, carbon-stock, and growth patterns for different species," they were able to estimate the net carbon sequestration that they could achieve in following through on a policy of planting 12.4 million seedlings annually starting in 2023. Furthermore, their analysis included predictions of the amount of carbon drained from organic soil, which works contrary to geological carbon sequestration and releases GHG emissions, predicted to be stable at 400 tons CO2 eq per year from 2020-2025.

Besides putting out aggressive measurements and plans to enhance carbon sequestration, Iceland is investing in NETs; at the end of 2021, the world's largest carbon capture plant was opened outside of Reykjavik (Note that, while this is a big accomplishment inside the country, it is unclear how much the Icelandic government contributed to this project, or if it came about primarily through collaboration between private companies). There are only 14 other direct-capture plants currently in operation in the world. This facility, called "Orca" and operated by the Swiss company Climeworks using purely renewable geothermal energy, pulls 4,000 metric tons of carbon dioxide out of the air per year and pumps it "into underground caverns where the gas, mixed with water, will slowly become stone as it cools." Leading up to this project, another company called CarbFix conducted a pilot study in Iceland of this method of direct capture and embedding into basalt rock. They found that within less than two years, the carbon solvent had interacted with the minerals in the rocks to form a solid carbonate mineral. Reported pricing for this technology varies. The Orca plant is reported to cost about $600-$800 per metric ton of carbon removed from the atmosphere. However, in another negative emissions facility, Climeworks was reportedly able to "[hold] the price down to about $400 per ton."

Boulder, CO Case Study

Fast Facts		
	Palo Alto	Boulder, CO
Population	66,573 (2019)	106,392 (2019)
Area (mi. sq.)	26 mi. sq.	27.37 mi. sq.
Population Density (population/mi²)	2,560.5 people/mi²	3955.06 people/mi²
Ecology	Baylands, foothills, grasslands, woodlands, forests	Plains grasslands, mountain grassland and meadows
Climate Goals	80% emissions reductions from 1990 levels by 2030; hoping for carbon neutrality soon	70% emissions reductions from 2018 levels by 2030, Become a Net-Zero City by 2035, Become a Carbon-Positive City by 2040

In the summer of 2021, Boulder updated its climate action plan to address the root causes of climate change, dismantle the systems that uphold the fossil fuel economy, and have greater impact beyond the scale of one city. The city's new framework also includes more aggressive emissions reduction targets for the community. Specifically, **Boulder plans to reduce Emissions 70% by 2030 (Using a 2018 baseline), become a net-zero city by 2035, and become a carbon-positive city by 2040**.

In 2017, the city began collaborations with Boulder County in which **each jurisdiction initiated similar but distinct soil carbon sequestration pilot projects on agricultural lands**. These initiatives were among the first active initiatives by local governments to develop natural climate solutions (NCS) based carbon drawdown strategies. During the last two years, they have continued soil sequestration pilot projects initiated in 2018 and are now expanding some of the techniques for soil health improvement and sequestration to other parcels. The city is now reviewing the best available systems for standardizing soil carbon monitoring across city projects.

From an interview with Brett KenCairn, the City of Boulder's Senior Policy Advisor for Climate and Resilience and Director of the Nature-Based Climate Initiatives (NCI), a key takeaway was that that **the project is still ongoing and does not have clear quantitative evidence to point to for any recommendations yet.** The first two years of the pilot were mostly unproductive and transitional due to bureaucratic red tape and prairie dogs that disrupted the natural environment. Since the project is still new and ongoing, there have not been cost-benefit analyses created or published to assess its impact. Similarly, the budget has not been finalized either. As the project continues, this will be an important consideration for the City of Palo Alto to follow up on.

When deciding to launch the soil sequestration project, the City utilized 20,000 acres of land that was previously purchased as a nature preserve. **Brett estimates that the project will sequester between 0.5 ton an acre to 2 tons an acre per year, or 10,00-40,000 tons of CO2e annually** (6.4%-25.6% of the reductions that Palo Alto needs to get to carbon neutrality). Rather than pursuing commercial technologies, he emphasized the importance of natural climate solutions to address multiple climate challenges at once. For example, investing in the sequestration project has a strong likelihood of reducing extreme carbon release events such as in wildfires, which could potentially result in 100,000 tons of carbon releases.

Most recently, Boulder created an initiative called Cool Boulder that has not been announced publicly yet. They plan to have more publicly facing documents and materials available by late-March or early-April. Rather than solely focusing on carbon sequestration, **the City wants to prioritize heat management as they believe reducing water in the atmosphere will be more effective**

than specifically targeting CO_2 with sequestration.

Beyond its own studies, Boulder has led coalition efforts such as within the Carbon Neutral Cities Alliance (CNCA) to incorporate natural climate solutions and carbon drawdown as part of its priorities. Similarly, Boulder convened a working group with Stockholm, Helsinki and Minneapolis to assess and develop opportunities in bioenergy-biochar as a carbon drawdown strategy. The project partners included Aalto University, the University of Helsinki, and the City of Helsinki. **They found that both new soil management practices and the addition of biochar in soils were cost effective, low risk, negative emissions technologies.** Estimation of potential contribution of new soil management practices are pending and subject to increasing research. In agriculture, biochar use could range from 2.5-20 tons biochar per hectare contributing to 7.5-60 tons of CO_2 per hectare. In Finland, this equals the total national emissions of 3-20 years. Boulder was recently invited to submit a $100,000 grant proposal on behalf of this group for funding from the newly created Carbon Drawdown section of CNCA's "Game Changers" Initiative. Boulder has also been invited to submit a full proposal around its bioenergy-biochar efforts to the Bloomberg Philanthropies' Mayors Challenge fund. These proposals are still in development and should be reviewed once completed.

Lastly, Boulder with the Urban Sustainability Director's Network (USDN) and Carbon Neutral Cities Alliance spearheaded Nature-Based Climate Initiatives (NCI) to produce an evolving framework and action pathways for city-based drawdown opportunities, as well as a growing resource database. NCI brings together cities, resource specialists, community-based organizations, scientists, innovators, land managers, and others to accelerate the implementation of carbon removal strategies. In 2020 and 2021, UDI, the Trust for Public Land, and other partners have been building a new urban lands carbon management analysis and decision support tool that can assist both local governments and community-based organizations. It a**nalyzes data to project where and how much carbon a city can capture and what critical life support services—reducing extreme heat, absorbing stormwater, reducing air pollution—this carbon drawdown can achieve**. Full capability versions of the software have been built for 8 cities across the US—Boulder (CO), Cleveland (OH), Columbia (MO), Fayetteville (AR), Iowa City (IA), Lincoln (NE), San Francisco (CA), and San Luis Obispo (CA).

Palo Alto is currently part of USDN, allowing for peer exchange and collaboration between local government sustainability leaders. In USDN's Impact Evaluation Report, they released the results of their 2020 Impact Survey, where members identified decarbonization as a top area of work. However, **they did not mention carbon removal, capture, storage, or sequestration as an integral component of any city's decarbonization plans.**

Seattle, WA Case Study

Fast Facts		
	Palo Alto	Seattle
Population	66,573 (2019)	737,015 (2021)
Area (mi. sq.)	26 mi. sq.	83.78 mi. sq.
Population Density (population/mi²)	2,560.5 people/mi²	8,797 people/mi²
Ecology	Baylands, foothills, grasslands, woodlands, forests (City of Palo Alto 101)	Lakes, sounds, wetlands. Urban city surrounded by water, mountains, and evergreen forests.

Climate Goals	80% emissions reductions from 1990 levels by 2030; hoping for carbon neutrality soon	Reduce total core greenhouse gas emissions 58% by 2030 and become carbon neutral by 2050.

Seattle is a forward-thinking city committed to creating a sustainable future. An urban center in the Pacific Northwest surrounded by lakes, sounds, mountains, and evergreen forests, Seattle is vibrant with natural beauty. To protect the City's natural environment and the health and future of their residents, in 2011, the Mayor and City Council adopted a bold climate protection goal for Seattle to become carbon neutral by 2050 and directed the creation of a plan to meet the goal. The resulting 2013 Climate Action Plan provided a coordinated strategy aimed at reducing GHG emissions while also supporting other community goals, including building vibrant neighborhoods, fostering economic prosperity, and enhancing racial and social justice. **Overall, the City aims to reduce total core GHG emissions 58% by 2030 and become carbon neutral by 2050.** So far, using a baseline year of 2008, Seattle's total core emissions have declined 5%.

