



Air Pollutant Reductions From Carbon Capture

**An Analysis of the Air Quality and Public Health Benefits
of Carbon Capture and Storage**

Authors and Contributors: Jeff Brown, John Thompson,
Ben Longstreth, John Graham, Marc Jaruzel, Deepika Nagabhushan,
Eliza Sheff, Katherine Dombrowski, Clay Jones

This work was supported by ClimateWorks Foundation and
Cynthia and George Mitchell Foundation

December 2023



CLEAN AIR
TASK FORCE

Table of Contents

	Summary	3
1	Introduction	4
2	Technical Background	5
3	Study Design and Methodology.....	6
4	Results from the Health Impacts Assessment	13
5	Discussion	14
6	Study Limitations.....	15
7	Conclusion	16

Summary

Technologies for capturing carbon dioxide emissions at the source are a key solution for decarbonizing large industrial facilities that lack other options for mitigating their contribution to climate change. This paper summarizes results from a Clean Air Task Force (CATF) investigation into the impacts of carbon capture systems on conventional air pollutant emissions—an aspect of carbon capture that has been less studied to date than energy and cost impacts. Specifically, CATF engaged Trimeric, an engineering and consulting firm, to model impacts on carbon dioxide and other air pollutant emissions if carbon capture equipment were installed on the main pollution

sources at four relatively high-emitting existing facilities in California and Texas: two fluidized catalytic crackers at petroleum refineries and two cement manufacturing plants. The analysis also estimated potential emissions of volatile organic compounds from the capture equipment. This report highlights key findings from the Trimeric analysis, as well as findings from follow-on public health analysis conducted by CATF and SC&A, an environmental consultant focused on public health. Additional sections provide background for this investigation, briefly describe the study approach and methodology, and discuss potential policy implications.

KEY FINDINGS

- Installing carbon capture systems at large industrial facilities such as refineries and cement plants can reduce conventional air pollutant emissions like sulfur dioxide (SO₂) and soot (particulate matter) and, in some cases, nitrogen oxides (NO_x), and produce substantial additional public health benefits from these reductions. These reductions occur because pollutants such as SO₂ and particulate matter must be removed from the flue gas stream before it enters the carbon capture system. The magnitude of the pollution reductions will depend on the pollution controls in use prior to the addition of a carbon capture unit.
- When the benefits from both CO₂ reductions and criteria air pollutant reductions are considered together, the total benefits are significantly greater than the costs of adding the technology.
- An engineering analysis of two cement manufacturing plants and two petroleum refineries in California and Texas finds that the use of the amine-based carbon capture system modeled would reduce CO₂ emissions by nearly 90%, reduce particulate matter emissions by more than 90%, and nearly eliminate SO₂ emissions from the largest point sources at these facilities. Modeled NO_x reductions vary from a few percent at the cement plants to more than 30% at the refineries. The carbon capture system itself produces a small net increase in VOC emissions at each facility. These results account for emissions associated with the use of extra fuel to provide steam to the capture unit.
- Carbon capture costs at these facilities range from \$60 to \$132 per short ton of total CO₂ captured for the refineries and \$67 to \$98 per short ton of total CO₂ captured for the cement plants. Costs for the facilities in California are higher than for the facilities in Texas primarily because of higher electricity and other energy costs in California.

SECTION 1

Introduction

Decarbonizing the industrial sector is essential to achieve net-zero carbon emissions on an economy-wide basis. Globally, the industrial sector emits approximately one quarter of all greenhouse gas pollution. Many industrial facilities produce large volumes of carbon dioxide (CO₂), either because they require large quantities of process heat or because they involve chemical processes that inherently generate CO₂ (cement production is an example), or both. At present, many of these industries lack any viable low-carbon alternatives. Carbon capture systems allow facilities that would otherwise be unabated emitters of greenhouse gases to reduce or eliminate their CO₂ emissions.¹

The operation of such systems, however, can require considerable energy. This has led to concern that even if carbon capture technologies succeed in removing CO₂ emissions, the increased fuel use to run the carbon capture equipment could degrade local air quality, particularly near facilities that are often already major emitters of pollutants that are known to have significant public health impacts. In addition, the carbon capture system itself can be a source of emissions—for example, from the breakdown of chemical solvents. On the other

hand, in order to achieve efficient operation of a carbon capture system additional pollution controls of the waste gas streams are required because air pollutants such as sulfur dioxide also interfere with the chemical and physical processes used to separate and capture CO₂. If the installation of carbon capture systems leads to further reductions in criteria pollutant emissions at large industrial facilities, then adding carbon capture can simultaneously improve local air quality and cut the carbon pollution that fuels global climate change.

