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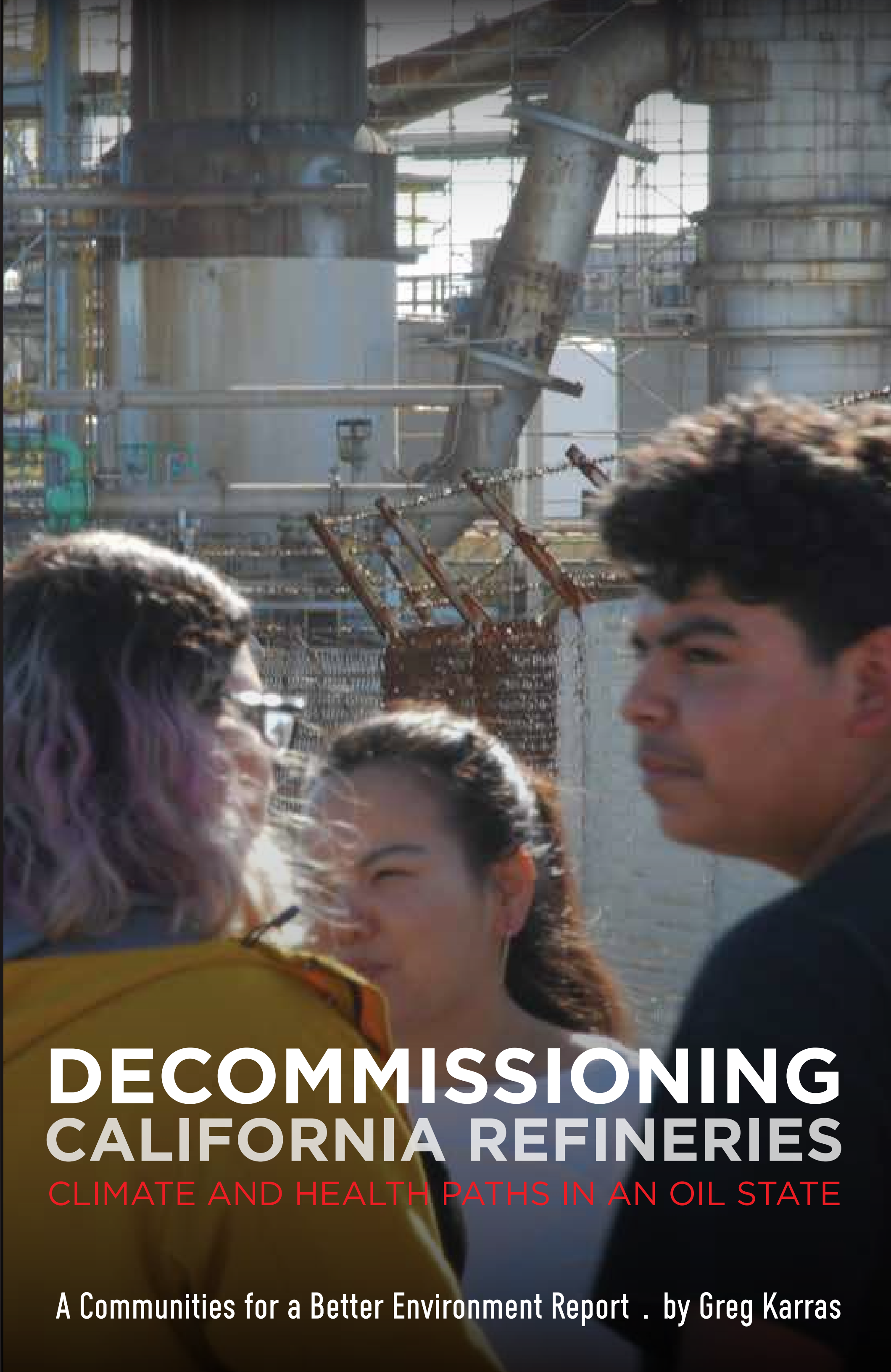
DECOMMISSIONING CALIFORNIA REFINERIES

A CBE Report . July 2020



DECOMMISSIONING CALIFORNIA REFINERIES

CLIMATE AND HEALTH PATHS IN AN OIL STATE

A Communities for a Better Environment Report . by Greg Karras

DECOMMISSIONING CALIFORNIA REFINERIES:

CLIMATE AND HEALTH PATHS IN AN OIL STATE

JULY 2020

A REPORT FOR
Communities for a Better Environment
Huntington Park, Oakland, Richmond, & Wilmington, California
www.cbecal.org

BY
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COMMUNITIES FOR A BETTER ENVIRONMENT (CBE) is a community-based environmental justice nonprofit group founded in 1978. CBE provides residents in blighted and heavily polluted urban communities in California with organizing skills, leadership training and legal, scientific and technical assistance to successfully confront threats to their health and well-being. CBE's mission is to build people's power in communities of color and low income communities to achieve environmental health and justice by preventing and reducing pollution and building green, healthy and sustainable communities and environments.

Relevant to this report, CBE's work for and with communities on the frontlines of the largest oil refining center in western North America has, over four decades, built uniquely independent site-specific knowledge and expertise regarding oil in California.

ACKNOWLEDGEMENTS

Many people helped to make this report possible in many ways. For their seminal work this research builds upon, gracious sharing of ideas and insights on various parts of the analysis, or both we wish to thank Ken Alex, Adrienne Bloch, Dave Campbell, Danny Cullenward, Steven J. Davis, Bill Gallegos, Erica Kent, Matt Krogh, Heather Kuiper, Ratha Lai, Roger Lin, Alan Lloyd, Jose Lopez, Elsa Monroe, Rachel Morello-Frosch, Steve Nadel, Simon Mui, Manuel Pastor, Alan Ramo, Jim Sadd, Mike Smith, Camille Stough, Janet Stromberg, Margaret Torn, Kelly Trout, Shoshana Wechsler, V. John White, James Williams, and Isabella Zizi.

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Most of all, CBE's members made this possible. It's no accident that CBE built independent, site-specific oil sector expertise over four decades in California. Our communities shared site-specific knowledge, framed crucial questions, and supported independent research to answer them, and did so consistently over 40 years.

Any error or oversight in this independent analysis is solely ours.

Thank you all!

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Cover photo: CBE
Printed with union labor.

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Supporting material is available online.
See Reference 1 herein.

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AUTHOR'S NOTE

Plague struck as this report went to press. Even as the virus, the partial economic shutdown to control it, and the injustice leaving black, brown, working class and institutionalized people more vulnerable take still more lives and livelihoods, *how to rebuild* is in question. Oil and gas activities were expected to rebound quickly and, potentially, to retrench thereafter.[1–3] † Authoritative assessments warned of lasting damage to prospects for stabilizing our climate at 1.5–2°C above pre-industrial levels in the absence of systemic structural change.[3, 4] The International Energy Agency called on governments and banks to rebuild the economy by investing in renewable energy instead of fossil fuels.[4] In short, side effects of the pandemic have proven relevant to what this report is about.

REFINING EFFECT: CAPACITY IDLED FOR WEEKS

Chart A illustrates a side effect of the virus on refining rates. Between March 20 and May 30, 2020, while personal travel was paused after California's March 19 shelter in place order, refiners in the state made 30 % less gasoline and 56 % less jet fuel than they had in any year of the previous decade.[5] By the first week of May, despite a glut of cheap crude, an unprecedented 33 % of the crude capacity they had used in that week every year for a decade was idled.[5] By mid June refining rates had begun to go back up.[5]

While unsustainable, the pause in travel could only idle refining capacity at all because the links in the petroleum fuel chain are *interdependent*—which is a key theme in the report.

EMISSION EFFECT: ONLY A BLIP

This side effect that idled refining capacity for a few weeks cut well-to-wheel petroleum emissions deeply—for a few weeks.[6] The unprecedented weekly variability since March 2020 (red line in Chart B) changed the annual emissions trajectory (black line) less in 2020 to date than it changed in prior years. The net effect on cumulative emissions (the shaded area under the black line) is weak. Cumulative emissions from 2013 to June 2020 changed

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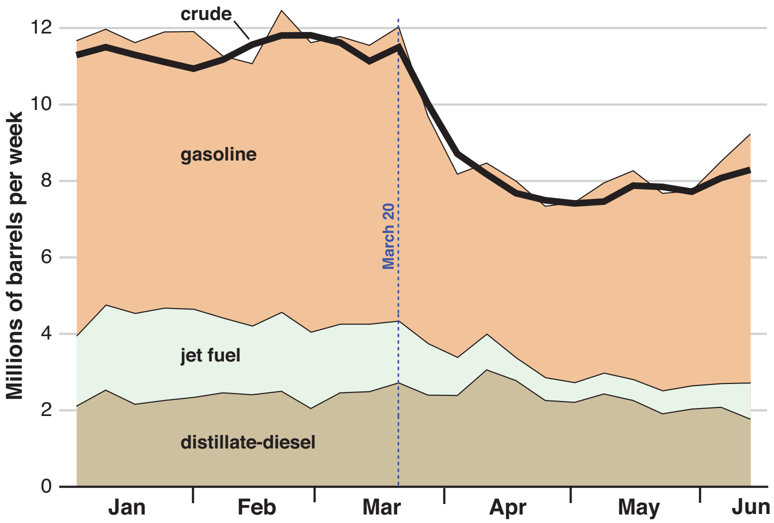
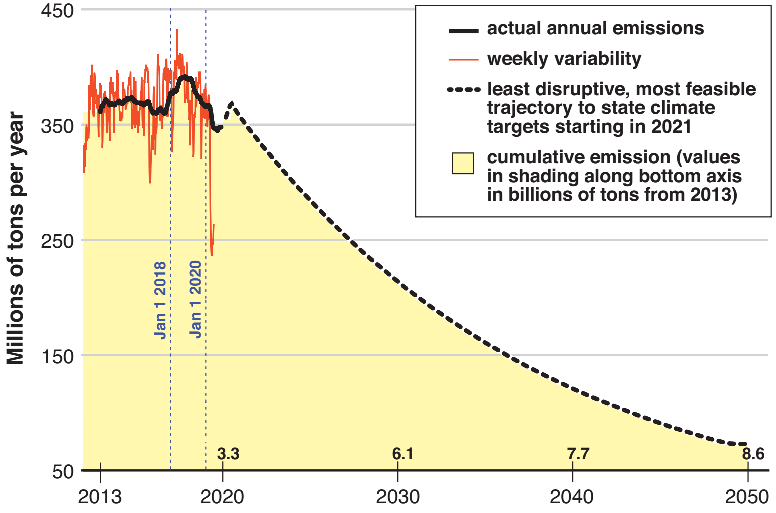
† References cited in this author's note are given on page iv.



A. California oil refining rates, January to mid-June 2020.[5]



B. CO$_2$e emissions from extracting, refining, and burning the oil refined in California assuming the least disruptive, most feasible path to state climate targets starting in 2021.[5–7] **Ton:** Metric ton little (+ 0.5 %) compared with those if the annual emissions had remained unchanged at their 2013–2017 rate. And by mid June the expected oil rebound[1–3] appeared to have begun (Chart A).

Year on year emission cuts of the same 4–7 % magnitude now expected in 2020 will be needed to hold global heating at 1.5–2°C.[3] The dashed black line in Chart B shows this for emissions from oil refined in California based on current information.[7] But this smooth trajectory shown assumes that sustained refining rate cuts start in 2021. Delay could force the annual refining rate cuts needed for meeting state climate targets to deepen exponentially, forcing them to dive from 20 % per year toward 80 % per year starting in 2026–2030.[7] That is the same timing of potential impacts from delay documented in this report.