In response to the Trump administration's withdrawal of support for the international Paris Climate Agreement in 2017, the City Council affirmed Seattle's commitment to the goals established in the Paris Agreement and directed the Office of Sustainability & Environment to identify the actions necessary to limit warming to 1.5 degrees Celsius. The resulting actions are designed to move beyond incremental change and fundamentally reshape Seattle's building and transportation systems for a fossil fuel-free future.

Since 66% of Seattle's core emissions come from transportation, their Climate Action Plan places a heavy focus on reducing emissions from this sector, primarily through rapid electrification of the public transportation system and reducing the need for private cars. While there are not many explicit efforts involving carbon sequestration and there are no known public activities involving the use of NETs, Seattle's urban forestry practices are well-developed and inform our recommendation for Palo Alto.

Seattle's urban forest is an increasingly important asset to their goals, playing a critical role in mitigating climate change impacts, including heat island effects, as well as supporting public health, providing habitat for wildlife, creating spaces for exploration and enjoyment, cleaning their air and water, and reducing the quantity of stormwater runoff, further helping water quality. Seattle's Urban Forestry Management Plan, published in 2020, provides a framework for policy and action that guides city government decision-making to help Seattle maintain, preserve, enhance, and restore its urban forest. The core of the plan is a set of outcomes, strategies, actions, and indicators that will support a healthy and sustainable urban forest across Seattle's publicly and privately owned land. Seattle has more than four million trees and its urban forest is a critical infrastructure system, which works in concert with other infrastructure such as drains, pipes, sidewalks, and wires to deliver important services. It is estimated that the replacement value of Seattle's existing urban forest (the cost to re-plant trees and nurture them to their current size) is close to $5 billion dollars.

The Urban Forestry Management Plan sets specific goals for canopy cover, tree planting, and restoring forested parklands:

- *Canopy Cover*
    - **Goal: Achieve 30% canopy cover by 2037**
        - As of 2016, they have achieved a 28% canopy cover across the city. However, in the areas of the City where the population is primarily people of color and people with low incomes, canopy cover is only 20%.
        - The City of Seattle's most recent canopy cover study found that the majority of our urban trees are found in two locations: residential areas, representing 67% of the land and containing 72% of Seattle's tree canopy, and in the right-of-way (which is interspersed throughout the city), representing 27% of the land and 22% of the canopy.

- *Tree Planting*
    - **Goal: Increase Seattle's tree canopy through City tree planting**
        - Since 2009, Trees for Neighborhoods has helped Seattle residents plant over 11,300 trees in their yards and along the street.
        - The Green Seattle Partnership has planted over 190,940 seedlings as part of forest restoration efforts. The Green Seattle Partnership is a collaboration between the City of Seattle, Forterra, community groups and nonprofits, businesses, schools, and thousands of volunteers working together to restore and actively maintain the City's forested parklands.
- *Restoring Forested Parklands*
    - **Goal: Restore 2500 acres of forested parkland by 2025**
        - Since 2005, Seattle has enrolled 1,691 acres of forested parklands and other natural areas in restoration.
        - In addition to getting closer to achieving their goal in acres restored, other key 2018 accomplishments include:
            - 170,697 native plants installed in their projects
            - 4,177 trees saved from the grip of invasive English ivy
            - 76,920 volunteer hours dedicated

Specific Takeaways for Palo Alto

While Seattle is a significantly larger city than Palo Alto and has a somewhat different ecological make-up, there are some helpful takeaways related to urban forestry. Seattle's Trees for Neighborhoods initiative was an effective public effort to grow their urban canopy and resulting amounts of sequestered carbon. In this program, households can request up to six free trees during their lifetime to be planted in their property. They receive help selecting the right tree and planting location, purchasing watering bags and mulch, receiving training on proper care, and assistance on applying for tree street permits, planting, and evaluating trees. This program presents an example for how Palo Alto could encourage uptake of tree plantings on private property. In addition, the Green Seattle partnership with nonprofits, businesses, communities, and schools may serve as a valuable framework for Palo Alto's future public-private partnerships. These are just two types of programs that Palo Alto might benefit from implementing if they wish to expand their urban canopy.

Copenhagen, DK Case Study

Fast Facts		
	Palo Alto	Copenhagen
Population	66,573 (2019)	602,481 (2017)
Area (mi. sq.)	26 mi. sq.	69.42 mi²
Population Density (population/mi²)	2,560.5 people/mi²	8679 people/mi²
Ecology	Baylands, foothills, grass-lands, woodlands, forests (City of Palo Alto 101)	Coastal city, urban setting, canals.
Climate Goals	80% emissions reductions from 1990 levels by 2030; hoping for carbon neutrality soon	Carbon neutral by 2025 (2005 baseline)

Copenhagen, Denmark aims to be the first carbon neutral capital in 2025 (100% reduction in emissions using 2005 as the baseline year). Although they are engaging in ambitious efforts to meet their goal, the path to carbon neutrality by 2025 appears to be unrealistic. Overall, however, they do serve as a model city for enacting aggressive climate efforts. One of their noteworthy efforts is their plan to establish a carbon capture facility adjacent to the port of Copenhagen that will remove emissions from the Amager Resource Center (ARC). ARC processes the waste from the nearly 650,000 residents and 68,000 businesses in the Copenhagen metropolitan area, emitting 560,000 tons of CO_2 annually. Designed by the Bjorke Ingels Group, the new carbon capture facility would capture 90% of ARC's annual CO_2e emissions, or 500,000 tons per year (320% of the CO_2e reductions Palo Alto needs to achieve carbon neutrality). The captured CO_2 would be pumped aboard ships, sailed out to the North Sea, and stored in drained underground oil reservoirs. While carbon capture is normally a very energy intensive process, the project at ARC aims to show that carbon capture can in fact be achieved with neutral energy consumption. This is possible as residual heat from the capture process can be re-harvested and turned into district heating.

Denmark is investing $2.4 million into this project. ARC and the Copenhagen Malmö Port will submit an application to the climate action EU Innovation Fund to receive funding for both the establishment of the facility, which is scheduled for completion in 2025, and its operations. The amount of financial support being applied for is in the range of $80 to $160 million, which will finance up to 60% of the costs of the establishment of the facility and its operations for the first ten years.

Copenhagen's efforts in carbon removal are at the leading edge of public agencies taking action to mitigate climate change. However, establishing a carbon capture facility is likely not feasible in Palo Alto due to prohibitive costs, lack of available land, and the relatively low potential mitigation impact of the measure.

APPENDIX B: NET/CARBON SEQUESTRATION CASE STUDIES AND COMPANIES TO CONSIDER

Green highlight: companies / case studies with the greatest potential for current/future implementation

Company / Case Study	Type of Technology	Overview	Cost Estimates (if Available)	Feasibility
NWO Canada	Biochar	At the Atikokan Generating Station (AGS), the plant converts coal to biomass to sequester carbon. Cost estimates suggest that it sequesters 16,475 metric tons of CO2 per year.	The average annual cost of operation is $988,550. A cumulative cost for all the scenarios shows that both land application scenarios cost more than $25 million over 25 years. Every year, it will cost $60 per metric ton of CO2.	The plant requires high total annual costs and relatively high unit costs for each metric ton of CO2 sequestered. For Palo Alto, this may not be a good case study to model because it requires the usage of coal plants in order to generate biomass.
Biochar Carbon Sequestration in Massachusetts	Biochar	Orange, Massachusetts contracted a research group from the Illinois Institute of Technology (IIT) to conduct an economic feasibility study on the purchase, installation, and use of a biochar pyrolysis system for managing waste in the town. Total acres and possible tons of biochar applications at 18 tons/acre in the area were 523,517 and 3,761,154 each.	The study found that while the technologies differ, final sequestration costs are similar, ranging from $82 to $119 per ton of CO2, with a mean of $102/ton CO2 for the four commercial-scale technologies.	A similar pilot project has the potential to be conducted in Palo Alto. IIT's conclusion was that solid organic waste management with biochar would be profitable if run as a side project of an existing private business, where labor to maintain the system would already exist.