To assess this hypothesis, CATF commissioned assessments of engineering, emissions, cost, and health impacts for combined carbon capture and pretreatment projects at four industrial facilities: two petroleum refineries and two cement manufacturing facilities, one each in California and Texas. Petroleum refining and cement production are among the top five categories of industrial sources for greenhouse gas emissions and both can also be large emitters of conventional air pollutants. We use these four case studies, across two states and two industries, to better understand the range of air quality impacts from retrofitting carbon capture equipment on major emission sources at large industrial facilities.

¹ A carbon capture system separates (or “captures”) carbon dioxide from other gases, preventing carbon pollution from being emitted to the atmosphere. In the carbon capture system evaluated, the separation occurs a post-combustion. Other systems include capture pre-combustion or systems that combust fuels with only oxygen, producing a concentrated stream of carbon dioxide. Direct air capture refers to the process of capturing carbon dioxide directly from the atmosphere and is not evaluated in this paper.

SECTION 2

Technical Background

The calciner kiln is the main source of CO₂ and air pollutant emissions at a cement plant; at a refinery, emissions may occur at multiple points, but the fluidized catalytic cracking (FCC) unit, which separates the hydrocarbon fractions of crude oil into gasoline and other refined petroleum products, is typically the single largest source.

This study considered amine-based scrubber systems suitable for carbon capture from cement kiln and FCC exhaust gases. These systems rely on reversible reactions between CO₂ and an alkaline solution called an “amine” or “solvent.” CO₂ in the exhaust gas stream is absorbed and bound by the solvent and later regenerated to create a pure stream of CO₂. The solvent is then recirculated to be used again. Conventional pollutants in the exhaust gas, such as sulfur dioxide (SO₂), nitrogen oxides (NO_x), and particulate matter (PM) are absorbed by the solvent and contribute to the formation of heat stable salts and other degradation products that can foul equipment and increase amine emissions from the absorber, creating a need to monitor impurities and periodically reclaim and replace solvent. Pretreatment to remove or reduce these contaminants in the exhaust gas stream before it contacts the amine absorber is a necessary and effective method for managing the accumulation of degradation products and reducing associated costs for reclaiming solvent, adding new solvent, and disposing of solvent waste.

This study evaluates the installation of carbon capture systems that use monoethanolamine (MEA) solvent. Newer generations of carbon capture solvents claim improved performance and lower cost, but most of these newer solvents are proprietary and less data about them is publicly available. By contrast, numerous non-proprietary studies have been published about MEA. To the extent that newer solvents perform better, the energy requirements and operating cost estimated in this study could be reduced. Capture systems can also be designed to capture a higher percentage of the CO₂ in a flue stream than the 90 percent modeled here.

One exception to the use of MEA capture systems as the basis for this analysis concerns estimates of VOCs. The Petra Nova carbon capture plant published results from three years of VOC monitoring and CATF determined that use of this data would be more representative of capture systems likely to be deployed than available estimates from MEA systems.²

The literature regarding carbon capture retrofits and their impact on criteria pollutant emissions is thin. This is partly because most previous studies of carbon capture costs and benefits assume a new facility that would be expected to meet stringent emissions control requirements regardless of its CO₂ status. In these instances, criteria pollutant emissions are usually already so low that incremental reductions from adding carbon capture equipment will have little significance to a local airshed. Where past studies have considered carbon capture retrofits at existing plants, they typically state that some pretreatment to remove SO₂, particulates, and other pollutants may be required, but do not include a before and after analysis of criteria pollutant emissions.