The plague has not bought us time in our climate crisis.

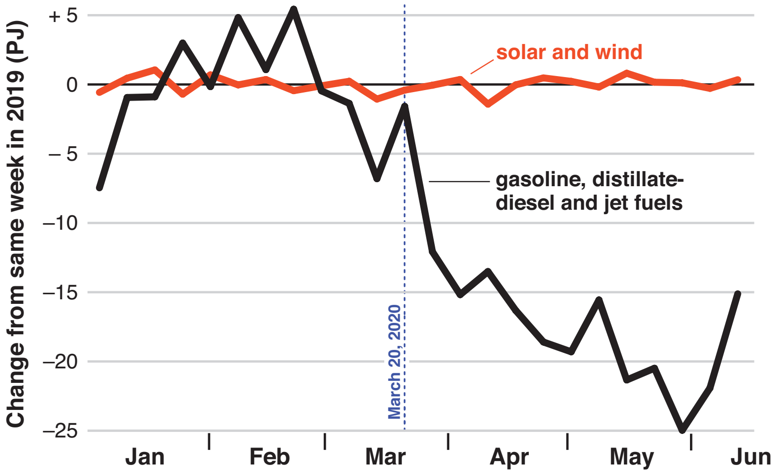
ENERGY EFFECT: A DIFFERENCE IN RESILIENCE

As California refining assets became unproductive in the weeks after the shelter in place order,[8] built investments in solar and wind power did not.[9] (Chart C.) And a similar pattern emerged globally.[1] This suggests that the resilience of clean electricity investments in future crises may be an under-appreciated advantage of decarbonizing transportation.

FOR THE FUTURE

Peoples' collective public health response to this virus began to change our energy system. But that unintended side effect is temporary. It was unplanned, sudden, and achieved by means too unjust to sustain year after year. The window for organizing gradual, smooth, *just* transitions to sustainable energy is closing. Our future is at stake.

Greg Karras
June 22, 2020



C. Oil refining *v.* solar and wind power: change from 2019 in California fuel energy production.[8, 9] **PJ:** Petajoule; 278 MWh.

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(1) Adam et al., 2020. *Global Energy Review 2020: The impacts of the COVID 19 crisis on global energy demand and CO_2 emissions.* Revised April 2020. International Energy Agency: Paris, FR. www.iea.org.

(2) *Short-Term Energy Outlook;* U.S. Energy Information Administration: Washington, D.C. June 9, 2020. https://www.eia.gov/outlooks/steo.

(3) Le Quéré et al., 2020. Temporary reduction in daily global CO_2 emissions during COVID-19 forced confinement. *Nature Climate Change.* https://doi.org/10.1038/s41558=020=0797-x.

(4) McGlade, C., and Wetzel, D. 2020. *Sustainable Recovery: World energy outlook special report in collaboration with the International Monetary Fund;* International Energy Agency: Paris, FR. www.iea.org.

(5) *Fuel Watch;* California Energy Commission: Sacramento, CA. https://ww2.energy.ca.gov/almanac/petroleum_data/fuels_watch/index_cms.html.

(6) Emissions to date estimated from crude vol. refined in state (ref. 5) and mean 2013–2017 petroleum fuel chain carbon intensity shown in this report.

(7) Trajectory to state climate targets estimated from recent data (ref. 6) and forecasts to 2021 (ref. 3) based on methods described in chapters 1–3 and tables S1–S17 of this report assuming (a) sustained petroleum emission cuts starting in 2021, (b) no change in the carbon intensity of oil, and (c) all non-petroleum emissions meet state targets. Importantly, delaying the start of sustained cuts until after 2025 would result in much steeper trajectories than that shown.

(8) From refined fuel volumes (ref. 5) and energy contents (Table 6, this report).

(9) *Renewables Watch;* California Independent System Operator: Folsom, CA. www.caiso.com/market/Pages/ReportsBulletins/RenewablesReporting.aspx.

Photo: CBE

Pathway (climate): A road map for the array of technologies and measures to be deployed over time, and for the cumulative climate emission trajectory associated with this sequence of actions. Path.

EXECUTIVE SUMMARY

This report compares emission, transition, and investment impacts of pathways that could be taken in California to identify the most feasible paths for climate and health protection. It focuses on oil—the most entrenched fossil fuel in this state.

Here, "climate protection" means meeting the state's 2050 climate limit. This cumulative emission limit is defined by state climate targets, and represents the state's share of global emission cuts for a better-than-even chance of holding global heating to between 1.5°C and 2°C above pre-industrial levels.

Major findings of this work and some immediate implications of these findings for policy actions are summarized below.

FINDING 1: **Phasing down oil refining is pivotal to climate and health in California.**

Emissions from burning oil accounted for nearly two-thirds of statewide carbon emissions and continued to increase from 2013–2017. From extraction to refining to refined fuels combustion in transportation and industry, the petroleum fuel chain is a series of interdependent and inherently polluting steps or "links." Breaking one link in the chain can cut emissions across the whole fuel chain. In California this link is refining. Refiners here are increasing production by importing more crude and exporting more product. They now import two out of every three barrels of crude refined here and export 20–33 percent of all fuels refined here. This means actions that limit refining here can cut emissions across the petroleum fuel chain.

FINDING 2: **To achieve California's climate and health protection goals refineries must process less oil.**

Even if all non-petroleum emissions are cut to their share of the state's 2050 climate limit *and* every measure to reduce petroleum fuel chain carbon intensity that is proven in practice is used, total statewide emissions will exceed the limit. Emissions from 2017–2050 exceed the climate limit by ≈ 4,800–8,350 million metric tons, or 46–79 %, without refinery feed rate cuts. Particulate matter (PM$_{2.5}$) co-emitted with this 4,800–8,350 Mt petroleum fuel chain CO$_2$e emission excess could kill ≈ 22,000–38,000 people through 2050. All paths to climate and health protection that are known to be feasible involve refining much less oil.

FINDING 3: **Paths to the climate limit that start now to decommission refining capacity minimize transition impacts.**

Pathways to the state's 2050 climate limit that start to cut oil use sooner allow decommmissioning more gradually. Starting now, in 2020–2022, the limit can be met by retiring only 4.4–8.6 percent of refining capacity annually. This gradual pace can be met for years by retiring export capacity, thus minimizing the risk of fuel price spikes for California drivers. Developing already-proven sustainable alternatives to replace communities' oil-dependent taxes and jobs at this rate would be hard work, but doable with transition support. Since refining is a jobs-poor business, this could create more jobs.

> *Our most feasible paths to climate and health protection decommission refining capacity gradually by starting to decommission it now.*

In contrast, waiting until 2027–2031 could force steep refining losses of 20–80 % per year to meet the limit. And waiting until 2033 would force as much as 90 % of all oil refining capacity to be lost in only one to three years on the remaining technically feasible paths which could still meet the climate limit by then.

FINDING 4: **Paths to the climate limit that start now to decommission refining capacity minimize stranded assets.**

California refiners over-built. Some refining capacity will not wear out before it must be decommissioned to meet the state's climate limit. Even if no new projects expand refineries, to meet the limit, otherwise operable capacity must be decommissioned at rates of 2.7–3.4 percent per year if we start now, 21–62 % per year starting in 2031, and 62–88 % per year starting in 2033. This means we can expect that refiners will fight even harder to keep using their climate-stranded assets if we wait until later to start decommissioning.

FINDING 5: **Paths to the climate limit that start now to decommission refining capacity support just transitions.**

Just transitions could make our path to climate stabilization feasible *politically*. When we cannot take the collective actions we must take to survive, our solution is clear: help each other. We could extend our social safety net to workers, families, and communities that now depend on oil taxes and jobs, extend our toxic site cleanup policies to clean up the toxicity that oil dependence has left in the soils and economies of our communities, and target support where it is needed most. But how much of this we can do for how many quickly enough depends on the path of transformative change we choose. Gradually retiring and replacing ≈ 5–7 % of our oil dependence annually over 30 years from 2020–2050 supports just transitions. Waiting until after 2030 and then being forced to replace nearly all of it in just a few short years to meet our climate limit does not.

> *To ensure a sustainable future, we had better start using all the tools in the policy toolbox.*

FINDING 6: **State policy threatens to foreclose feasible paths to the state's 2050 climate limit.**

State policy prohibits state agencies from applying plant-specific carbon cutting limits and other technology-forcing measures to refineries under the state's carbon trading scheme. This carbon trading-only policy for refining has failed to cut petroleum fuel chain emissions or incentivize a switch from oil to sustainable alternatives. Further, it failed because of inherent limitations of carbon trading that appear unresolvable. But state law mandates this failed policy through 2030. That could irreversibly foreclose our most feasible paths to climate and health protection.

SOME STARTING POINTS

This research suggests some immediate, technically feasible and mutually-reinforcing actions which, taken together, would help to ensure that achieving climate and health protection could be economically sustainable for all Californians—and thus, more likely to prove feasible *politically*. Communities could organize to hold our public officials accountable for these actions:

Support just transitions

1. Extend our social safety net so that all those whose jobs or communities are now dependent on oil are guaranteed support for job transition, health care, college tuition, housing, and retirement security. *State* officials could take this action.
2. Establish Just Transition Bonds to remedy site-specific legacy impacts, including pollution and deferred development of sustainable economic alternatives. Secure a Bond from each refiner up front to ensure against abandonment upon closure. *City, county,* and *state* officials could take this action.
3. Quantify local taxes and fees paid by oil companies and develop sustainable alternatives to replace these revenues locally as refineries decommission. *City* and *county* officials could take this action.

Decommission refining capacity

4. Acknowledge that quickly starting a gradual decommissioning of refining capacity is an essential part of the most feasible paths to achieving state climate goals with proven technology. The state's *Air Resources Board* could take this action.

5. Set facility-specific refinery combustion emission limits on pollutant mass and oil feed throughput which decrease at rates needed to ensure that state climate and health protection goals are met (e.g., –5 % or –6 % per year starting in 2020 or 2022, respectively, assuming action number 9 below). *City, county, regional* and *state* officials could take this action.
6. Ensure that California's transportation fuel-switching effort outpaces its need to decommission refining capacity through aggressive measures to ensure clean mobility for all people. *State* officials could take this action.

Change the rules

7. Challenge the environmental injustice of permitting harmful refinery emissions solely to export fuels that Californians do not use or need. *City, county, regional* and *state* officials can take this action.
8. Revise state law to rescind the exemption from carbon-cutting emission limits on refineries and the carbon trading-only policy for oil refining enacted by Assembly Bill 398 in 2017. *State* legislators and *Governor Newsom* could take this action.
9. Reject new construction projects that would expand or prolong the operable duration of oil refining capacity. *Governor Newsom* could take this "moratorium" action by executive order. Alternatively, *communities* can continue to hold public officials accountable for rejecting these projects.

From well to wheel, extracting, refining and burning fuels made from the oil refined in California emits more carbon than all other activities in the state combined.

INTRODUCTION

Machines that burn oil are going away. We will burn much less oil, either to prevent the increasing accumulation of pollution impacts that could cause the collapse of human societies as we know them, or as a footnote to the collapse of our societies and economies on which the petroleum fuel chain now feeds. Which path we take matters.