Stockholm Biochar Project	Biochar	Stockholm successfully opened a large-scale biochar plant fueled by garden waste from city residents. Four additional biochar plants are planned to be completed in the following years. All five plants are expected to produce 7,000 tons of biochar by 2020, which can sequester 25,200 tons of CO_2 (the equivalent of taking 3,500 cars off the road) and produce corresponding 25,200 MW/hour of energy (the equivalent of heat for 400 apartments). Currently, the project sequesters 8,333 tons of CO_2 per year.	Within eight years, the project will deliver a revenue on the city's investment estimated at over $972,240.	As a driver of revenue and carbon sequestration efforts, Palo Alto should consider a similar pilot project. It is especially insightful because this project reduces carbon emissions while engaging people in the fight against climate change. Stockholm has published a replication manual and checklist for cities and organizations that are interested in replicating the program.
Echo2	Biochar	Echo 2 transforms green waste from plantation forestry, agriculture, food and wood processing that would otherwise end up as GHG emissions by being burned or landfilled into bioenergy and biochar. Each tonne of biochar is over 80% pure carbon and removes 2.88 metric tons of CO_2 per metric ton of product, for centuries. The company were contracted by Microsoft for a storage guarantee of 600 years.	Not listed on their website; For a more detailed financial background, email contact@puro.earth.com.	Echo2 seems to be a rising commercially viable option. With investments from Microsoft, it will likely provide clearer options for purchase in the future. Palo Alto should consider revisiting their services as they develop in the future.

Carbofex	Biochar	Their technology produces biochar using a combined heat and power system and turning it into materials for water filtration and horticulture.	Shopify's director of sustainability estimates that it produces "one of the lowest-cost engineered carbon removal solutions out there (around $100 per tonne), where the carbon dioxide is coming from the atmosphere and being stored long term (100-plus years)."	This company is a feasible option for Palo Alto, but more investigation needs to be done into pricing. CO2 Removal Certificates (CORCs) are purchased in auctions at Puro.earth. If the City registers online, they can place purchase bids for specific carbon removal methods, quantities and prices of CORCs. Many CORC buyers start with a pilot. They choose to neutralize the emissions of a geography, an office, a conference, or the business flights in a year. Other companies decide to become completely net-zero with carbon removal. For further impact, CORCs can be bundled with products and services to make them carbon neutral.
Svante	Sorbent Carbon Capture Technology	Location: Burnaby, BC Canada Svante offers companies in industries with unavoidable emissions a commercially viable way to capture large-scale CO2 emissions from existing infrastructure at half the capital cost of traditional solutions due to process intensification. A single Svante plant would capture a million tons of carbon a year, equal to eliminating the annual emissions of more than 200,000 cars.	A 30-tonne per day CO_2-capture pilot plant at Husky Energy's Pikes Peak South Lloyd thermal project costs $12.3 million and was funded by multiple investors. Svante plans to roll out production of its carbon capture technology in full capacity to serve the broad commercial market by the end of 2023.	Palo Alto could invest in putting a small Svante model in a local plant and claim the credits as the company has raised over $75 million in funding and is engaging in partnerships with several companies across the carbon capture space, including Chevron Technology Ventures, Oxy Low Carbon Ventures, Climeworks, and Opus-12.

Solex Energy Science	Sorbent Carbon Capture Technology	Location: Calgary, AB, Canada Solex Energy's indirect heat transfer technology can play a key role in optimizing and improving the efficiency of CO2 capture processes at larger plants and labs.	Not listed on their website. For more information, their contact form is listed here.	This company seems to offer technology for plants rather than governments or clients seeking to start a pilot. However, they express an eagerness to work with any group that has a challenge for them, so Palo Alto could reach out for more information to learn about funding sorbent capture to claim carbon credits, but likely needs a partner that has more industrial capabilities.
SRI International	Sorbent Carbon Capture Technology	Location: Menlo Park, CA The U.S. Department of Energy's Office of Fossil Energy and NETL continue to support the engineering scale development of SRI International's mixed-salt process (MSP), which will enable cost-effective implementation of technologies that can be applied to the existing fleet of fossil fuel-fired plants, new plants, industrial facilities and the removal of CO2 from the atmosphere. SRI is designing and building an optimized, engineering scale (0.5 MWe) MSP test system for field testing at the coal-fired Abbott Power Plant located on the University of Illinois at Urbana-Champaign campus. Pilot and commercial demonstration plants have been operating at its headquarters since 2010.	Not listed on website; contact here, customer.service@sri.com, or +1 (650) 859 – 2000	SRI's technology may be for more industrial cities than Palo Alto as they target existing fossil fuel plants; they're carbon capture technology is still in development and not commercially available for inclusion in our menu of options. However, they frequently work with clients and are the most local carbon capture company. Their contact information is listed on their website here or customer.service@sri.com.

Climeworks	Sorbent Carbon Capture Technology	Location: Zurich, Switzerland Contact: Natalie Khtikian by email at Natalie.Khtikian@climeworks.com Overview: Climeworks builds facilities for direct air capture of carbon with sorbent methodologies; then, they partner with CarbFix to turn this CO2 concentrate into mineral carbonate. In addition to expanding their own sequestration plants and capabilities, they partner with individuals, organizations, and expressed an interest in partnering with Palo Alto to offset their carbon footprint by removing carbon from the environment	The Orca plant Climeworks built in Iceland cost $10-15 million to build, and each ton of carbon sequestered costs $600-$800 once the plant is in existence. In addition to building facilities, Climeworks offers a monthly offset subscription service to remove 100 kg ($120)/month; 50 kg ($60)/month; 30 kg ($36)/month.	Natalie expressed that Climeworks would likely not build a facility in Palo Alto, but that partnerships, investment, and purchasing of offsets through them is certainly a possibility.
NASA Johnson Space Center, in collaboration with Jacobs	Sorbent Carbon Capture Technology	This Liquid Sorbent Carbon Dioxide Removal System was designed as an alternative to the current CO2 removal technology used on the International Space Station (ISS), which uses solid zeolite media that is prone to dusting, has a low absorption capacity, and requires high regeneration temperatures and frequent maintenance. "This highly efficient plant will reduce Johnson Space Center's greenhouse gasses by approximately 20,000 metric tons of carbon dioxide annually, which is a 15 percent reduction, and is equivalent to eliminating the emissions from over 4,000 passenger vehicles or powering 2,400 homes in Texas."	No pricing estimates are listed on their website.	This is likely not a feasible study for Palo Alto to further consider. As used on the International Space Station, the scope seems out particularly outside the realm of options available to Palo Alto as a city.

European CO2 Test Centre Mongstad (TCM) in Norway	Solvent Carbon Capture Technology	The main objective of TCM is to test, verify and demonstrate different technologies related to cost-efficient and industrial scale CO2 capture. It also provides advisory services to carbon capture projects. TCM was developed by a consortium involving Gassnova, Statoil, Sasol and Shell.	Estimated to have a total cost of about $1.02 billion and projected to capture 100,000 metric tons of CO2 per year. TCM estimates a price range of $28–40/metric ton for the 2012–2020 period.	When compared with other options, TCM has competitive per unit costs and projects substantial offsets. However, this comes at the expense of massive capital costs. TCM provides advisory to carbon capture projects, and should be consulted in the event that Palo Alto decides to move forward with solvent carbon capture as a pilot project.
Boundary Dam Project	Solvent Carbon Capture Technology	Located in Canada, it is the only operational CCS project that is based on chemical absorption processes. The Project aims to make a viable, technical, environmental, and economic case for the continued use of coal with the deployment of the world's first commercial-scale, post-combustion CCS project on a coal-fired power plant.	The total cost is $1.3 Billion to capture about one million metric tons of CO2 per year using Shell's CanSolv® PCC process from a rebuilt 139 MWe (gross) coal-fired power plant.	This is not feasible for Palo Alto because it requires the continued use of coal plants.
Gorgon, Australia Plant	Solvent Carbon Capture Technology	It is soon to become the world's largest CCS operation when completed. It plans to capture 3 to 4 million metric tons of CO2 each year and it is expected that 100 million metric tons of CO2 will be captured and stored over the life of the project.	The total cost of the project is roughly $2.2 billion, but has an estimated cost of $26 per metric ton. Over a three year period, it costed $1.25 million	As the world's largest CCS operation, Palo Alto will likely not be able to use this example as a particularly useful model to emulate due to scale. However, the per unit cost is one of the lowest currently available and could provide insights into how to drive down the price.