In the United States, however, most industrial-sector carbon capture projects are likely to involve existing facilities—for the simple reason that few new, large-scale refineries, pulp mills, cement plants, or primary steel mills are being constructed. The heavy industry plants that already exist are typically multi-billion-dollar facilities that can operate for many decades, and sometimes for more than a century (in fact, the two refineries selected for this analysis are 106 and 118 years old, and the two cement plants are 65 and 46 years old). And because many older plants are not subject to the stringent pollution control requirements that would apply to new plants, emissions intensity (i.e., the amount of pollution per unit production) can vary widely and idiosyncratically across facilities within the same industry. While reductions are anticipated at all existing plants, the magnitude of the pollution reduction that can be achieved by adding carbon capture will depend on the pre-existing level of air pollution at the plant.

² Emissions from MEA capture systems have been found to be well controlled. The Technology Center Mongstad has conducted several testing campaigns using MEA solvents. These found that use of a water wash effectively reduces emissions to the atmosphere, achieving very low (parts per billion) emissions of the MEA solvent itself and nitrosamines below the detection limit. Anne Kolstad Morken et al., *Energy Procedia* 114 (2017) 1245 – 1262.

SECTION 3

Study Design and Methodology

Our analysis takes a case study approach, focusing on four existing facilities in California and Texas: the PBF refinery in Martinez, California; the ExxonMobil refinery in Beaumont, Texas; the CalPortland cement plant in Mojave, California; and the Texas Lehigh cement plant in Buda, Texas. All these plants are large enough to support commercial-scale carbon capture retrofits and have relatively high levels of emissions for their industries.

CATF reviewed emissions data collected by state and federal regulatory agencies—specifically, the U.S. Environmental Protection Agency (EPA), the California Air Resources Board, and the Texas Council on Environmental Quality. A short description of each facility is provided in the text box.

Facilities Studied for this Analysis

PBF Energy refinery in Martinez, California

The Martinez facility is located roughly 35 miles north and east of San Francisco and had a FCC capacity of 157,000 barrels per day. Martinez emits 1,433,000 tons of CO₂ per year in a flue stream that is 15% CO₂ (dry volume). Martinez is the largest source of refinery SO₂ emissions in the state and is the state's second-highest industrial emitter of PM.

ExxonMobil refinery in Beaumont, Texas

ExxonMobil's Beaumont refinery is located near the Gulf Coast, approximately 90 miles east of Houston. Its FCC unit has a capacity of 115,000 barrels per day, making it the third largest of the 22 FCC units CATF identified in Texas. Of these units, it has the fourth highest CO₂ emissions (1,544,000 tons per year) and a flue stream that is 16% CO₂ (dry volume). Other refineries emit more total SO₂, but Beaumont had a high SO₂ emissions intensity among those we considered. Beaumont's PM pollution fell in the middle of the range.

CalPortland cement plant in Mojave, California

Located in the Mojave Desert, roughly 50 miles southwest of Bakersfield and approximately 100 miles north of Los Angeles, the CalPortland cement plant produces multiple cement products including Portland cement and oil well cement. It emits 1,450,000 tons of CO₂, 700 tons of SO₂, and 200 tons of PM per year. The CalPortland flue stream is 19% CO₂ (dry volume).

Texas Lehigh Cement Company plant in Buda, Texas

Located in central Texas, approximately 20 miles south of Austin and 65 miles north and east of San Antonio, the Buda cement plant occupies a 360-acre site and produces multiple products including Portland cement and oil well cement. It emits 1,482,000 tons of CO₂ and more than 1,800 tons of SO₂ and 250 tons of PM per year. The Texas Lehigh flue stream is 16.5% CO₂ (dry volume).

Using permit data and results from stack tests performed on these facilities, Trimeric assessed each plant's need for pretreatment controls and evaluated MEA-based scrubber systems designed to achieve 90% capture of CO₂ emissions from the calciner kiln (in the case of the cement plants) and the FCC unit (in the case of the refineries). Where data for a particular parameter was not publicly available, Trimeric developed estimates. Based on these engineering studies, Trimeric then estimated equipment and operating costs for the carbon capture system and calculated expected changes in CO₂ and criteria pollutant emissions (including, specifically, SO₂, NO_x, and particulate emissions). Costs and emissions associated with any auxiliary boiler required to run the carbon capture system were included in the results for each facility. Separately, CATF estimated the potential for increased emissions of other air pollutants, including volatile organic compounds (VOCs), from the carbon capture system itself. CATF based the VOC emission estimates on the results of three years of monitoring of VOC emissions at the Petra Nova carbon capture project. The Petra Nova project data provides the best available estimate of VOC emissions from the capture system itself, as this project is the longest-running capture system for which data is available, and such emissions are expected to be similar. These represent an estimate only, as different solvents and VOC control mechanisms may result in higher or lower emissions.