Sustainable energy technologies that are proven, available now, and obviously more economic than societal collapse could replace oil and other fossil fuels. But critical oil infrastructure, permitted mainly in working class communities and communities of color, is still growing. Environmental, economic, and racial injustice weaken societal capacity to break free of this toxic path. Societal capacity to organize—political feasibility—has emerged as the primary barrier to solving our existential pollution crisis.

California has this problem. It hosts the largest oil refining center in western North America. It has the worst air pollution in the nation, and yet it has allowed its oil sector's critical infrastructure to grow in low-income communities of color, where this pollution is disparately severe compared with the state average. It uses pollution trading—the exchange of money for permits to pollute—leaving communities largely on our own to fight refinery and oil terminal expansion projects.

Communities rose up to stop tar sands projects in many inspiring efforts that for a decade have held to a trickle the flood of cheaper, dirtier oil that refiners sought. But some projects slipped through. The petroleum fuel chain emits more carbon from extracting, refining, and burning fuels made from the oil refined in California than all other activities in the state combined, and as other emissions have begun to decline, its emissions have not.

In fact its emissions increased from 2013–2017 as refiners here increased production for exports that sold for more money than the entire oil sector spent on permits to emit under the state's carbon trading scheme. They could do that because no refiner faced any limit on carbon emissions from its plant. They still can because politicians caved in to their demand to make carbon trading the *only* curb on those emissions. Since 2017, state law has prohibited state air officials from setting a carbon-cutting limit on any oil refining plant under this carbon trading scheme.

Governor Brown argued this law was the best "compromise" that was politically feasible. Yet state climate policy has ignored the need, first voiced by the Oil, Chemical & Atomic Workers Union decades ago, for a mandate that assures workers a just transition.

Equally important to political feasibility, communities must predict how fast to transition their job and tax bases from oil to sustainable alternatives. But by letting any polluter delay emission cuts at any time, pollution trading makes it harder to make this very prediction.

Our situation raises a crucial question:

> **What is the least-impact, most socially just, most feasible path to climate and health protection in California?**

Despite its claims to climate leadership, the state has not answered or even defined this question specifically for the oil sector in California. Instead, it has relied on the oil companies and other carbon emitters to figure it out under a carbon trading program called cap-and-trade. When pressed for its own independent analysis at its Climate Scoping Plan Hearing on December 14, 2017, California Air Resources Board Chair Mary Nichols explained:

> "That's the point of cap-and-trade … we think that the people who have these emissions are smarter about where they can get the reductions cheaper, and that's what they will do."

And so it is that, in our crisis with oil, we have to find our own way. Research reported here reveals specific answers to this question about the least-impact, most socially just, most feasible path to climate and health protection in California.

Cumulative emissions to 2050 were estimated for the extraction, refining, and refined fuel combustion associated with oil refined in California along 161 potential pathways. A "pathway" is a road map for the array of technologies and measures to be deployed over time and for the emission trajectory to be caused by these actions.

High quality local, state, and federal data on current conditions were assessed to define the starting point for these paths, as described in Chapter 1, *Decoding the Petroleum Fuel Chain in California*. This fuel chain emits from the extraction, refining, and combustion of fuels made from oil refined here. It imports crude on top of the crude extracted here. It exports refined fuels on top of those burned in transportation and industry here. Its local and global footprint is driven by the quantity and quality of oil feeding refineries in California.

Pathways are defined and differences among them are described in chapters 2 and 3. Paths assessed span the range of plausible future emissions per barrel of oil used, oil usage rates (refinery feed rates), and start dates for refinery feed rate reduction (decommissioning) through 2050.

Pathways' emission impacts were compared based on the state's climate targets and the risk of premature deaths from breathing co-emitted $PM_{2.5}$ air pollution. State climate targets quantify a

path of continuously declining emissions that add up to a total cumulative emission limit through 2050. This climate limit is consistent with the state's share of global emission cuts for a 67 % chance of holding global heating to between 1.5°C and 2°C. The comparisons used a conservative best-case assumption that all other, non-petroleum emissions will be cut to their share of the climate limit. Chapter 2 describes these analyses.

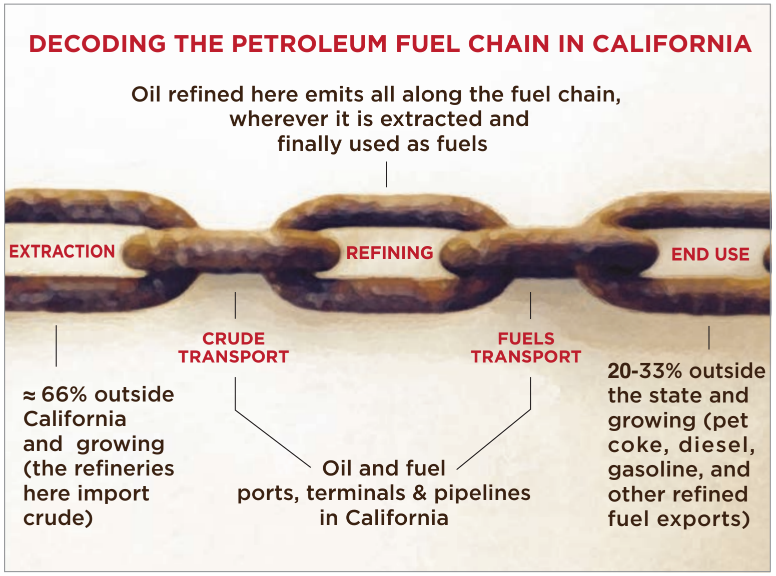
Transition impacts along paths to the climate limit were compared based on the pace of refinery decommissioning to meet the limit and refining capacity that could remain in service through 2050 along each pathway. These analyses are described in Chapter 3.

Stranded asset impacts along pathways to the climate limit were compared based on the refining capacity that could remain in service if it is used for its operable duration. Operable duration was estimated from data on actual usage of critical equipment in California refineries. Chapter 4 describes these analyses.

Based on the results of these analyses paths were compared to inform just transition plans and responses to the failure of current oil sector policy. These comparisons reveal crucial differences in the extent of disparately severe localized transition impacts between early action and delayed action paths, and the critical role of social justice to the feasibility of climate stabilization.

Chapters 5 links the state's climate policy failure with oil to inherent limitations of carbon trading that threaten to foreclose feasible pathways to climate stabilization. Chapter 6 describes some opportunities that emerge from this research for strategic action and sustainable climate and health policy, in a blueprint for organizing just transitions out of our crisis with oil.

A glossary is included at the back of this book to help to solve the mystery of any unfamiliar terms you might find in the text. Data and methodological details of this research are given in a separately bound "Supporting Material" appendix that is available online free of charge.[1]



1. DECODING THE PETROLEUM FUEL CHAIN IN CALIFORNIA

Current conditions define the starting point for any path into our future. Finding our way depends in large part on decoding the petroleum fuel chain in California—the sequence of interdependent links in a fuel chain that extracts oil, refines it here, and burns refined fuels in motor vehicles, aircraft and industry. Conditions that define our starting point include the current function, setting, and emissions footprint of this fuel chain, and what is changing it.

FUNCTION

Petroleum fuels transportation. Gasoline, distillate-diesel and jet fuel account for some nine-tenths of California refinery fuels production.[1] Oil-based fuels supply more than 90 % of transportation energy needs in California today,[2] refiners here supply those fuels, and gasoline and distillate-diesel oils—the ground transportation fuels—account for more than 80 % of the statewide refined fuels production that is used here.[1]

But the oil industry's political assertion that this dependence on oil is necessary and good for our economy is simply false.

As early as 2011, Williams and colleagues showed that an array of proven technologies featuring decarbonized electricity and electric-drive transportation could be deployed economically over time to meet California's climate targets.[3] Since then they showed that this pathway could work in the U.S. as a whole.[4] Electric cars go three times as far per unit fuel energy as gasoline cars.[5] And while the old combustion technology is mature,[6] the new technology will improve. By 2015, as measured by total ownership cost with subsidies, battery-electric cars already appeared less expensive than petroleum cars in the United Kingdom, Japan, Texas—and California.[7]

Meanwhile, ten of the last 11 U.S. recessions followed on oil price spikes.[8] Even at recent, relatively stable-to-low oil prices,[9] crude oil imports[1] cost California an estimated $27.6 billion annually. And oil is a capital-intensive, jobs-poor technology. Federal employment and revenue data[10] show that oil refining employs the fewest people per dollar economic activity of any sector in California's economy.

GASOLINE IS AN OUTDATED TECHNOLOGY

Even if burning gasoline wasn't too polluting there's a better way to get get around in cars. Electric cars can go three times as far on the same amount of energy.[5] That's because gasoline-fired cars waste so much fuel energy as heat.

Those fuel savings add up. Looking at the whole cost of buying and driving the car, with current subsidies battery electric cars are cheaper than gasoline cars now by some accounts.[7] By others, with the better batteries that are coming they will be cheaper soon.

How fast things change depends on which technology we permit, build and subsidize. But the laws of thermodynamics won't change: Electricity is a more efficient transportation fuel than gasoline.

If we had solar energy, charging stations and electric vehicles instead of refineries, gas stations, gasoline cars and diesel trucks, we wouldn't switch to oil now. Oil is not the best transportation technology—it is the one that was built here first.

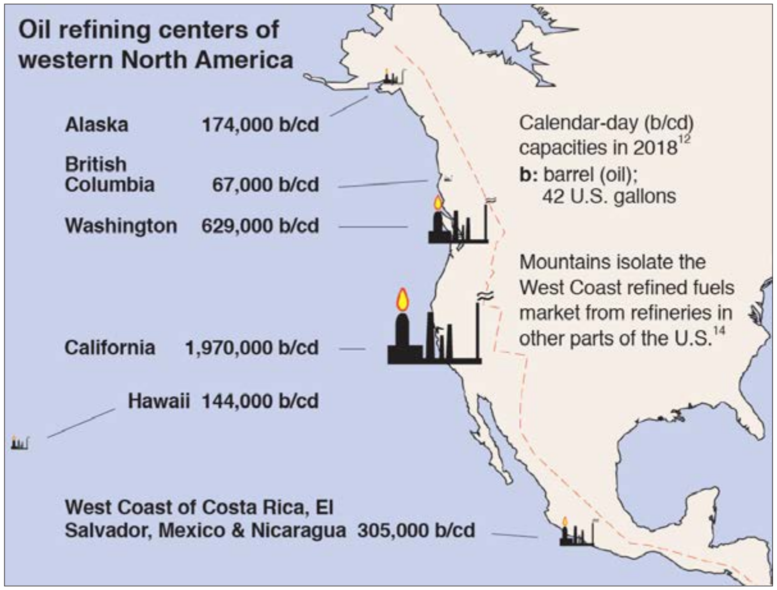
SETTING

The oldest oil refinery operating in the state was first built in 1896.[11] Today, California hosts the dominant oil refining center in western North America. Statewide refining capacity is more than three times that of the next largest western North American refining center, in Puget Sound, WA, and more than six times that of all Pacific-coast Mexico and Central America combined.[12]