Quest, Canada CCS Facility	Solvent Carbon Capture Technology	It was designed to capture, transport and store more than a million metric tons of CO_2 annually deep underground. In less than five years since its start up, Quest has captured and safely stored five million metric tons of CO_2. It was operated by Shell on behalf of the Athabasca Oil Sands Project and was made possible through funding for CCS from the governments of Alberta and Canada, which provided C$745 million and C$120 million of funding respectively.	Total capital costs required to reach commercial operation on October 1, 2015 were approximately $790 million. In 2020, the average cost was $76.86 per metric ton.	While the Quest Facility has stored over five million metric tons of CO_2 over five years, this advancement has come at remarkably high annual average costs. It also stores CO_2 below the surface of the earth and heavily relies on the continued utilization of oil and fossil fuels. Since long term impacts of geologic sequestration are still being investigated and fossil fuels are known to have adverse environmental impacts, Palo Alto should consider more reliable and sustainable forms of sequestration.
Shell-Cansolv	Solvent Carbon Capture Technology	Location: Houston, TX The first commercial post combustion CO_2 capture plant, based on regenerable amine technology, designed by Shell Cansolv was started successfully in Q3, 2013. The CO_2 capture facility is designed to capture 170 metric tons of CO_2/day from a gas-fired boiler's emissions, however, due to boiler limitations, the plant is running at a capacity of 120 tonnes of CO_2/day.	Not listed on website; contact here	Cannot be determined without price; however likely requires high fixed costs and land area beyond the scale of Palo Alto. Still, Shell is one of the leading Carbon Capture companies and could be a useful partner in establishing a pilot project.

	Solvent Carbon Capture Technology	Location: London, Great Britain Provides solvents that have been developed and optimized over the last 12 years, leading to successful utilization at numerous plants worldwide (for example, TCM above). This innovation has been developed into two widely-used commercial solvents: APBS-CDRMax® was developed to extract CO2 from flue gas in large scale industrial plants and APBS-CARBex® was specifically designed for biogas/RNG upgrading.	Not listed on the website, but a specialist can be contacted for more details on their website.	This company provides technology to plants rather than fully fledged systems to sequester carbon all on its own. The city could consider a collaboration with Carbon Clean but should look more towards commercial plants that use its technology.
Fluor	Solvent Carbon Capture Technology	Location: Irving, TX Fluor Econamine FG Plus technology is a proprietary carbon capture solution with more than 30 licensed plants and four decades of operation. They work with clients to customize solutions to their specific problems. When in operation, one of its plants will produce 4,776 metric tonnes per day of supercritical carbon dioxide, which will be available for sequestration via enhanced oil recovery.	Pricing is not listed on their website. Contact for further inquiries here. Their telephone number at their headquarters is +1-469-398-7000	It cannot fully be determined without pricing options, but this company is likely not a good fit within Palo Alto because it needs to be attached to an existing plant or facility. However, since they have already helped launch 30 licensed plants over 40 years, they are a possible place that the city can work with to create a program elsewhere and claim the credits.
Honeywell	Solvent Carbon Capture Technology	Location: Austin, Texas Honeywell will leverage UT Austin's proprietary advanced solvent technology to create a new offering targeted at power, steel, cement and other industrial plants to lower emissions generated from combustion flue gas in new or existing units.	Pricing is not listed on their website. Contact Tehani Manochio further inquiries at tehani.manochio@honeywell.com. Their telephone number at their headquarters is 973-216-0684	Since this project relies heavily on flue gas, this company is likely not a good fit within Palo Alto because it needs to be attached to an existing plant or facility.

44.01	Mineral-ization	Location: Muscat, Oman and London, UK 44.01's technology takes captured CO2, puts it underground, and accelerates its natural reaction with peridotite.	Pricing is not listed on their website. Contact for further inquiries here.	Since 44.01 has not scaled this technology up to work with a city yet, it does not seem feasible at the moment. Furthermore, long- term impacts of geologic sequestration are still being investigated, and Palo Alto should consider more reliable forms of sequestration.
Blue Planet	Mineral-ization	Location: Los Gatos, CA Blue Planet's method involves turning CO2 into carbonate rocks, which can be used as a substitute for limestone rock, a primary component of concrete.	Pricing is not listed on their website. Contact for further inquiries here.	San Francisco Bay Aggregates is designing & building the first commercial facility to use Blue Planet Systems' patented carbon mineralization technology. While this technology has not been fully commercialized yet, Palo Alto could potentially try to partner with the SF Bay Aggregates effort or work with Blue Planet to launch a pilot initiative in Palo Alto.
CarbFix	Mineral-ization	Location: Reykjavík, Iceland. Carbfix captures carbon emissions at the source from the emitter (power plant or other industry). They also take carbon from companies like Climeworks that have captured carbon through DAC. Regardless of how it is captured, the carbon is then dissolved in water and injected underground, into naturally occurring reactive rock formations of suitable composition (basalt). Carbfix technology turns CO□ into stone in less than two years.	CarbFix's Hellisheidi Plant process costs about $25/ton, not including capital costs. For more information about pricing, contact CarbFix here.	The technology to capture carbon emissions at the source requires partnership with a local or regional plant or emitter to implement. After this partnership is established, it also requires capital investment to create the direct injection infrastructure. Furthermore, long- term impacts of geologic sequestration are still being investigated, and Palo Alto should consider more reliable forms of sequestration.

Carbicrete	Mineralization Carbon Capture Technology	Location: Montreal, Canada Carbicrete has developed a method for sequestering carbon in concrete, claiming its product captures more carbon than it emits. Carbicrete's technology enables the production of cement-free, carbon-negative concrete using industrial by-products and captured CO2. CarbiCrete offers precast concrete manufacturers the process, materials and support to produce this high-quality precast concrete within their existing plant.	Pricing is not listed on their website. Contact for further inquiries here.	Carbicrete's commercialization is limited. Currently, its carbon curing process can only take place in the controlled environment of a factory, restricting its use to products such as CMUs and concrete panels that are cast in advance of being delivered to a construction site. To better serve their market, Carbicrete is developing a new technology that won't be ready for another 5-10 years.
Charm Industrial	Mineralization Carbon Capture Technology	Location: SanFrancisco, CA. Charm Industrial technology takes atmospheric CO2, captures it in biomass, converts the biomass to a carbon-rich-energy-poor liquid, and injects it into rock formations that have stored crude oil and gas for hundreds of millions of years.	Individual household cost: $50/month to remove 83.3 kg of CO2e/mo Company-level cost: $150/month to remove 250 kg of CO2e/mo Cost can increase for larger-scale CO2 removal.	Charm Industrial's offset is feasible for Palo Alto. However, Charm Industrial is bought out through 2024. If Palo Alto makes a purchase now, Charm Industrial can start offsetting some of Palo Alto's emissions in 2025.
Global Thermostat	Sorbent Capture Technology	Location: New York, USA. Global Thermostat's patented technology captures and concentrates carbon directly from the atmosphere and/or from industrial emissions. The carbon can then be sold to various industries that can re-use it in their manufacturing processes.	Not specified on the company's website, but inquiry can be made by emailing invest@globalthermostat.com.	Unable to assess the company's feasibility to Palo Alto. Inquiry can be made by emailing info@globalthermostat.com.

Carbon Engineering	Sorbent Direct Air Capture Technology	Location: Squamish, British Columbia, Canada. Carbon Engineering uses an air contactor, where the air is pulled in by a huge fan and passes over thin plastic structures that are coated in a potassium hydroxide solution. This solution removes carbon from the air and binds the carbon into a liquid solution, where it remains as a carbonate salt. The air is then released, minus the carbon.	The levelized cost of CO2 captured from the atmosphere ranges from $94 to $232 per ton.	This technology is not feasible for Palo Alto because it uses the CO2 it captures to recover oil from the ground, therefore, it is not sequestering carbon.