Results from the Trimeric and CATF emissions analyses were then used to estimate the expected health benefits of applying necessary pretreatment controls to operate the carbon capture system, using EPA's CO-Benefits Risk Assessment (COBRA) software tool. COBRA calculates the effect of changes in emissions on ambient concentrations of fine particulate matter, or PM_{2.5}, a type of pollution that has been linked to a variety of serious health effects, including asthma attacks, chronic bronchitis, hospital admissions, and increased mortality.³ Specifically, COBRA was used to: (1) estimate changes in ambient concentrations of PM_{2.5} (at the county level) as a result of changes in SO₂, NO_x, direct PM, and VOC emissions⁴ from the subject facilities following the installation of carbon capture and pretreatment

systems; (2) calculate associated changes in adverse health outcomes (e.g., mortality, hospital admissions, non-fatal heart attacks, asthma attacks); and (3) assign an economic value to these health outcomes. The direct (non-PM_{2.5}) health benefits of reducing SO₂ and NO_x were not calculated.

Finally, CATF engaged SC&A, a consulting firm, to examine health risks in the vicinity of the four facilities based on their estimated emissions of hazardous air pollutants before and after the installation of carbon capture equipment using EPA's Human Exposure Model (HEM4).

Refinery results

For the Martinez refinery, Trimeric's engineering analysis identified the need for four add-on pretreatment control technologies to ensure that the CO₂ capture equipment can operate effectively: an alkaline sorbent injection system, a selective catalytic reduction (SCR) unit (to replace existing selective non-catalytic reduction (SNCR) units), a combined direct contact cooler (DCC) and SO₂ scrubber, and a wet electrostatic precipitator (ESP). The Beaumont refinery already previously installed some of these controls and therefore only two add-on pretreatment controls were needed: an alkaline sorbent injection system and a wet ESP.

At both sites, the amine absorber would treat both the FCC exhaust gas and exhaust gas from the CO₂ capture unit's new auxiliary boiler. The need to run an auxiliary boiler reduces net carbon capture for the system as a whole from 90% to 87%. At Martinez, substantial NO_x reductions (73%) are obtained by upgrading the SNCR unit to an SCR and via NO₂ removal in the amine absorber. At Beaumont, which already has an SCR, there is a 33% reduction in NO₂ from the amine absorber. SO₂ emissions are reduced by 99% or more at both facilities, via the addition of an SO₂ scrubber at Martinez and the removal of SO₂ in the amine absorber at both refineries.⁵ Filterable PM emissions are reduced by 95% or more at each facility via the installation of a wet ESP, capture in the amine absorber, and removal in the new

³ The term "fine particulate matter" refers to particles that are less than 2.5 microns in aerodynamic diameter—hence the acronym PM_{2.5}. These very small particles are of particular concern from a health perspective because they can penetrate deep into the human lung. PM_{2.5} may be emitted directly but it is also formed in the atmosphere from precursor pollutants such as NO_x and SO₂.

⁴ Note that COBRA was run with the Trimeric results for emissions of SO₂, NO_x, and direct PM from the four facilities; internal CATF calculations were used to estimate increases in VOC due to amine-based capture technology.

⁵ On a mass basis, emissions of SO₂ from the Martinez FCC unit are 162 lbs/hr; in Trimeric's modeling, this rate drops to 8 lbs/hr from pretreatment, and to nearly zero after treatment in the carbon capture system.

SO₂ scrubber included for Martinez. Condensable PM emissions are reduced by 95% or more via installation of dry alkaline sorbent injection to remove sulfuric acid and a wet ESP to remove condensable PM. These reductions, including the tons reduced, are summarized in Table 1.