1. California refineries in service: Energy Commission data

Company name[a]	Refinery name[a]	Commissioned
Chevron Corp.	El Segundo Refinery	1912
Chevron Corp.	Richmond Refinery	1902
PBF Energy	Torrance Refinery	1907
Phillips 66	Rodeo Refinery	1896
Phillips 66	Santa Maria Refinery	1955
Phillips 66	Wilmington Refinery	1917
Shell Oil Products	Martinez Refinery	1915
Tesoro Rfg. & Mktg.	Carson Refinery	1938
Tesoro Rfg. & Mktg.	Golden Eagle Refinery	1913
Tesoro Rfg. & Mktg.	Wilmington Refinery	1923
Valero Refining Co.	Benicia Asphalt Refinery	1982
Valero Refining Co.	Benicia Refinery	1968
Valero Refining Co.	Wilmington Asphalt Ref.	1980
Valero Refining Co.	Wilmington Refinery	1969
Greka Energy	Santa Maria Asphalt Ref.	1932
Lunday Thagard	South Gate Refinery	1937
Kern Oil & Refining	Bakersfield Refinery	1934

[a] Ownership and names of owners have changed over time, and some companies operate separately-located facilities as one refinery: California Energy Commission data are shown.[11]



Concentrated around the major seaports of the Los Angeles and San Francisco Bay areas, this oil refining behemoth imports twice the volume of crude that is extracted in California. Two-thirds (≈ 66 %) of the oil refined here was imported from other states and nations during 2013–2017.[1] More than three-fourths of the imports were foreign oils, mainly from the Persian Gulf and South America.[13]

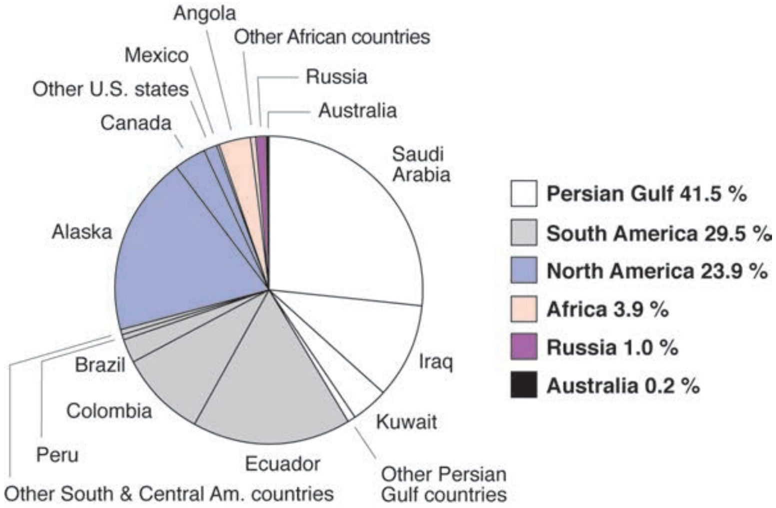
And further buttressing the refiners' position in this setting, mountain ranges effectively isolate the West Coast refining market, which refiners in California dominate, from other U.S. refining districts.[14]

Refiners here export globally. They export transportation fuels mainly to other West Coast states and eastern Pacific nations, and industrial fuels mainly across the Pacific to nations such as Japan, China and India.[14,15] They exported 20–33 % of all the fuels they produced from 2013–2017. The 33 % figure accounts for jet fuel burned in cross-border flights.[1] (*See* also page 93.)

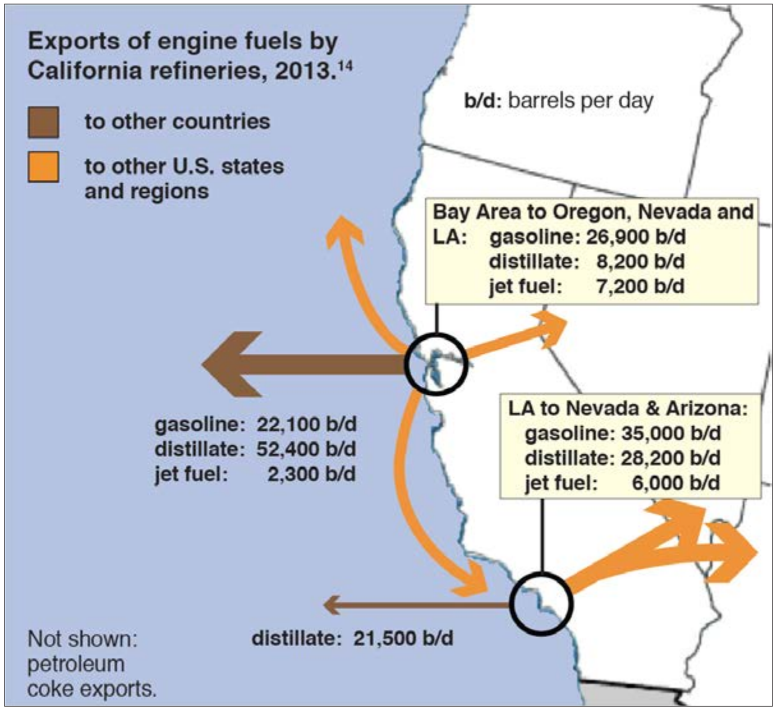
The reach of the fuel chain anchored by oil refining here is growing. Foreign crude imports have grown as crude supplies from California and Alaska dwindle,[16] and foreign exports of refined fuels have grown when West Coast fuels demand declined.[17] Refineries in California imported ≈ 71.2 million barrels (≈ 19 %) more crude from other states and nations and exported 1.20–1.53 billion gallons (17–22 %) more refined fuels to other states and nations in 2017 than in 2013.[1]

> *The environmental footprint of California's oil sector is driven by the quantity and quality of oil refined in the state.*

Oil refining makes crude oil useable. This is the essential link in the middle of the petroleum fuel chain. Without refining, crude could not be used in the transportation and industrial systems we have now, and would not be extracted. The quantity of oil refined is a critical driver of the fuel chain's environmental footprint. But not the only one: the quality of oil matters too, and that has much to do with how refineries make crude oil into transportation fuels.



1. California oil imports by region of the world, 2013–2016.
Global extraction outside the state fed 66% of the 3.01 billion barrels of crude oil refined in the state from 2013–2017.[1,13]



CARBON INTENSITY (CI)

Making engine fuels from denser, more contaminated crude takes more work, which takes more energy. It increases the processing and energy intensities of oil refining.[18] Burning more fuel per barrel for that energy, refiners emit more combustion pollutants.

(See *how refineries work* in the last chapter of this report for more detailed background on this and other side effects of refining lower quality oil.)

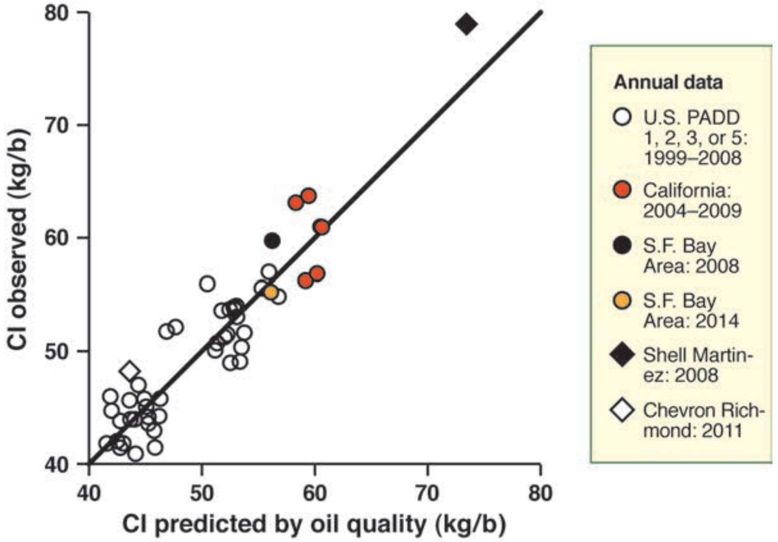
In fact, the quality of crude refined can affect refinery emissions of carbon dioxide equivalents (CO_2e) dramatically.[18–24] Refining the densest crude feed on average, California refineries emit more CO$_2$e, as measured in kilograms emitted per barrel of crude refined, than those in any other major U.S. refining region.[18,22–24] *See* Chart 2.

Notice that instead of the total mass in kilograms (kg), the CO$_2$e emission measurement used directly above is in kilograms per barrel of oil (kg/b). This measures carbon intensity (CI): the amount of climate emission caused by a given amount of activity at a particular emission source. That's useful in a couple of ways. For one thing, it allows us to focus on emissions caused by something else besides the volume of oil that is used—in this case the *quality* of the oil used.

Refining relatively lower quality crude drove California refining CI to a current 2013–2017 average of ≈ 59.3 kg/b.[1] This far exceeds the U.S. average from refining the less dense, better quality current U.S. average crude feed (≈ 49.3 kg/b).[1] But much higher CI is observed among individual refineries (≈ 79 kg/b)[24] and worst-case estimates for refining tar sands-derived oils can substantially exceed 100 kg/b.[18,20] Current statewide refining CI falls within the range of potential future conditions. The same is true for extraction and refined fuels burning.

The CI of extracting the oils refined in California (≈ 89.8 kg/b) exceeds that of the current average U.S. crude feed (≈ 66.1 kg/b),[1] but the extraction CIs of some potential future oil feeds could be as high as ≈ 200 kg/b.[1,20] Similarly, the end-use combustion CI of California refinery fuels production (≈ 462 kg/b, 2013–2017)[1] could be lower or higher depending on how much dirty-burning petroleum coke gets into the future fuels mix as a byproduct of refining lower-quality, denser oil.

A second way this measurement is useful is that, when we know both CI (kg/b) and oil feed rate (barrels), we can know the total mass (kg) emitted and how much each of the two big drivers of oil emissions here—the quantity and quality of oil used—affect these emissions.



2. Oil feed quality predicts refinery carbon intensity.

CI: carbon intensity (kg CO$_2$e/b); refining carbon intensity is shown.

b: barrel (oil). **PADD:** Petroleum Administration Defense District.

Making engine fuels from lower quality oil requires more intensive processing and more energy, burning more fuel and creating more CO$_2$ in refining. The closeness of the observed data to the diagonal line in the chart illustrates how closely oil feed quality predicted the refinery carbon intensity (CI) observed. Data shown are from previous work by CBE and the Union of Concerned Scientists.[18,22–24]

CARBON INTENSITY AND FEED RATE DRIVE MASS EMISSIONS.

Refinery 1 fed 147,000 barrels of oil per day and emitted 11.3 million kilograms of CO$_2$e per day, or about 77 kg per barrel. Refinery 2 fed 144,000 b/d and emitted 8.5 million kg/d or ≈ 59 kg/b. Refinery 3 fed 254,000 b/d and emitted 12.3 million kg/d, or ≈ 48 kg/b. This example is based on actual data from three California refineries.

Refinery 1 emits much more than refinery 2, even though refineries 1 and 2 have nearly the same feed rate, because refinery 1 emits many more kilograms per barrel—its **carbon intensity** is higher.

Refinery 3 emits more than refinery 1, even though its carbon intensity (kg/b) is lower, because refinery 3 processes many more barrels of oil per day—its **feed rate** is higher.