Sorbent Carbon Capture Technologies

Overview: Solid sorbent technology offers a CO2 capture alternative to overcome some of the energy and regeneration requirements associated with CO2 solvent absorption. Solid sorbents capture CO2 from flue gas by chemical, physical, or mixture absorption.

1. Cost Estimates: The World Resources Institute reported a range of costs for sorbent capture between $250-$600 per metric ton depending on the technology choice, carbon energy source and the scale of its deployment.
2. Feasibility: Many sorbents have only been tested at the lab scale under ideal conditions, meaning that much research and development is still needed before sorbent technologies can be commercially accessible. Manufacturing costs are likely to be much higher than for simple amines with solvent capture, demanding high capital investments and large amounts of land for power plants.

Key Takeaways: Sorbent technologies are still a new and emerging type of carbon removal. While some scholars have noted its potential for capturing carbon, this type of technology will not be viable until the costs, benefits, and long term impacts are fully understood.

Carbon Utilization Technologies

Overview: Carbon utilization is a broad term that refers to the different ways that captured carbon oxides - principally carbon dioxide (CO2) and occasionally carbon monoxide (CO) – can be used or recycled to produce economically valuable products or services. Carbon utilization focuses on the development of materials through four key pathways. One such pathway turns carbon into fuels or chemicals through a process known as conversion. Through conversion pathways wasted carbon can be transformed into synthetic fuels, plastics, and solid carbon products. Another pathway, carbon uptake, relates to the creation of algae to use as food, soil supplements, fuels or specialty products. Mineralization, which is outlined below, is generally considered to be another form of carbon utilization. This is because many mineralization technologies create inorganic materials, such as cements and aggregates, that can be utilized in the built environment. The fourth pathway for carbon utilization is services - or direct use. This pathway includes enhanced oil recovery (EOR), which is one of the most widely practiced forms of carbon utilization today.

1. Cost estimates: Due to a wide array of carbon utilization methods and pathways, the cost of carbon utilization varies greatly. Some notable cost estimates include:
   a. Flash Joule Heating Graphene Production will eventually be able to bring the cost of graphene down from a range of $67,000-$200,000 per ton to roughly $100 per ton of carbon removed. However, it is unclear when this technology will be scalable and commercialized.
   b. Microbial Electrosynthesis Conversion Pathways, which produces acetic acid, formic acid, and ethanol, all of which can be used in energy production, from carbon dioxide and electricity currently has a minimum selling price of $107.76 per kilogram of carbon.
2. Feasibility: Many of these technologies have only recently been developed and thus are not commercially viable yet.

Key Takeaways: Carbon utilization can be a smart long term investment due to its ability to recycle captured carbon into usable material. There are a large number of carbon utilization projects and companies in the U.S. and across the world that are working on building technologies to transform carbon into something useful. We recommend that the City of Palo Alto start by exploring the projects sponsored and supported by the National Energy Technology Laboratory and the U.S. Department of Energy.

Carbon Offsets

Overview: Carbon offsets reduce or remove greenhouse gas emissions to compensate for emissions created elsewhere. The most popular methods for cities to offset their carbon emissions are land restoration and tree planting. However, as climate-focused technology advances, individual companies are using new and creative technology to reduce carbon emissions concentrated in targeted sectors such as waste and agriculture.

1. Cost Estimates: The cost of carbon offsets varies from companies selling offset credits.
2. Feasibility: Short term carbon offsets that also sequesters carbon can be a feasible method to reduce its emissions.

Key Takeaways: Sequestered carbon offsets can be an effective way to reduce Palo Alto's emissions. However, it is worth noting that there's a significant difference in traditional carbon offset and sequestered carbon offsets. Traditional offsets, for example, is when a company or city invest in a project outside its boundary that reduces emissions such as paying to build a solar farm that replaces fossil fuel generation. However, traditional offsets have mixed reviews as it tends to overstate the amount of carbon being reduced elsewhere compared to the amount being emitted by the buyer. Sequestered carbon offsets reduces emissions from a particular sector such as waste and permanently sequesters the captured emissions. An exemplary company doing such method of carb offset is Charm Industrial.

Enhanced Mineralization Sequestration

Overview: Above ground mineralization, also known as enhanced mineralization, is a carbon removal technology by which weathering, or the exposure of carbon dioxide to crushed basalt or olivine, is sped up via industrial processes in order to sequester carbon.

1. Cost Estimates: Surface mineralization (or enhanced mineralization) costs about $8 per metric ton of carbon and is implementable on a local scale, but only if materials are already mined. If mining is needed, costs increase dramatically.
2. Feasibility: The basic chemistry of enhanced mineralization is well understood and the technology to mine, grind, and disperse rock is widely available. Research on enhanced mineralization as a form of carbon removal, however, remains in comparatively early stages, with much more work to be done to evaluate its efficacy and social and environmental sustainability. The first major field trials, looking at on-site weathering of mining wastes, are under way in Canada. (Source)

Key Takeaways: In the San Francisco Bay Area, there is sufficient surface ultramafic rock for surface carbon mineralization to be feasible and effective. However, most uses of surface mineralization is primarily on farmlands, and specifics as to how much it sequestered is not standardized or readily available. If the City of Palo Alto wants to explore the possibility of utilizing surface mineralization within the city limits to offset carbon, we suggest starting with the California Collaborative for Climate Change Solutions' (C4) Working Lands Innovation Center.

Graphene Filters

Overview: Chemical engineers have developed a graphene filter to capture carbon that surpasses the efficiency of commercial capture technologies, and will eventually be able to reduce the cost of carbon capture down to $30 per ton of carbon dioxide. Unlike the FJH Graphene Production mentioned in the section on carbon utilization, graphene filter technology does not produce graphene. Instead, it uses thin filters made out of graphene to capture carbon with greater precision. The most notable research and development in this space is being led by EPFL.

1. Cost Estimates: This technology is only a little over a year old, and thus is unlikely to be ready for commercialization soon. The goal is for this technology to bring the cost of carbon capture down to $30 per ton of CO_2.
2. Feasibility: Considering the fact that this technology has only recently been invented, it is not

ready for large scale implementation or commercialization yet.

Key Takeaways: If graphene filter technology can truly bring the price of carbon capture to as low as it promises, this could be a viable option for Palo Alto. However, this technology is currently very young and thus is not ready for commercialization yet.

Engineered Molecules

Overview: Scientists are engineering molecules that can change shape by creating new kinds of compounds capable of singling out and capturing carbon dioxide from the air. The engineered molecules act as a filter, attracting only the element that it was engineered to seek out.

1. Cost Estimates: Accurate cost estimates are not available yet. Engineered molecule technology developed by MIT Energy Initiative estimate operating costs will be around $50 to $100 per ton of CO2 captured once their technology is ready for commercialization.
2. Feasibility: This technology is not ready for implementation yet.

Key Takeaways: While this technology may be far from commercialization, Palo Alto has the advantage of being close and connected to Stanford University, where Jennifer Wilcox, a chemical engineer, and her colleagues have engineered a cheaper, carbon-based sorbent, similar to activated carbon, with embedded nitrogen functional groups and controllable pore structure that can be optimized to select for CO2. The material can be quickly cooled and heated. Also, CO2 nestles into the pores without forming a chemical bond, so it takes little energy to desorb the CO2. Palo Alto could potentially partner with Wilcox's team to encourage the scaling up of their technology and ultimately use it for carbon capture in Palo Alto's borders.

Membrane Carbon Capture

Overview: Membrane Carbon Capture is a nascent capture strategy using gasses pushed through selective membranes to separate out the Carbon Dioxide. Current industrial membranes are based on thin-film polymeric materials, but there are many promising approaches in need of further study. This particular field is very far from becoming commercially viable, as the materials used as the selective membrane studied in an analysis of the future of membrane capture for Direct Air Capture is not commercially available.