Estimated cost impacts for new pretreatment controls and for the carbon capture and compression system itself are summarized in Table 2. Normalized to the amount of CO₂ captured, the total cost of capture for the Martinez FCC is estimated at \$132 per (short) ton of CO₂; cost of

capture for the Beaumont FCC is estimated at \$60/ton.⁶ The cost of carbon capture at Martinez is significantly higher than at Beaumont for two reasons: (1) significantly higher energy costs in California as compared to Texas, and (2) the need for additional pretreatment controls at Martinez. The required addition of pretreatment controls at Martinez accounts for 35 percent of the cost of adding carbon capture; at Beaumont, which has an existing SCR unit and SO₂ scrubber, pretreatment requirements account for less than 5 percent of the total cost of adding carbon capture.

Table 1: Summary of Emissions Reductions at Martinez and Beaumont FCC Units

Reduction in Emissions of Various Pollutants from CCS Addition at Studied Refinery FCC Units*					
Refinery	CO ₂ Reduction	Criteria Air Pollutants Reduction			
	CO ₂	NO _x **	SO ₂	Filterable PM	Condensable PM
Martinez	87% 1,250,000 TPY	73% 351 TPY	99+% 673 TPY	97.5% 61 TPY	96% 296 TPY
Beaumont	87% 1,344,000 TPY	33% 55 TPY	99+% 160 TPY	95% 151 TPY	95% 59 TPY

* TPY=tons per year. Calculation of % Reduction is (Original Emissions less Emissions w/ Pre-Treatment and CO₂ capture, including New Auxiliary Boiler)/(Original Emissions).

** NO_x reduction for Martinez is greater than for Beaumont because Beaumont has an existing SCR that achieves high efficiency NO_x control. This study included an upgrade of Martinez's SNCR to an SCR, resulting in higher NO_x removal efficiency.

⁶ Throughout this report, we use “ton” to refer to a short ton, i.e., 2,000 pounds. Some parameters in this report are given in metric tons, equal to 1,000 kilograms or 1.1 short tons. Reported costs are in 2022 dollars.

Table 2: Comparison of CO₂ Capture Costs for Martinez and Beaumont FCCs

	Martinez	Beaumont
Annualized Costs (\$MM/yr)		
Annualized Capital Cost	55	28
Annualized Energy Cost	113	48
Other Annualized Costs	54	31
Total Annualized Costs	222	107
Contribution to Cost of FCC CO₂ Capture (\$/ton FCC CO₂ Captured)		
CO ₂ Capture and Compression	124	74
Add-on Pre-Treatment Controls	45	3
Total Cost of Add-on Controls and CO ₂ Capture	169	77
Contribution to Cost of Total CO₂ Capture (\$/ton FCC CO₂ + Aux Boiler CO₂ Captured)⁷		
CO ₂ Capture and Compression	97	58
Add-on Pre-Treatment Controls	35	2
Total Cost of Add-on Controls and CO ₂ Capture	132	60

Cement plant results

The two cement plants included in this analysis are currently equipped with SNCR for NO_x control⁸ and filter systems for PM control. Trimeric found that both plants would require new add-on controls—specifically, an SO₂ scrubber and a wet ESP—to reduce concentrations of SO₂ and PM entering the carbon capture unit. These add-on controls, together with operation of the amine absorber, virtually eliminate SO₂ emissions and reduce PM emissions by 93% to 97.5%. NO_x reductions were small (on the order of a few percent), as the only source of these reductions is absorption of NO₂ in the amine solvent.

Table 3 summarizes results for the criteria pollutants Trimeric modeled. With the exception of NO_x, the reductions are similar, in percentage terms, to those

obtained for the two petroleum refineries. The 87% (rather than 90%) reduction in CO₂, for example, is likewise due to the need to run a new auxiliary boiler to operate the carbon capture system.

Table 4 summarizes results from Trimeric’s cost analysis for the cement plant case studies. Normalized to the amount of CO₂ captured, the total cost of capture for the Mojave plant is estimated at \$98/ton and the total cost of capture for the Buda plant is estimated at \$67/ton. The need for pretreatment controls accounts for 10-15 percent of the cost of adding CO₂ capture and compression. As with the two refineries, capture costs are significantly higher for the Mojave plant than for the Buda plant because of differences in energy costs between California and Texas.

⁷ The costs per ton are lower when considering both the CO₂ from the FCC and from the auxiliary boiler because the same costs are divided by a larger amount of CO₂.