FOOTPRINT

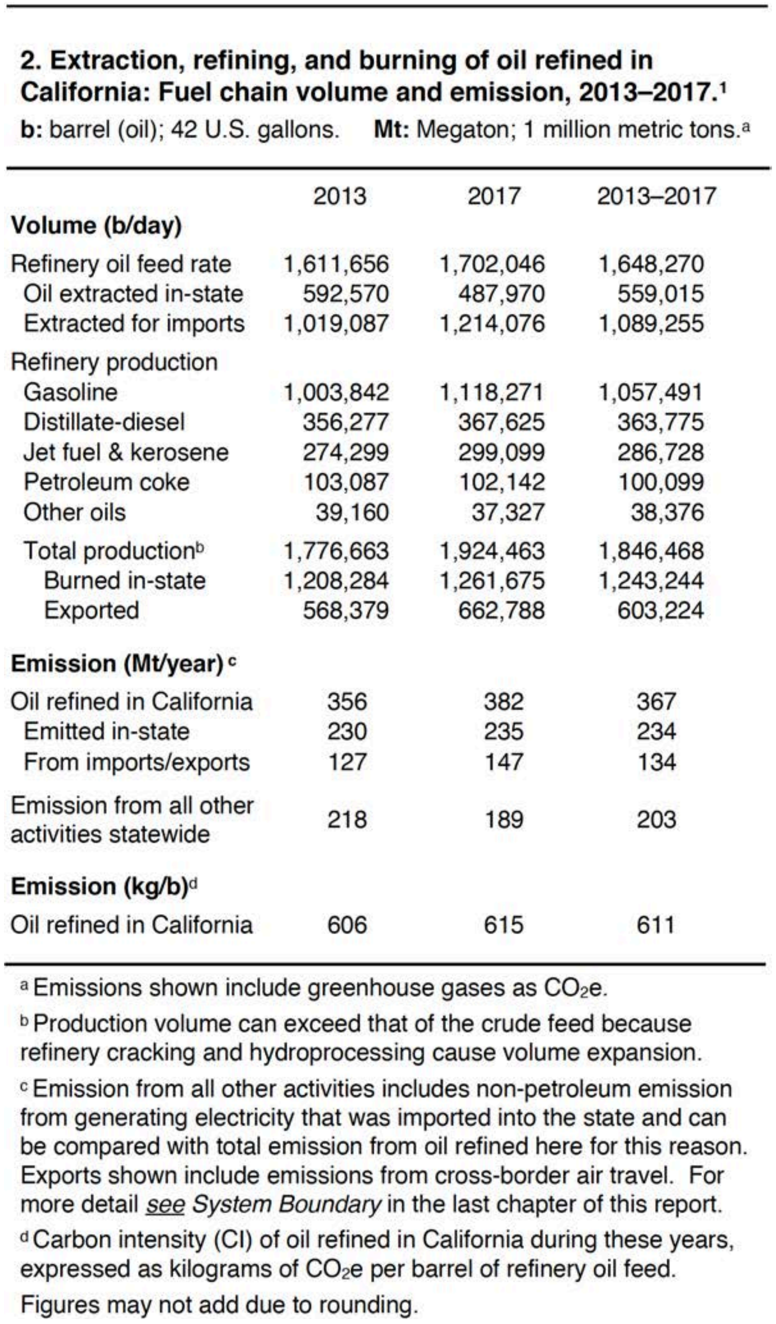
Oil refined here emits all along the fuel chain, wherever it is extracted and the refined fuels are burned. And because the refiners can import more oil and export more fuels as in-state oil extraction and refined fuels demand decline, the emissions are not constrained by how much fuel Californians use or how much oil the state keeps in the ground.

Emissions from the extraction of in-state and imported oil refined here, refining the oil here, and burning the fuels produced by this in-state refining both here and elsewhere define the emission footprint of this fuel chain. This report estimates trajectories for these *petroleum fuel chain* emissions—starting with the emissions from oil refined in California summarized in Table 2.

California can boast some of the highest-quality data on the petroleum footprint anywhere. This is especially true for CO_2e emissions since 2013, when the “compliance” phase of its carbon trading began—and oil sector activity, which is seen as critical economic data. Instead of reporting fuel chain emissions directly, however, the state reports them in many categories and merges them with other emissions in some of those categories. Data reported this way must be separated out and then added up.[1]

And despite including emissions from power plant exports of electricity the state imports, the state’s CO_2e inventory excludes emissions from extracting refiners’ oil imports and burning their fuels exports.[1, 25] Data gaps don’t explain the error: the state has detailed oil import and use data.[1] Its source- and fuel-specific CI data must be applied to its oil import and fuels export volumes to measure the wrongly excluded emissions.[1] Finally, we use a multi-year average, to better account for variability in electricity generation emissions, as hydropower supply varies between wet and dry years.[1] For more detail see the Supporting Material.[1]

This analysis reveals huge petroleum fuel chain emissions. From 2013–2017 the extraction, refining and end-use in transport and industry of oil refined in California emitted ≈ 1,840 Mt CO_2e



2. Extraction, refining, and burning of oil refined in California: Fuel chain volume and emission, 2013–2017.[1]

b: barrel (oil); 42 U.S. gallons. **Mt:** Megaton; 1 million metric tons.[a]

	2013	2017	2013–2017
Volume (b/day)			
Refinery oil feed rate	1,611,656	1,702,046	1,648,270
Oil extracted in-state	592,570	487,970	559,015
Extracted for imports	1,019,087	1,214,076	1,089,255
Refinery production			
Gasoline	1,003,842	1,118,271	1,057,491
Distillate-diesel	356,277	367,625	363,775
Jet fuel & kerosene	274,299	299,099	286,728
Petroleum coke	103,087	102,142	100,099
Other oils	39,160	37,327	38,376
Total production[b]	1,776,663	1,924,463	1,846,468
Burned in-state	1,208,284	1,261,675	1,243,244
Exported	568,379	662,788	603,224
Emission (Mt/year)[c]			
Oil refined in California	356	382	367
Emitted in-state	230	235	234
From imports/exports	127	147	134
Emission from all other activities statewide	218	189	203
Emission (kg/b)[d]			
Oil refined in California	606	615	611

[a] Emissions shown include greenhouse gases as CO_2e.

[b] Production volume can exceed that of the crude feed because refinery cracking and hydroprocessing cause volume expansion.

[c] Emission from all other activities includes non-petroleum emission from generating electricity that was imported into the state and can be compared with total emission from oil refined here for this reason. Exports shown include emissions from cross-border air travel. For more detail *see System Boundary* in the last chapter of this report.

[d] Carbon intensity (CI) of oil refined in California during these years, expressed as kilograms of CO_2e per barrel of refinery oil feed.

Figures may not add due to rounding.

(Mt: Megaton; 1 million metric tons). By comparison, all other activities in the state combined emitted ≈ 1,020 Mt CO_2e from 2013–2017.[1] Total CO_2e emissions were ≈ 2,860 Mt. The 1,840 Mt from oil refined in California accounted for ≈ 64% of total statewide emissions.

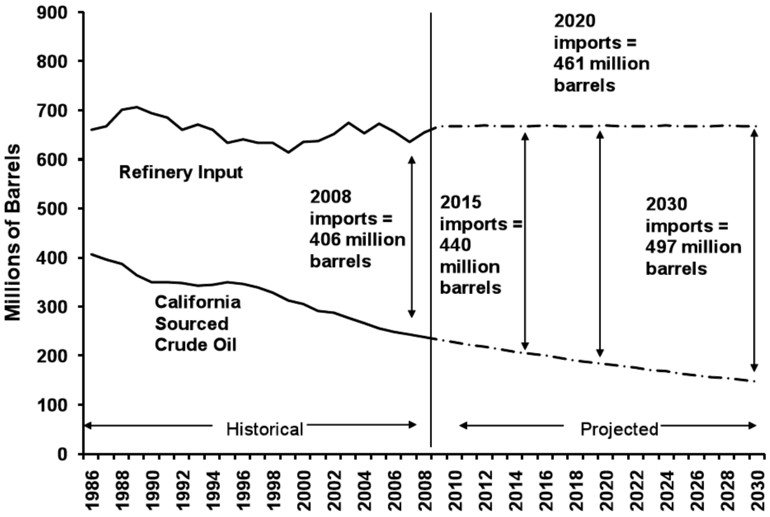
Extraction, refining, and refined fuels use account for approximately 15%, 10%, and 75%, respectively, of these fuel chain emissions—but the interdependence of these links in the chain is the crucial point. Across the fuel chain, ≈ 64 % of CO_2e emitted within the state and ≈ 36 % emitted from the extraction of imported oil and the combustion of exported refined fuels.[1] Refining lower quality oil for export increased fuel chain emissions by up to 60 %: Exporting up to one of each three barrels refined[1] increased the oil volume across the fuel chain up to 150 % of what it would be without exports. The fuel chain CI of using denser oil here (≈ 611 kg/b)[1] is ≈ 107 % of that for the U.S. average crude feed (≈ 566 kg/b).[1] And 107 % of 150% is ≈ 160 %. The toxic impact is even more severe locally. The CI of refining denser oil here is ≈ 120 % of that estimated for the lighter U.S. average feed.[1]

This fuel chain interdependence has another implication. Even if extraction and refining emissions could be fully captured, three-quarters of the fuel chain emissions could still emit from burning refined fuels—unless one of the links in the chain breaks.

TRENDS

Current trends suggest that natural limits, and human responses to them, already affect the path of the petroleum fuel chain here.

Growth has reversed in the crude supply and market that refineries in California were first built to tap. The extraction of in-state oil resources peaked in 1986 and has declined by half since then.[16] The use of finished petroleum products peaked on the West Coast ≈ 2010.[17] For the first time in history, refiners supplied a smaller volume of finished petroleum products to the West Coast in the decade ending in 2016 than they did in the decade before.[17]



3. California Energy Commission refinery oil imports forecast. **barrel (oil):** 42 U.S. gallons. Excerpted from a 2010 report by the Commission.[26] As in-state oil dwindles refiners maintain (shown) or increase (not shown) their oil feed rates by importing more and more oil.

But instead of shrinking their fuel chain's footprint here, refiners' path-dependent reactions to these strategic disruptions threaten further carbon lock-in. Across the West Coast[17] and here in the refining center that anchors its fuel chain,[1,26] refiners have increased production on increased oil imports and refined fuels exports. And as they sell their exports in more distant markets that command lower prices, they are seeking to expand their infrastructure for importing and refining price-discounted lower quality oil. Reviews of proposed projects revealed these crude-switching plans across the state.[23, 24]

The extraction, refining, and end-use in transportation and industry, of oil refined in California emitted more than 1.8 billion metric tons of air pollution, nearly two-thirds of total statewide emissions, from 2013–2017.

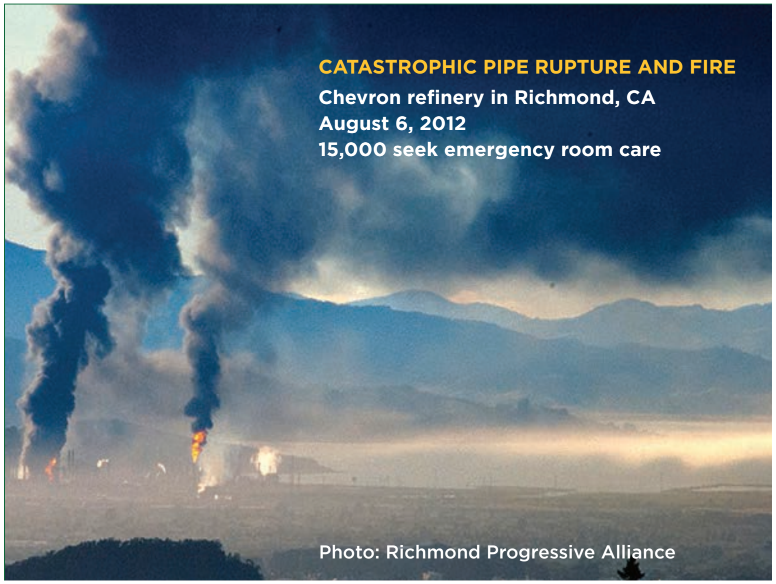
Recurrent spills, fires, and explosions, and consequent efforts to reduce their frequency and magnitude, forced frequent partial shutdowns at California refineries. Judging by U.S. Chemical Safety Board deployment priorities, refinery "incidents" here—a 1999 fire in Avon,[27] 2012 fire in Richmond,[28] 2014 acid spill in Martinez[29] and 2015 explosion in Torrance[30]—ranked among the worst industrial disasters in the nation. Workers were injured and killed.[27–29] Nearby communities were poisoned.[28,30] Refinery process equipment was damaged.[27,28,30] And hazards that lead to such disasters continued to arise frequently. For example, breakdowns, emergency shutdowns, process upsets and planned shutdowns to address hazards at five California refineries caused significant flare emissions on 68 days in 2016.[31] That's a plant average of once every 27 days.