1. Cost Estimates: $3,000-$10,000 per ton of CO2. The range is wide because of a lack of current
2. Feasibility: Some research is being done, but this technology is not ready for Direct Air Capture. Selective membranes currently available may be more apt for flue gasses, where concentrations of CO2 are higher. However, much more research and development is needed.

Key Takeaways: This strategy could be useful in large scale CO2 production scrubbing where CO2 concentrations are around 15%, but direct air capture is currently not ready for primetime. The membrane filter materials commercially available are not ready to sequester the atmosphere where the density of carbon is orders of magnitude lower. This particular strategy is one that the City of Palo Alto can keep an eye on, but is not promising in the near term.

Calculation of Sequestration Estimates

A true calculation of the City's carbon sequestration would require a detailed inventory and measurements of all street trees, trees on private property, and trees within parks and preserves in Palo Alto. Such an inventory is virtually infeasible due to the cost and labor restraints that it would entail. Because no inventory exists, we cannot say exactly how much carbon sequestration the City's trees provide. This is part of the reason that no cities are including tree sequestration estimates in their total emission inventories; there is no standardized methodology for doing so.

To obtain an estimate of carbon sequestration for the city and identify areas where gains can be made, we calculated estimates for yearly sequestration for the entire city, including all parks, preserves, and private trees. These areas were not included in the canopy coverage estimates provided by the city in 2021. (36.8%) To provide an example of where improvements could be made, we then identified areas within the City's jurisdiction that could provide the greatest impact with additional planting.

To calculate the sequestration potential of the urban canopy, we used the US Forest Service's i-Tree program suite. This program is the standard for many municipalities and is used by Palo Alto's Urban Forestry Section. Using the i-Tree Canopy tool, we estimated the canopy coverage of the city and then estimated sequestration by the area of coverage.

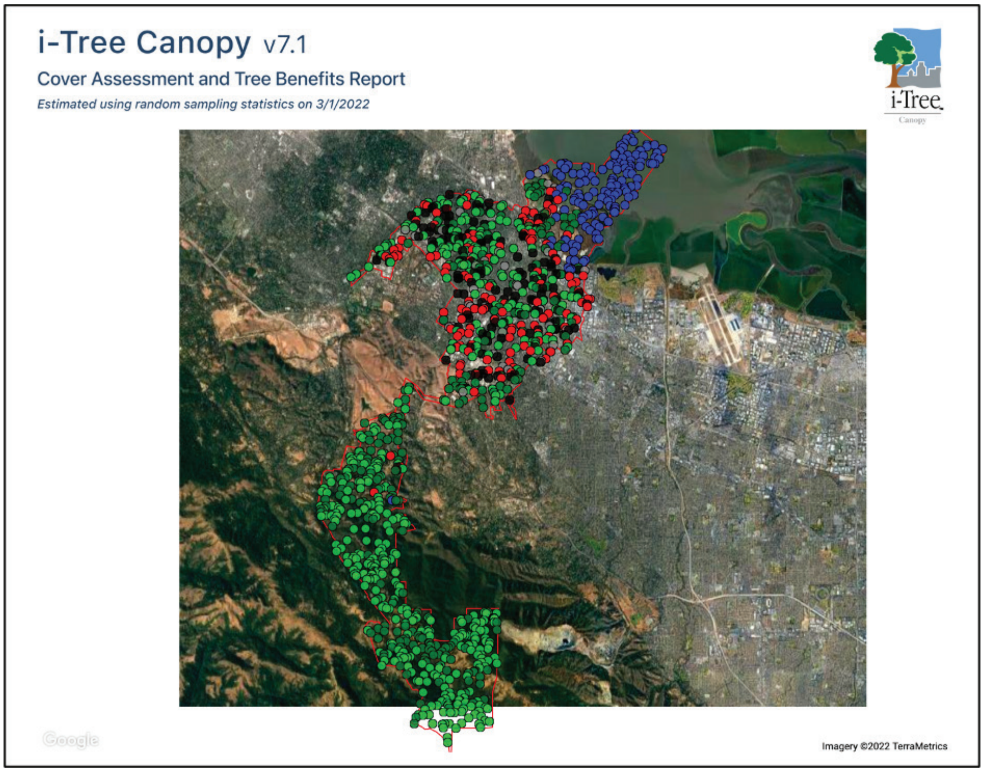
i-Tree Canopy estimates canopy coverage within an area by randomly selecting location points using Google satellite imagery, and then the user classifies the survey points based on what they can identify. We then converted this estimate to an estimation of carbon sequestered with the formula used for average carbon sequestered per meter squared of canopy coverage.

Limitations of this approach include human-error in the classification of each randomly sampled location, as Google Imagery can be difficult to interpret at small scales. We also believe that estimating sequestration by average area of canopy coverage is an incredibly broad approach. A more accurate approach would be to randomly sample plots within the city and complete an inventory of the trees within these areas. An example of this approach can be found in a study of Bristol's urban forest. When using i-Tree Eco, this approach could also help inform the number and type of trees that the city would need to plant to reach its goals. (Walters 2021)

Palo Alto's Tree Coverage

To obtain a comprehensive estimate of the current amount of CO2 sequestered per year by trees within Palo Alto as a whole, we included the entire city, including its forested regions in the preserves. Using 1144 survey points, we classified each survey point into one of 6 categories. i-Tree documentation suggests between 500-1000 survey points for an accurate estimate. (Figure 1) "Tree/ Shrub" describes a survey point covered in canopy. Because it is difficult to distinguish between height of trees and low-lying shrub type vegetation, we included both.

1. "Plantable/Grass/Soil" describes a survey point covered by an area that could host a tree. These often included grassy areas in parks, grass or soil covered areas on private property, like yards.
2. "Impervious Road" describes a survey point in a road, parking lot, or railway.
3. "Impervious Building" describes a survey point that hosts a building or structure.
4. "Impervious Other" describes a survey point that could not host a tree but was not a building or road. This often included sidewalks, pools, sports and recreation areas, airport property, and areas obviously cleared for utilities.
5. "Water / Bayland" describes areas that are not plantable and were excluded from our canopy coverage estimates. Our total survey points reached the suggested n=1000 after this exclusion.



Resulting estimations are listed below:

Cover Type	Survey Points	% Cover	Area (km²)
Plantable	232	23.20%	13.57
Impervious Buildings	137	13.70%	8.01
Impervious Other	36	3.60%	2.11
Impervious Road	127	12.70%	7.43
Tree / Shrub	468	46.80%	27.37
Water / Bayland	144 – excluded	0	0

To estimate the yearly sequestration for this area of canopy coverage, we used the literature's yearly net-carbon sequestered per square meter estimate for the state of California. This net-carbon sequestered per square meter estimate includes the carbon sequestered through tree growth minus estimated carbon lost through decomposition due to tree mortality. The estimation that includes the growing season length for the state of California is 0.288 kgC/m^2 (Nowak, 2013). To convert this from units of Carbon (C) to Carbon Dioxide to (CO2), as is standard for our analysis, we multiply by the ratio of molecular weights (44/12) (EPA). Our final net-carbon sequestered per area of canopy coverage in Palo Alto estimation is 1.055 kgCO2 /m^2. A limitation to this analysis is that we have assumed that forested areas behave like urban trees. This is likely an overestimation of net sequestration because forest trees face more competition for light and space and are much less maintained, lowering their yearly sequestration.

Total Sequestration of the Palo Alto Urban Canopy:

27.37 km^2 => 27,370,000 m^2 * 1.055 $kgCO2/m^2$ = 28,875,350 kgCO2 per year
= **28,875.35 Metric Tons CO2 per year**

Percentage of remaining 80x30 emissions currently sequestered by urban canopy:

28,875.35 Metric Tons CO2 per year / 156,000 Metric Tons CO2 per year
= 18.5%

In determining what additional gains the city could make by planting more trees and increasing the total canopy coverage, we asked: what if the city planted every available spot in the city proper or in the preserves? This is largely a theoretical exercise, as an unknown and likely significant portion of the area designated as "plantable" is on private property or otherwise inaccessible to the city.