⁸ Trimeric did not consider an SCR upgrade for more NO_x control, as SCRs have not seen widespread use at U.S. cement plants and the NO₂ / NO_x ratio was expected to be low for these cement plant flue gases.

Table 3: Summary of Emissions Reductions at Mojave and Buda Cement Plants

Reduction in Emissions of Various Pollutants at Studied Cement Plants*					
Cement Plant	CO ₂ Reduction	Criteria Air Pollutants Reduction			
	CO ₂	NO _x	SO ₂	Filterable PM	Condensable PM
Mojave	87% 1,263,000 TPY	2% 54 TPY	99+% 699 TPY	97.5% 92 TPY	93% 97 TPY
Buda	87% 1,290,000 TPY	2% 59 TPY	99+% 1,821 TPY	97.5% 115 TP	93% 121.8 TPY

* TPY=tons per year. Calculation of % Reduction is (Original Emissions less Emissions w/ Pre-Treatment and CO₂ capture, including new auxiliary boiler)/(Original Emissions).

Table 4: Comparison of CO₂ Capture Costs for Mojave and Buda Cement Plants

	Mojave	Buda
Annualized Costs (\$MM/yr)		
Annualized Capital Cost	30.7	30.8
Annualized Energy Cost	100.3	48.8
Other Annualized Costs	32.2	35.6
Total Annualized Costs	163.2	115.2
Contribution to Cost of Cement CO₂ Capture (\$/ton cement plant CO₂ Captured)		
CO ₂ Capture and Compression	113.7	74.9
Add-on Pre-Treatment Controls	11.6	11.9
Total Cost of Add-on Controls and CO ₂ Capture	125.3	86.5
Contribution to Cost of Total CO₂ Capture (\$/ton cement plant CO₂ + Aux Boiler CO₂ Captured)		
CO ₂ Capture and Compression	88.5	58.3
Add-on Pre-Treatment Controls	9.0	9.1
Total Cost of Add-on Controls and CO ₂ Capture	97.5	67.4

Changes to emissions of other pollutants

The PM reductions associated with adding carbon capture systems to these facilities will reduce emissions of PM-related hazardous air pollutants (HAPs), including:

- **From cement kilns:** Metals (compounds containing arsenic, cadmium, chromium (VI), cobalt, lead, beryllium), particulate divalent mercury, manganese chloride and selenium compounds.
- **From refinery FCC units:** Metal compounds (containing titanium vanadium, chromium (VI), chromium (III) iron, cobalt, zinc barium, lanthanum, cerium, praseodymium, neodymium, samarium, gadolinium, sodium, magnesium), nickel dust, and particulate divalent mercury.

In our case study facilities, adding carbon capture reduced PM emissions by more than 90%. Consequently, these PM HAPs are reduced by a similar percentage. The absorber tower, which captures CO₂ by bringing it into contact with an amine solvent, also releases VOCs (including some HAPs) that are not present in the uncontrolled plants. These can include amine that slips through the absorber and amine degradation products. The carbon capture absorber system includes controls such as a water wash to limit release of amine and amine degradation products.

CATF estimated VOC emissions from the CO₂ absorbers for each of our case study capture systems based on monitoring of VOC levels from the Petra Nova carbon capture project. Although the Petra Nova permit had a limit of 24.53 tons per year of VOC, the monitored VOC levels were only 2.84 tons per year.⁹

The emissions estimated below were normalized to the amount of CO₂ that would be captured at each of the four plants we studied. It is important to recognize that this data does not reflect each amine that has been proposed for use in a capture system nor every capture system design; different amine solvents can release different levels and types of VOCs and different capture unit designs may successfully prevent VOC emissions to different degrees.

Table 5 provides estimates for the anticipated VOC levels based on three years of monitoring data from Petra Nova. Note that these figures represent an increase in emissions compared to the no-carbon-capture base case (by contrast, all the figures shown in Tables 1 and 3 represent emission *reductions* relative to the base case). The estimated VOC levels are also presented as a percentage of the current plantwide VOC emissions reported in the National Emission Inventory.