The hazards manifest from processing flammable, corrosive and toxic chemicals in huge volumes at high temperatures and pressures, and from corporate cost-cutting on maintenance, on staffing, and on cheaper but more hazardous process materials and feedstocks.

Oil refining is inherently hazardous. Severe process conditions wear parts fast. Periodic inspections and repairs are crucial to forestall the next disaster—and simply to keep refining oil. Such maintenance shutdown turnarounds (_see_ *Plant 'turnaround'* box on page 24) continued to occur each Spring and Fall.

Continued oil use has made healthy-to-breathe air unachievable. Nearly 50 years after the U.S. Clean Air Act of 1970 saved lives by spurring a massive effort to capture pollutants from burning fossil fuels before they emit from smoke stacks and tailpipes, it's time to ask if this captures enough pollution. It does not. Some toxic combustion products inevitably escape capture.[32]

Along with each Mt of CO_2e, from 2013–2017 total fuel chain emissions from oil refined in California included ≈ 75.9 metric tons (t) of particulate matter ($PM_{2.5}$), ≈ 2,110 t of nitrogen oxides (NO_x) and ≈ 58.6 t of sulfur oxides (SO_x).[1] Breathing these



CATASTROPHIC PIPE RUPTURE AND FIRE

Chevron refinery in Richmond, CA
August 6, 2012
15,000 seek emergency room care

Photo: Richmond Progressive Alliance

REFINERY WORKERS STRIKE FOR PLANT SAFETY

Martinez, CA 2015.

Photo: California Nurses Association

PLANT 'TURNAROUND'

Rebuilding, repairing, or even fully inspecting parts of a refinery for needed repairs while it is running is a bit like trying to fix a car while it's driving down the road—probably impossible and certainly unsafe.

Refiners turn off and 'park' (shut down) that equipment, then inspect and repair or rebuild it, then restart it. They call the planned sequence of equipment shutdown–maintenance/rebuild–startup a plant 'turnaround.'

Turnaround: A planned, periodic, and temporary shut down of a refinery process unit or plant to perform maintenance, overhaul and repair operations and to inspect, test, and replace process materials and equipment.

pollutants and others continued to harm people's health. For example, detailed work by the Bay Area Air Quality Management District,[33] and a confirming review of that work by independent health experts[34] estimated the population-level mortality risk from chronic exposures to $PM_{2.5}$. This report uses the lowest of these estimates, ≈ 0.060113 premature deaths per t $PM_{2.5}$ emitted (≈ 4.563 d/Mt CO_2e emitted).[1] This estimate excludes health risks from other toxic effects, other pollutants, and indirect emissions such as those from climate-related wildfires, and it underestimates risks for vulnerable populations and for areas with more stagnant air conditions.

Based on this estimate, $PM_{2.5}$ co-emitted with the 1,840 Mt of CO_2e emitted from extracting, refining, and end-use of oil refined in California during 2013–2017[1] killed more than 8,000 people.

That's on average everywhere. Closer to the stacks and tailpipes, which are concentrated in low-income California communities of color, it's worse. People of color are disparately exposed to the pollution from burning refined fuels in transportation statewide.[35] Within 2.5 miles of refineries, the health experts found,[34] mortality risk associated with refinery $PM_{2.5}$ emissions is 8–12 times that in the Bay Area as a whole.

Brechin reports an example of the wealthy and privileged choosing to build polluting industries elsewhere—across the Bay from their San Francisco Peninsula homes—as early as the

THEY COULD JUST SAY IT'S *INHERENTLY* POLLUTING.

> *"Most modern combustion systems produce low concentrations of criteria and toxic pollutants at individual emission points while emitting large volumes of air and the end-products of combustion (carbon dioxide and water). This makes traditional 'end-of-pipe' air pollution controls very expensive due to the relatively small mass of NO_x or $PM_{2.5}$ when compared to the large mass of air, water and CO_2. While the the concentrations may be low at each emission point, the high volume and large number of sources can add up to significant criteria pollution, and to a lesser extent toxic air contaminants, in the atmosphere. Any reduction of fuel use will result in emission reductions of these compounds ... reducing fuel consumption, all of the air pollution by-products of fuel burning are also reduced: criteria, climate and toxic pollutants."*

Bay Area Air Quality Management District refinery strategy report.[32]

3. Petroleum fuel chain CO_2e co-pollutant emissions data.
t: metric ton. **Mt:** Megaton; 1 million metric tons.

Co-pollutant [a]	$PM_{2.5}$	PM_{10}	NO_x	SO_x
Mass emitted (t/year) [b]				
Inside the state	17,900	19,500	496,000	13,800
Outside the state	10,000	11,000	277,000	7,700
Fuel chain	27,900	30,500	773,000	21,500
Fuel chain co-emission factor (t/Mt CO_2e) [c]	75.9	83.1	2,107	58.6

[a] Particulate aerosols ($PM_{2.5}$, PM_{10}) and oxides of nitrogen (NO_x) and sulfur (SO_x) are among the toxic 'smog-forming' combustion products that co-emit with CO_2, the predominant combustion product by mass.

[b] Mean from 2013–2017 based on Air Resources Board data; *see* Table S7 in Supporting Material[1] for data and methodological details.

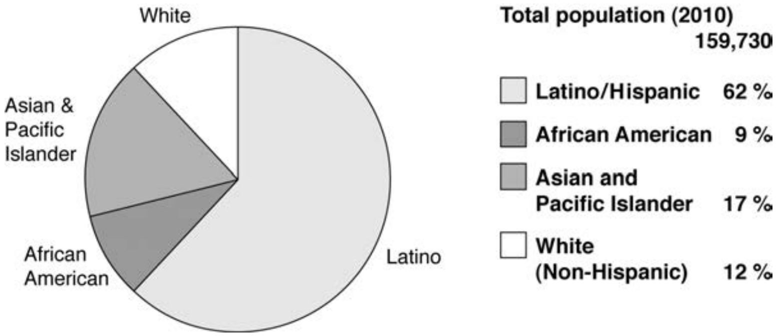
[c] Metric tons of the co-pollutant emitted per Mt of CO_2e emitted from 2015 in-state emission data.[1] The factors shown apply to the fuel chain; its various equipment and fuels co-emit at various rates.

1800s.[36] By 2010 refineries accounted for 93% of the disparity in particulate emission burdens between people of color and non-Hispanic whites caused by all industries in the state cap-and-trade scheme combined.[37] New extraction projects are banned in state waters near the wealthier coast but are still permitted where drilling is concentrated, in communities of color and low income around Kern County and in Wilmington.[38] Diesel trucks are routed mainly through low-income communities of color along I-880 in Oakland instead of I-580 in the wealthier and whiter Oakland hills, and through Southeast Los Angeles and Wilmington on an expanding I-710 instead of I-405 to the west. Statewide and in general, major oil infrastructure grew where communities had less say, not where communities had more say.

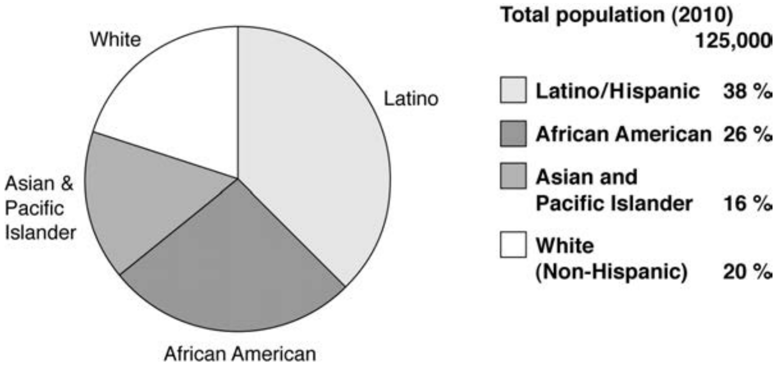
Communities that host refineries are rising to organize for more say. Grassroots efforts stopped, slowed, or downsized oil refining expansions in Santa Fe Springs (2002), Richmond (2009 and 2014), Benicia (2013–2016), Rodeo (2013–2020), Nipomo (2014–2017), Wilmington/Carson (2016–2019), and elsewhere. And, seeing more of the wider threat in the "bomb trains" that would feed oil to some of these expansions, communities across the state began to join in stopping them. Instead of the massive switch to refining high-carbon Canadian tar sands oil in California that the industry had pushed for since 2007,[23] by 2017 Canadian heavy crude imports were held to only ≈ 1.4 % of total crude refined statewide.[1,39]

In these ways human responses to the inherent hazards of oil have limited the geography of major oil infrastructure within California and have begun to limit its growth.

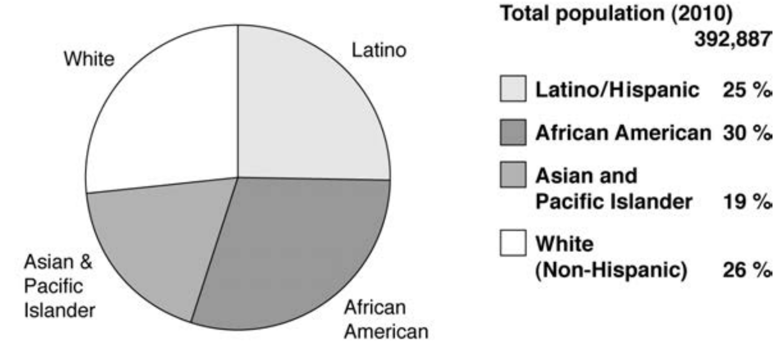
But statewide from 2013–2017, as non-petroleum emissions began to decrease, petroleum fuel chain emissions increased. *See* Table 2 (p.19).



4A. Community demographics by race in Wilmington, CA.[a]



4B. Community demographics by race in Richmond, CA.[a]



4C. Community demographics by race in Oakland, CA.[a]

[a] Hispanic whites are included only in the Latino/Hispanic count to avoid double-counting. Data from the 2010 U.S. Census.

Photo: CBE

2. WHY MUST OIL REFINERIES BE DECOMMISSIONED?

All known paths to climate stabilization cut petroleum use.[3,4,40–43] In California, where refiners import oil to export refined fuels,[1] this means refining less oil here. We can. Proven, economically feasible alternatives can replace enough oil-based transport fuels to stabilize our climate.[3] We can retire and replace the energy function of refining capacity—we can *decommission* refining capacity here. And to meet the state's climate limit, we must.