Total Additional Sequestration of the Palo Alto Urban Canopy If *All* Plantable Area Covered:

13.57 km^2 => 13,570,000 m^2 * 1.055 $kgCO2/m^2$ = 14,316,350 kgCO2 per year
= **14, 316.35 Metric Tons CO2 per year**

Percentage of remaining 80x30 emissions additionally sequestered by urban canopy if *All* plantable area covered:

14,316.35 Metric Tons CO2 per year / 156,000 Metric Tons CO2 per year
= 9.2%

Analysis & Discussion

Based on our estimates, the **current trees in Palo Alto sequester 18.5% of the reductions needed to get the City to carbon neutrality after they meet their 80 x 30 goals**. If the canopy coverage of the entire city, including the Preserves, increased from 46.8% to 70% by planting every "plantable" area, the city could sequester 43,191.7 Metric Tons CO2/yr or **27.6% of the remaining reductions needed.**

Private Tree Expansion

We conducted another analysis of the City's canopy without including the preserves, using the defined areas from the Urban Canopy Master Plan. Results from our analysis showed a 34.6% canopy cover – within the margin of error from the City's analysis in 2022, which were 36.8%. To estimate a 3.2% increase in canopy within this boundary, the City's Urban Forestry Manager indicated a 40% goal for canopy coverage, we repeated the above process the area that this increase would entail.

Estimated total "city area" 32.93km^2 * .032 => 1.054km^2 => 1,054,000m^2 * 1.055 $kgCO2/m^2$ = 1,111,970 kgCO2 per year
= **1,111.97 Metric Tons CO2 per year or about 0.7% of the remaining reductions needed**

In our conversation with the City's Urban Forestry Manager, Peter Gollinger, it was apparent that the city had already planted a great deal of the street tree and other locations within the City's jurisdiction. Therefore, we think that additional plantings to get to this 40% goal within the city must be on private property. A best practice to increase this we found in Seattle's Trees for

Neighborhoods program. Every autumn, the program gives out 1,000 trees a year to schools, businesses, and homeowners. In order to know exactly how many trees it would take to increase the canopy coverage to the 40% goal, we recommend the city conduct a random sample study of the City's urban canopy and borrow methodology from the Bristol study. (Walters 2021) Since such a study is outside the scope of our project, we are assuming that a planting initiative could last 5 years, but would likely need to be extended.

In a conversation with Lou Stubecki, Seattle's Trees for Neighborhoods' Program Manager, we received a breakdown of the program's costs. They contract with the University of Washington Botanic Gardens to store and maintain the 5-7 gallon tree saplings until the event days where residents can pick up their trees and attend planting tutorials and classes administered by the contractor. Their program focuses on equity and prioritizes planting within heat island and lower income census tracts within the city by focusing outreach in these communities. After residents receive their trees, they receive mailed watering reminders and emails from staff until year 5, when the tree has been established. The average tree cost in this program in 2021 was $57 per tree (Seattle looked for bargains on certain species). The average cost per tree of mulch and water bags was $19, and the City required 19,000 sets for the total program. Contactor costs were $43,000 predicted to increase to $50,000 next year. The cost of outreach and publications was $8,000. Administrative costs depended on how many program managers there were (ideally arborists); Seattle has one.

To create a comparable program in Palo Alto, we calculate the costs by summing the following. This total cost is an estimate, as contractor, supply costs, and administrative costs may be higher in the Bay Area than they were in Seattle.

Cost	**Estimate**
Hiring a Program Manager	$100,616 (average salary in Public Works dept. FY 2022 Budget)
Trees	$60,000 (Assuming $60 per tree – program manager estimates tree cost will only rise)
Munch and Water Bags	$19,000
Contractor costs	$50,000 (Partner with the nonprofit Canopy or local nurseries to provide services)
Outreach	$8,000 (Same as Seattle's)
Total yearly cost	$237,616

In order to plant the most effective sequestering tree species, we ranked the per tree sequestration estimates provided in the Urban Canopy Master Plan. These top five trees come only from those included in the City's street trees, and there may be species that are even more effective than these. We limited our analysis to street trees because we know they are adaptable in this climate. By prioritizing planting of protected trees, like Coastal Live Oaks and Redwoods, the City could ensure a degree of protection for the trees indefinitely.

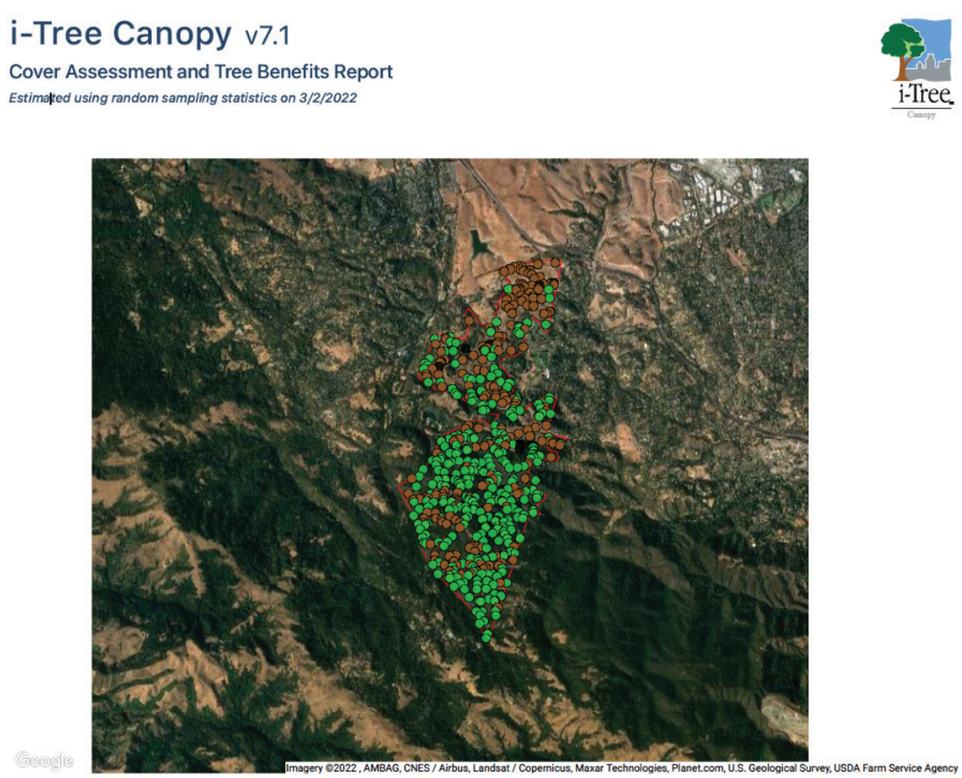
Common Name	**Species**
Modesto Ash	Fraxinus velutina 'Modesto'

Holly Oak	Quercus ilex
Coast Live Oak	Quercus agrifolia
London Plane	Platanus acerifolia
Liquidambar	Liquidambar styraciua

Reforestation of the Foothills Preserve

The preserves that the city owns in the foothills present a unique opportunity for enhancing the carbon sequestered within city limits. A significant portion of these preserves are grasslands dominated by annual species that arrived with early European settlers. In fact, many of today's grasslands were evergreen forests or oak woodlands before woodcutting and livestock grazing took their toll. (Foothills Park Nature Preserve) By planting native tree species in these grassy areas, the city could reforest the area and return the environment to its original state, while also reaping carbon sequestration benefits for the city.

To evaluate this possibility, we performed a similar canopy analysis on the Pearson-Arastradero Preserve and Foothills Nature Preserve. In this analysis, we limited our classifications to 1) "tree cover," 2) "plantable area," and 3) "impervious" (includes buildings, lakes, and roads/paths). Each classification is defined the same as it was for the estimates within the city proper. For survey points in transitional areas between obvious forests and grasslands (that often included shrubbery), we classified them as "plantable."



Our resulting estimations are listed below:

Cover Type	Survey Points	% Cover	Area (km^2)
Plantable	208	37.82%	2.99
Impervious	9	1.64%	0.13
Tree Cover	333	60.55%	4.79

To estimate yearly sequestration, we used the estimated national average yearly net-carbon sequestered per square meter of forest canopy cover (Nowak, 2013). This is estimated at 0.14 kgC/m2 tree cover/yr and is less than the sequestration of urban trees due to differences in the lifestyle of trees in different contexts. This is also a national average not specific to California. To calculate the estimated effect of a total reforestation of the Preserves, we assumed all plantable area would become tree cover. The costs of reforestation vary widely, we used the average costs per acre as defined in 2009 literature review by the Congressional Research Service to be $532.