Table 5: Estimated Increase in VOC Emissions

Facility	Estimated VOCs Based on Monitored Levels (short tons per year)
Martinez refinery	2.78 (0.14%)
Beaumont refinery	2.99 (0.24%)
Mojave cement plant	2.81 (14%) ¹⁰
Buda cement plant	2.87 (1.5%)

⁹ <https://www.osti.gov/servlet/url/1608572> 52. The specific VOCs emitted at Petra Nova were not identified. The individual VOCs were identified in the permit for Project Tundra, a coal plant CCS project in North Dakota. The Project Tundra air permit indicated that formaldehyde, acetaldehyde and acetone can occur as breakdown products when the amine solvent is exposed to oxygen.

¹⁰ The reported current VOC emissions at the CalPortland facility are significantly lower than at the other plants and therefore a similar increase in VOCs from the capture unit result in a higher percentage increase at CalPortland.

CATF also conducted a sensitivity analysis to evaluate how potential emissions of VOCs, including nitrosamines, from the carbon capture system compare to EPA health standards. Certain amines can form nitrosamine as a breakdown product through reactions with nitrate or nitrite in the flue gas. Extensive monitoring for nitrosamines conducted on carbon capture systems using such amines in Norway found that use of a water wash limited nitrosamines to below the detection limit.¹¹ Because nitrosamine levels were below the detection limit, CATF is unable to accurately estimate potential

nitrosamine emissions below that level. As a sensitivity analysis, CATF had SC&A evaluate the potential risks if the most harmful type of nitrosamine was consistently at levels just below the detection limit, a scenario that is unlikely given that the detection limit was never exceeded, as well as the monitored VOCs found at the Petra Nova project.¹² Even in this case, SC&A determined that health risks from the plant after adding the carbon capture system remained an order of magnitude below EPA's "ample margin of safety" threshold.¹³

¹¹ Multiconsult, *Karbonfangstanlegg Norcem Brevik Konsekvensutredning* [Carbon Capture Plant Norcem, Brevik Consequence Investigation] (Nov. 1, 2019), Doc. No. 130435-PLAN-RAP-02; Jacob N. Kudsén et al., *Pilot plant demonstration of CO₂ capture from cement plant with advanced amine technology*, 63 *Energy Procedia* 6464 (2014).

¹² For the SC&A analysis, CATF used the VOC speciation provided in the air quality permit application for Project Tundra.

¹³ The SC&A analysis also showed that even with these conservative nitrosamine assumptions the overall risk from hazardous air pollutants at the cement plants declined.

SECTION 4

Results from the Health Impacts Assessment

Table 6 summarizes results from CATF’s analysis of potential health benefits from criteria pollutant emission reductions at our case study facilities following the installation of carbon capture and flue gas pretreatment systems. As discussed in the foregoing methodology section, these results were generated using COBRA and are driven by reductions in ambient PM_{2.5}, which are a function of both direct PM_{2.5} emissions and secondary PM_{2.5} formation from precursor pollutants. Note that the estimates of monetized health benefits shown in the table reflect mortality impacts only.

In terms of health impacts, by far the largest benefit is seen at the PBF refinery in Martinez, California. This reflects both the high emissions—and hence large emission reductions—modeled for this facility and its relative proximity to the San Francisco Bay area, a major population center.

Table 6: Summary of Annual Public Health Benefits

Facility	Reduced Annual Mortality (low estimate)	Reduced Annual Mortality (high estimate)	\$ Total Annual Health Benefits (low estimate)	\$ Total Annual Health Benefits (high estimate)	Top Counties*
Martinez refinery	27.4	62.1	305,666,000	687,188,000	Contra Costa, San Joaquin, Alameda, Stanislaus, Los Angeles, Fresno, Santa Clara, Sacramento
Beaumont refinery	2.2	5.0	24,464,000	55,144,000	Jefferson, Harris
Mojave cement plant	2.5	5.6	27,640,000	62,176,000	Kern, Los Angeles, Ventura
Buda cement plant	5.5	12.5	61,660,000	138,931,000	Hays, Travis, Bexar, Williamson

*Note: Counties are listed in order of their contribution to total health benefits. All the counties listed are in the same state as the subject facility.