Proof of this need starts with two facts. Persistent pollutants build up in our environment over time. And when this pollution buildup exceeds a critical natural limit, its impacts on us become irreversible. Thus *cumulative* emission, rather than the emission rate in any one year, is driving anthropogenic climate forcing.[40–42] And—although they do not express this cumulative emission limit directly—California's climate emission targets for 2020, 2030, and 2050 are based on these facts.

Chart 5 illustrates an example for one plausible path to 2050 in California: no change in the feed rate volume or carbon intensity of oil, assuming steady cuts in all other non-petroleum emissions to their share of the state's 2050 climate limit. The buildup of cumulative emissions over time is shown in Gigatons (Gt): billions of metric tons. The solid black rising curve shows total statewide emissions, including petroleum fuel chain emissions and, below the dashed curve, all other non-petroleum emissions. As shown, the total emissions (solid curve) rise far above the climate limit (red line).

Refineries must cut feed rates—process less oil—to achieve California's climate and health protection goals.

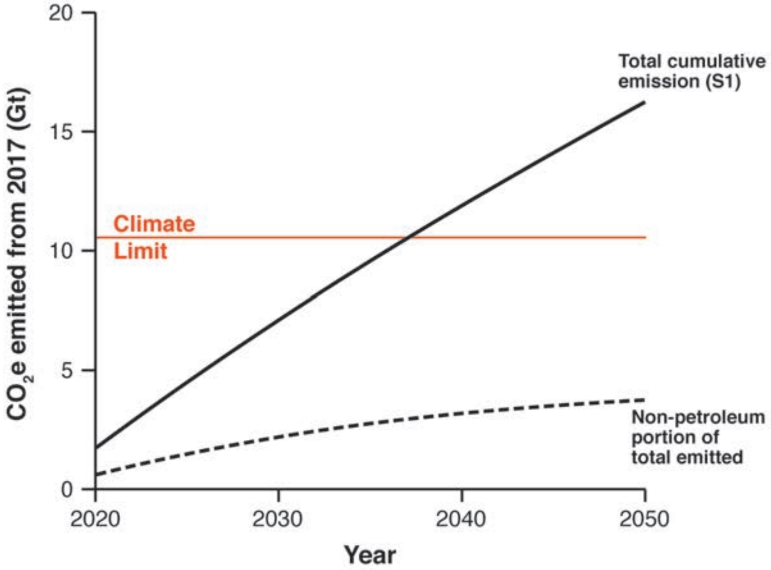
In other words, even if we do everything else, and also stop the carbon intensity of oil from increasing, emissions from the petroleum fuel chain will exceed the state's climate limit *unless* we cut its oil feed rate.

CLIMATE LIMIT

This climate limit represents the state's share of global emission cuts by mid-century that give us all a 67 % chance of holding the increase in global average temperature to between 1.5°C and 2°C above pre-industrial levels with medium confidence.[1]

That's close to but not quite as good as the goal agreed by the world's nations at Paris in 2015—to hold this increase to well below 2°C and pursue efforts to limit it to 1.5°C. Deeper cuts could be needed here for a better than 67 % chance, for achieving 1.5°C, for California's *per capita* share of effort, or if unproven and limited carbon sequestration technologies cannot get us the rest of the way to "carbon neutrality" for climate stabilization.[1] Cuts to the state's 2050 climate limit are the minimum need.

Cumulative emissions must be limited because CO_2e builds up in the atmosphere over time to cause climate impacts for centuries. The cumulative limit is a budget that ongoing emissions can use up. If cumulative emissions exceed it—as illustrated by the black curve crossing the red line in Chart 5—the impacts of that CO_2e buildup could be irreversible.[40, 42]



5. Example of cumulative emission without oil feed rate cuts, assuming steady progress to California's 2050 climate limit by all other (non-petroleum) emissions.

Gt: Gigaton; 1 billion metric tons. **CO_2e:** carbon dioxide equivalents.

Emissions from oil refined in California could cause total cumulative emission (black line) to irreversibly exceed the state's 2050 climate limit (red line) even if all other emissions (dashed line) meet state climate targets. The example shown assumes no change in the feed rate or carbon intensity of oil (Scenario S1 without oil feed rate cuts).[1]

California's climate targets through 2050 define its climate limit.[1] The targets seek continuous, proportionate annual emission cuts during three periods: first, back to the emission rate in 1990 by 2020, then 40% below the 1990 rate by 2030, then 80% below the 1990 rate by 2050.[44] Now that we are close to the first, 2020, target, and have reliable actual emission data from 2013–2017,[1] we are looking at the proportionate annual cuts to the 2030 and

2050 targets. With these cuts, a certain amount of CO$_2$e will be emitted each year through 2050. The climate limit is simply the sum total of these proportionately declining annual emissions.

Cumulative emission trajectories defined by the state's climate targets are shown in Chart 6. They start with actual emissions, measured as the 2013–2017 average over wet and dry hydropower years,[1] in 2017. Reduced emissions defined by the targets add to each subsequent year. The non-petroleum (brown shading), petroleum fuel chain (yellow shading), and total (green curve) trajectories bend downward because of these steady emission cuts. The climate limit (red line) is the total emission through 2050, ≈ 10.5 Gt (≈ 10.522 billion metric tons).[1]

CI SCENARIOS

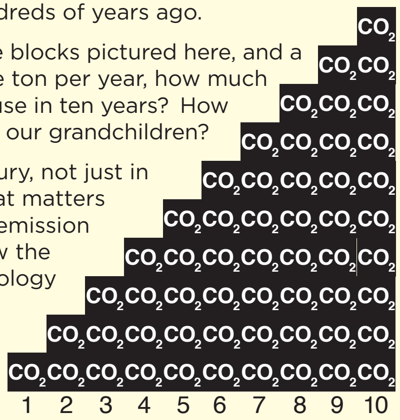
How severe the impacts of uncut oil use could be depends on how much will emit per barrel of oil: the *emission intensity* of the extraction, refining, and end uses of oil refined here. Table 4 summarizes plausible carbon intensity (CI) scenarios.

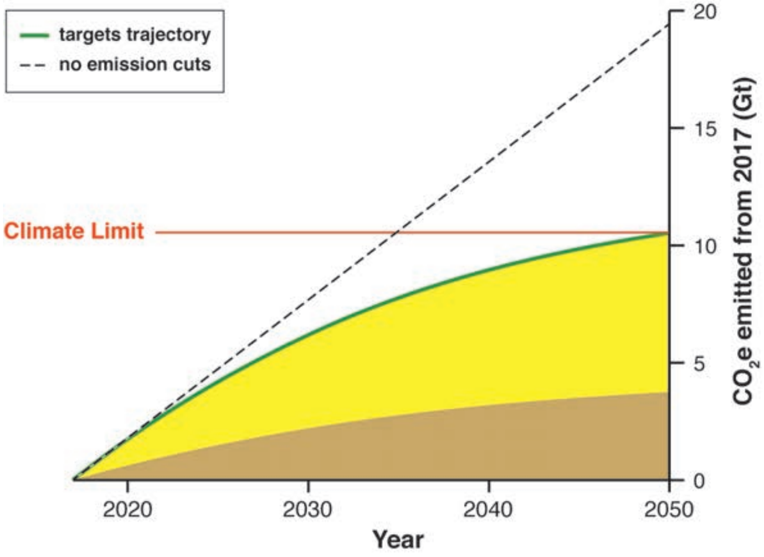
CUMULATIVE EMISSION

Many types of pollution don't "go away" after being emitted. When more gets emitted tomorrow it builds up. Carbon dioxide (CO$_2$) is an extreme example of this. Some of the CO$_2$ in the upper atmosphere was emitted hundreds of years ago.

So if a ton of CO$_2$ is one of the blocks pictured here, and a new refinery burner emits one ton per year, how much cumulative emission will it cause in ten years? How much of that CO$_2$ could affect our grandchildren?

How much emits by mid century, not just in any one particular year, is what matters most in the end. Cumulative emission is a good way to measure how the choices about polluting technology we are making now will have long-lasting future effects.





6. Cumulative emission limit defined by state climate targets.
Gt: Gigaton; 1 billion metric tons. **CO$_2$e:** carbon dioxide equivalents.
🟨 Petroleum fuel chain 🟫 All other non-petroleum activities

This chart: To stabilize our climate we must limit cumulative emission through 2050. State climate policy seeks to do this by making steady annual emission cuts to specific targets for emission/year in 2030 (–40%) and 2050 (–80%). Assuming steady progress by all emitters to the targets, the chart shows cumulative emission from all activities in the state (green line), including those from oil refined here (yellow shading) and those from all non-petroleum activities (brown shading). Cumulative emission along this state climate targets pathway through 2050 defines California's 2050 climate limit (red line).

This climate limit (≈10.5 Gt) represents the state's share of global emission cuts by mid-century for a 67% chance of holding the increase in global temperature to between 1.5ºC and 2ºC above pre-industrial levels with medium confidence. Deeper cuts could be needed for a better than 67% chance of success, for achieving 1.5ºC, for the state's *per capita* share of effort, or in the event that currently unproven and limited carbon sequestration technologies cannot achieve zero-emission "carbon neutrality" for climate stabilization without additional direct cuts in the remaining emissions after this climate limit is met.

For data and methods details see the Supporting Material.[1]

In one plausible scenario, this fuel chain CI would not change much. Community resistance could block high carbon projects. Refiners would not invest in major rebuilds enabling significant changes in fuel chain CI. In this scenario (S1), fuel chain CI stays ≈ 611 kg/b, the actual average[1] measured from 2013–2017.

CI increases in other scenarios. Refiners are increasing crude imports and refined fuels exports, and, as their export markets command lower prices, seeking price-discounted crude.[1, 17, 23, 24, 26] In these scenarios those trends continue and refiners win permits for major rebuilds to refine those higher carbon oil imports. The major rebuilds would be staged, from 2020–2031, to avoid fuel supply disruption, and the resultant CI changes are predictable (*see* Supporting Material[1] tables S11 and S12).

In scenario S2, heavy oil replaces half the current statewide crude feed, and fuel chain CI could reach ≈ 711 kg/b.

In the worst-case scenario (S3), heavy oil and tar sands bitumen could each replace 40% of the current crude feed, and fuel chain CI could reach ≈ 785 kg/b.

Scenario S4 is the best case for lower CI.[1] It assumes all of the feasible rebuilds for the lowest CI crude available *and* the most efficient, lowest CI extraction and refining technologies and measures demonstrated in practice—even tough measures such as switching from fossil fueled steam reforming to solar-powered hydrolysis for hydrogen production. Rebuilds would be staged through 2026, four years before the state has assumed similarly effective best-case extraction and refining measures might be achievable.[45] In this plausible but extreme proven technology scenario, fuel chain CI could be cut to ≈ 555 kg/b.

These scenarios define the range of petroleum fuel chain carbon intensities through 2050 that is plausible in California based on proven technologies which are available now.

4. Carbon intensity: Petroleum fuel chain scenarios to 2050.

b: barrel (oil); 42 U.S. gallons.

kg/b: kilograms CO_2e per barrel oil.

Assumptions	
Scenario S-1	No change from 2013–2017 carbon intensity (CI).
Scenario S-2	Switch to low-quality oil: Heavy oil replaces 50% of the current oil feed.
Scenario S-3	Switch to very low-quality oil: Heavy oil and natural bitumen each replace 40% of the current oil feed.
Scenario S-4	Switch to lighter U.S. average oil feed quality and install all feasible refining and extraction upgrades.