Additional sequestration if planted areas defined as canopy covered:

2.99 km^2 => 2,990,000m^2 * 0.513 $kgCO_2/m^2$ = 1,533,870 $kgCO_2$ per year
= **1,533.87 Metric Tons CO2 per year or about 1% of the remaining reductions needed for carbon neutrality.**

Costs of reforestation:

3km^2 = 741 acres * $532 = **$394,212** => $257 per tCO2 removed

Blue Carbon

Three areas in Palo Alto's baylands show potential for restoration and increasing tidal influence, which can enhance the carbon sequestration potential of this natural solution. It takes time after wetlands are restored for them to sequester carbon at the scale that is needed to meaningfully offset carbon emissions. For this reason, in the lead up to a standard methodology for counting carbon credits from Palo Alto's baylands, it is a worthwhile investment now to restore and maintain as vibrant a coastal ecosystem as possible, including increasing the tidally-influenced landmass in the coastal wetlands.

The 121 acres of tidally influenced wetlands in the Renzel Wetlands can possibly be expanded by increasing tidal influence through a pipe. The Remanent March, currently completely disconnected from tides, could also be connected to add an additional 9 acres of wetlands. Finally, the Flood Basin has the potential to be more tidally influenced; however, increasing these wetlands might be less desirable when weighing the need to control vectors, such as mosquitos, that use these ponds to breed. Each of these solutions require further research and study of their environmental impacts. From the perspective of carbon sequestration, though, more wetlands can translate into a direct benefit of offering carbon credits when the methodology is officially created and if these lands are well-maintained.

Besides bolstering and maintaining the current tidal wetlands and increasing native plant growth, there are local, regional, and statewide collaborations that could benefit Palo Alto's Blue Carbon potential.

- Local scale: Palo Alto co-operates a part of the Baylands with East Palo Alto (the Don Edwards Wildlife Preserve), and their baylands border Mountain View. With these local partners, Palo Alto can collaborate to enhance the sequestration potential of their baylands, but specific carbon credits for these actions cannot be quantified now.

- Regional scale: "Before 1850, the region sustained 1,400 square kilometers of freshwater wetlands and 800 square kilometers of salt marshes; today, only 125 square kilometers of undiked marshes remain of the original 2,200 square kilometers, representing a 95 percent loss of crucial habitat." Because there is so much potential for restoration of wetlands in the Bay Area, Palo Alto can partner with different municipalities to fund and support increased sequestration potential. While Palo Alto could be a valuable partner and advocate for policy change, the logistics of jurisdictional overreach and sharing of carbon credits makes this an infeasible solution for Palo Alto's own carbon neutrality. Palo Alto can collaborate with the U.S. Army Corps of Engineers to have clean mud that is dug up from the Bay to be used for wetlands restoration; however, the immediate ability to count this action towards a carbon credit towards neutrality is not currently available, but is 5-10 years off.
- State scale: Palo Alto can lobby for state legislation such as 2017 AB 388 to allow for California's Greenhouse Gas Reduction Fund to be used for wetland restoration in the future; this action, however, will not immediately translate to carbon credits towards neutrality. However, it can make current investments in wetlands more affordable for the sake of eventually being applied to carbon sequestration credits when the methodology and guidance is available.

APPENDIX E: CREATING THE MENU OF OPTIONS AND BUILDING THE SUBJECTIVE LINEAR MODELS

After conducting extensive research on carbon sequestration practices and NETs, we put all of the potential solutions that we had found into a menu of policy options. The policy options included in the menu reflected the most commercially feasible interventions currently available to Palo Alto. We divided these policy options based on what is implementable within Palo Alto's borders, and what is only feasible outside of Palo Alto, but with the City claiming the carbon credits.

Although many possible options are not practically or financially feasible for Palo Alto, we consider interventions to be theoretically feasible if they meet a simple standard of ready commercialization. Our goal is to provide Palo Alto with a wide range of options, even if not all of them are necessarily viable, so that the client can decide for themselves what interventions it would like to pursue.

To compare the policy options in a standardized way, we constructed two subjective linear models: one for the solutions within Palo Alto, and one for the solutions outside of Palo Alto. A subjective linear model is a framework where one chooses criteria relevant to the decision, weights those criteria based on their relative importance to each other, and then assigns each policy option values for each criteria. The policy option with the greatest weighted score is the best option based on the model's specifications. In each of these models, we weigh the policy options based on attributes that are relevant to the client and that are consistent across their 80x30 goals:

- Cost: Capital investments + price per metric ton of carbon reduced
  - Weight: 0, because of the client's recommendation
- Amount of carbon sequestered/removed, standardized at metric tons per year: The potential amount of carbon sequestered/removed by the technology per our recommended action
  - Weight: 30%
  - Value scales: percent of the 156,000 reduction needed
- Commercialization: The degree to which the method is ready to be adopted and scaled within California's 2045 time limit
  - Weight: 25%
  - Value scales:
    - Very high - 90
    - High - 75
    - Medium - 50
    - Low - 25
    - Very low - 10
- Public Health: "Improve public health through reduced incidents of diseases/death attributed to pollution, increased use of active transportation options (e.g., walking, biking), etc."
  - Weight: 5%
  - Value scales:
    - Good - 80
    - Neutral - 50
    - Bad - 20
- Resource conservation: "Increase resource conservation in building energy, vehicle fuels, and water; increase natural habitat conservation and regeneration; and decrease waste generation"
  - Weight: 5%
  - Value scales:
    - Good - 80
    - Neutral - 50
    - Bad - 20
- Livecycle emissions: "Reduce emissions associated with the extraction, manufacture, and

transport of energy resources (e.g., natural gas production, distribution)"
    - Weight: 5%
    - Value scales:
        - Emissions neutral - 90
        - Requires low emissions to maintain - 75
        - Requires some emissions to maintain - 50
        - Requires lots of emissions to maintain - 25
- Equity: "Address an existing inequity in the community, such as disproportionate poor air quality, access to transit, flood risk, etc."
    - Weight: 5%
    - Value scales:
        - Good - 80
        - Neutral - 50
        - Bad - 20
- Land use: How much land does this intervention require, and is it feasible within the defined geographical limits that these models employ
    - Weight: 5%
    - Value scales:
        - Requires a little land - 80
        - Requires a medium amount of land - 50
        - Requires a lot of land - 20
        - Requires an insane amount of land - 10

Using the results of this modeling, we recommend policy interventions for Palo Alto to work towards carbon neutrality. The weights that we used were based on our own individual assessments of necessary considerations, their relative importance to one another, and the availability of information to decide how they are affected (for example, equity is important, but difficult to measure and quantify with brand new solutions, so it is weighted the lowest). All of the weights combined add up to 100%. The attributes that are most easily calculated or that we feel the most confident about are weighted higher because they will hold more weight in our final recommendation. Furthermore, the attributes of "Commercialization" and "Land Use" are weighted the highest after "Amount of carbon sequestered" (weighted the most because it is most obviously the outcome of interest in our model) because they are two factors that indicate feasibility but that are quantifiable and comparable across all of the possible options. While we discussed our weights and attributes with the client, these weights remain subjective, so we have attached an interactive spreadsheet (Pretty Subjective Linear Model) so that individuals from the City of Palo Alto can adjust their weights and attributes as needed when making policy decisions. Changes to the weights in the yellow columns will result in changes throughout the spreadsheet of the relative values of different options.

There is a significant degree of uncertainty in our model due to the emerging nature of the NET industry. Some technologies or companies offer more information than others on their websites, or are more responsive through email or phone than others. Furthermore, some companies or interventions are so new that not enough time has passed for the academic community and the public sector to assess their long-term consequences, particularly in areas of equity, public health, and lifetime emissions. Values that remain uncertain are marked in purple cells. We recommend that Palo Alto continue monitoring these companies as research on their more long-term impacts and commercialization change since this is a rapidly expanding field. Options that are infeasible today may be more applicable in five years time, and the values that are currently designated in the model can be updated to reflect such changes.