SECTION 5

Discussion

This analysis demonstrates that adding carbon capture to the selected cement and refinery facilities would result in substantial public health benefits due to the reduction in conventional air pollution. These reductions are required as part of the proposed carbon capture installations because cleaning the flue stream is necessary to the effective functioning of the carbon capture equipment. Among the plants studied, the size of the public health co-benefits is a function of the level of pollution emitted by the plant prior to adding a carbon capture system and the number of people in the surrounding community. For example, the Martinez FCC unit has fewer pollution controls than the Beaumont FCC and thus the pollution reductions achieved at Martinez would be greater than at Beaumont. Importantly, in all of the four plants considered, the conventional pollution reductions result in significant public health improvements and lives saved alongside the significant carbon pollution reductions.

Cost has traditionally been a barrier to installation of carbon capture. In our analysis, estimated CO₂ capture costs range from as little as \$60 per ton at the Beaumont, Texas refinery to as much as \$132 per ton at the Martinez, California refinery. We did not attempt to estimate costs for CO₂ transport and storage, but based on other studies, these costs would be expected to add no more than about \$15 per ton.

In addition, the reduction in conventional air pollution may also result in additional savings or value for the facilities. More broadly, the large public health benefits identified by this analysis indicates that the total climate and public health benefits achieved by adding carbon capture are well in excess of the costs of such equipment, with combined benefits ranging from \$260-295 million per year at Mojave to \$536-918 million per year at Martinez.¹⁴ The total benefits were 1.5 times greater than costs at the low end and 4 times greater than costs at the high end, with an average of 2.6 times more benefits than costs. This confirms the overwhelming public value of implementing such projects, whether through additional public support or adoption of pollution standards.

¹⁴ The cost of carbon pollution used is based on the analysis by Rennert et al, *Comprehensive Evidence Implies a Higher Social Cost of CO₂*, <https://www.nature.com/articles/s41586-022-05224-9>.

SECTION 6

Study Limitations

Our study is an example of desk research: the estimates we report were developed using modeling tools, engineering analyses, and data reported in the literature. To better understand cost and emissions impacts in practice, more carbon capture and storage equipment must be deployed and changes in pollution monitored and assessed. A second limitation is that our study design evaluated facilities with relatively high criteria pollutant emissions. Adjustments would need to be made to extrapolate from these results to a wider set of facilities, some of which would start from a baseline of lower emissions.

Other limitations of our study approach, however, may tend to overstate costs and understate emissions benefits. As with nearly all new technologies, carbon capture systems can be expected to improve as they evolve and as operators gain experience with commercial-scale applications. The 90% capture rate analyzed does not reflect the upper limit of possible capture rates; recent studies indicate that capture rates of 95% or higher are achievable. Cleaner and more efficient CO₂ absorption methods, for example, could

reduce costs while also reducing emissions associated with the capture system. As we have already noted, a new generation of solvents may offer improved performance, reduced cost, and lower VOC emissions relative to MEA, the older, non-proprietary solvent assumed for this analysis. In addition, other carbon capture technologies like cryogenic capture are being developed that could result in even greater criteria pollutant reductions and no amine-related VOCs.¹⁵

The analysis also does not account for potential offsite emissions from the additional electricity consumption associated with operating a carbon capture system, or carbon dioxide transport and storage. Emissions from offsite electricity generation would depend on the local power mix. There are several options available to mitigating offsite impacts—for example, purchase of low-carbon sources of electricity to power carbon capture equipment; design of capture systems to use (and capture emissions from) internal (on-site) sources of energy; and reduction in energy needed for carbon transport by selecting sequestration sites located close to capture sites.

¹⁵ https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3819906



SECTION 7

Conclusion

This analysis of carbon capture opportunities at four large industrial facilities in California and Texas shows that **adding carbon capture would achieve both deep reductions in carbon pollution and significant reductions in other pollutants that harm our health.** Accounting for these combined reductions increases the public benefits of adding carbon capture systems. At all the units studied, modeled CO₂ emissions were reduced by close to 90%, emissions of SO₂ were nearly

eliminated, and particulate emissions were cut by more than 90%. Impacts on NO_x emissions were more varied, due to the nature of NO_x formation, with minimal expected benefits at the two cement plants but more significant reductions modeled for the refinery cases. While reductions in conventional pollutants are expected at all facilities in these categories, the magnitude of the improvement will depend on how clean a facility is before the addition of carbon capture.