Analysis	**S-1**	**S-2**	**S-3**	**S-4**
Plant rebuilds and timing [a]	No None	Yes 2020–2031	Yes 2020–2031	Yes 2020–2026
Oil feed blend				
density (°API)	27.2	21.5	13.7	31.3
sulfur (wt. %)	1.31	2.14	3.52	1.43
CI change (kg/b)				
Refining	None	+ 17.9	+ 50.3	– 17.8
Extraction	None	+ 39.4	+ 75.9	– 26.9
End use [b]	None	+ 42.4	+ 48.1	– 10.7
Scenario fuel chain CI (kg/b)	611	711	785	555

[a] Major facility rebuilds for very different types oil, for emission-cutting efficiency and fuel switching upgrades, or both would be required in scenarios S2, S3, and S4. These plant rebuilds would be staggered to avoid fuel supply disruption. The S-4 rebuild period is shorter to represent the best case for CI reduction. (California's Draft 2017 Scoping Plan assumed the same mass reduction percentage as in S4 could be achieved from refining and extraction by 2030.)

[b] Oil quality-driven changes in refinery by-production of petroleum coke account for the changes shown in refined products end use CI.

See Supporting Material tables S11–S13 for data and methods.[1]

Figures shown may not add due to rounding.

CLIMATE AND HEALTH IMPACTS

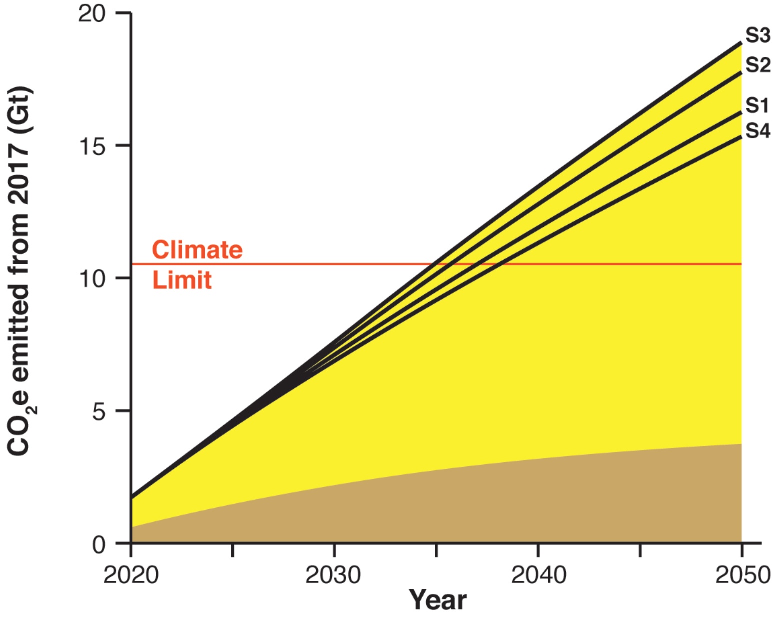
Chart 7 illustrates cumulative statewide emissions in petroleum fuel chain carbon intensity scenarios S1–S4 along paths without oil refinery feed rate cuts. Even if non-petroleum emissions are cut to their climate limit trajectory (brown shading), petroleum fuel chain emissions (yellow shading) will drive total emissions (black curves) far above the climate limit (red line). Emissions from uncut oil use across the fuel chain of oil refined in California—from extraction, refining, and refined fuels use in transportation and industry—would cause the impacts.

Total emissions on these uncut oil use paths exceed the climate limit by ≈ 5,720 Mt (≈ 54%) in scenario S1, ≈ 7,220 Mt (≈ 69%) in scenario S2, ≈ 8,350 Mt (≈ 79%) in the plausible worst-case scenario S3, and ≈ 4,800 Mt (≈ 46%) in best case scenario S4.[1]

PM$_{2.5}$ co-emitted with this 4,800–8,350 Mt petroleum fuel chain CO$_2$e emission excess could kill ≈ 22,000–38,000 people through 2050. This is based on the lowest estimate of co-emission risk discussed in Chapter 1 (≈ 4.563 d/Mt CO$_2$e).[1,33,34]

But impacts of these uncut oil use paths would be irreversible long before 2050. Emissions along these paths exceed the climate limit by 2035–2038.[1] And since we cannot cut to zero overnight, the momentum of these paths would be irreversible even sooner,[1] likely around 2031, and in the worst case, as early as 2027.

This critical timing reveals the importance of decisions based on proven measures we know will work now. There is no time, and too much at stake, to experiment with unproven measures that could turn out to be false solutions. For example, proving that carbon captured from refinery stacks will stay underground could take a century. Meanwhile the climate limit would be breached before 2050 due to uncut use of fuels refined in California alone, even if non-petroleum emissions meet their limit trajectory *and* extraction and refining emissions go to zero.[1] There's no way to pipe carbon underground from all those moving cars.



7. Cumulative emission along petroleum fuel chain pathways without refinery oil feed rate cuts.[1] Assumes non-petroleum emissions are cut to their share of California's 2050 climate limit.

CO$_2$e: CO$_2$ equivalents, 100-year global warming potential.

Gt: Gigaton, 1 billion metric tons.

🟨 Petroleum fuel chain emissions without refinery oil feed rate cuts. Extraction, refining, and end use (e.g., transportation) emissions.

🟫 Other (non-petroleum) emissions, at their share of the climate limit.

— Climate limit: Total statewide cumulative emission from 2017–2050 defined by state climate targets; California's share the 1.5–2°C climate trajectory based on equivalent global emission cuts.

Petroleum fuel chain carbon intensity scenarios:

S1. No change in current rate of emission per barrel of oil.
S2. Switch to low-quality oil starts 2020, complete by 2031.
S3. Switch to very low-quality oil from 2020–2031.
S4. Switch to lighter U.S. average oil feed quality and install all feasible refining and extraction upgrades, 2020–2026.

CRITICAL PATH

The only way to meet our climate limit involves refining less oil, these results prove. The way to do that and still get around is to replace the transportation function of the refining capacity we must retire, which we can do with proven alternatives, others have shown.[3–7] And since oil refined here could still be burned elsewhere we must do both. We need to retire and replace the function of—to decommission—refining capacity.

Photo: CBE

3. WHEN SHOULD THE DECOMMISSIONING START?

The later we start to decommission refining capacity, the more of it we must decommission each year to meet our climate limit. This gets harder, faster, the longer we wait.

Prove that for yourself with the example in this box:

THE EFFECT OF DELAY ON ANNUAL REFINERY CUTS IS SIMPLE MATH.

Suppose a polluter emits ten tons per year, and its climate limit for the next three years is a cumulative total of 24 tons.

What happens if it starts the cuts now? It could cut emissions by 1 ton per year for three years to meet the 24 ton limit. That would emit 9 tons this year, 8 tons next year, and 7 tons the third year. Here's the math: 9 tons + 8 tons + 7 tons = 24 tons.

What if it waits a year? After emitting 10 tons this year it could cut emissions by 2 tons per year in each of the next two years to meet the limit: 10 tons + 8 tons + 6 tons = 24 tons. But that 2 tons per year is twice the pace of the 1 ton per year cut if it starts now.

What if it waits two years? It would emit 20 tons during those two years. Only 4 tons would be left out of its total limit of 24 tons. To meet the limit it must cut 6 tons in the third year: 10 tons + 10 tons + 4 tons = 24 tons. But cutting 6 tons in a year after waiting two years is **six times** the one-ton-per-year pace if it starts now.

Chart 8 shows how delayed refining rate cuts cause this impact. As delaying the cuts allows more emissions buildup (rising on the right axis) the annual oil feed rate cuts needed to meet the climate limit deepen (falling on the left axis). And, the data show,[1] these *annual* cuts to the limit (blue curve) deepen faster and faster with delay from 2020 to 2031 (bottom axis).

Starting now (blue curve in 2020), the climate limit can be met by retiring ≈ 5% of refining capacity each year, but delay forces much deeper, tougher cuts—until it's too late to meet the limit.[1] The blue curve lets us see the road we're going down, and when to hit the brakes, before we go over a climate change cliff.

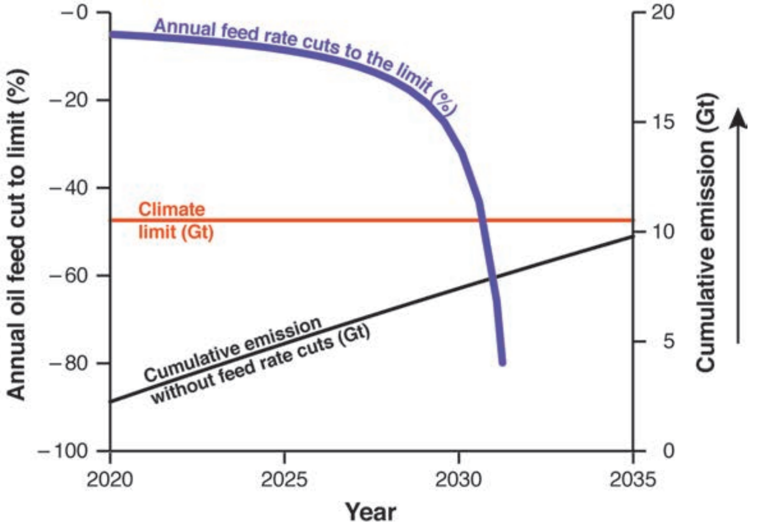
We can see the "cliff" ahead because as emissions (black line) approach the climate limit (red line) and the time left to meet it shortens, it's clear we'd need deeper cuts faster to meet the limit. The shape of the blue curve's downward dive is just simple math. (*See* the example in the box above.)

CAPACITY RESERVE

In Chart 8 the maximum annual feed rate cut is 80% because on these paths, 20% of current refining capacity would remain in operation through 2050. Since carbon intensity would not change on these paths, this means a maximum cut in annual oil sector emissions of 80%, consistent with the state's climate target for 2050. This 20% capacity reserve is a "safe case" estimate for future air travel.

We have proven alternatives for all the major petroleum fuels except jet fuel. Petroleum-biofuels blends, reduced air travel, or both are technically feasible, but petroleum-free jet fuel has not been demonstrated in practice.[46] There is no time, and too much at stake, to rely on unproven measures that may not work. We cannot assume current air travel *and* zero oil refining by 2050.

Jet fuel and kerosene combined accounted for ≈ 15.5% of California refinery production from 2013–2017.[1]



8. Effect of delay on annual refinery feed rate cuts to the 2050 climate limit: Scenario S1, 20% capacity reserve.[1]

Paths shown start refining rate cuts in different years and assume non-petroleum emission cuts to their share of California's climate limit.

Gt: Gigaton; 1 billion metric tons.

Reading the chart left to right: As oil feed rate cuts are delayed, cumulative emission (black line) approaches the climate limit (red line), and deeper annual feed rate cuts are needed to meet the limit (blue downard curve). Delay narrows the gap between cumulative emission and the limit *and* shortens the time left to meet it: the combined effect forces annual cuts that meet the limit to deepen nearly exponentially.

The example shown assumes no change in the carbon intensity of oil, steady progress to state climate targets by all non-petroleum sources, and 20% of current refining capacity remaining in service.[1] It does not show how oil feed rate cuts bend the cumulative emission trajectory downward to meet the limit, or the effects of plausible changes in carbon intensity or in the amount of refining capacity left in service.

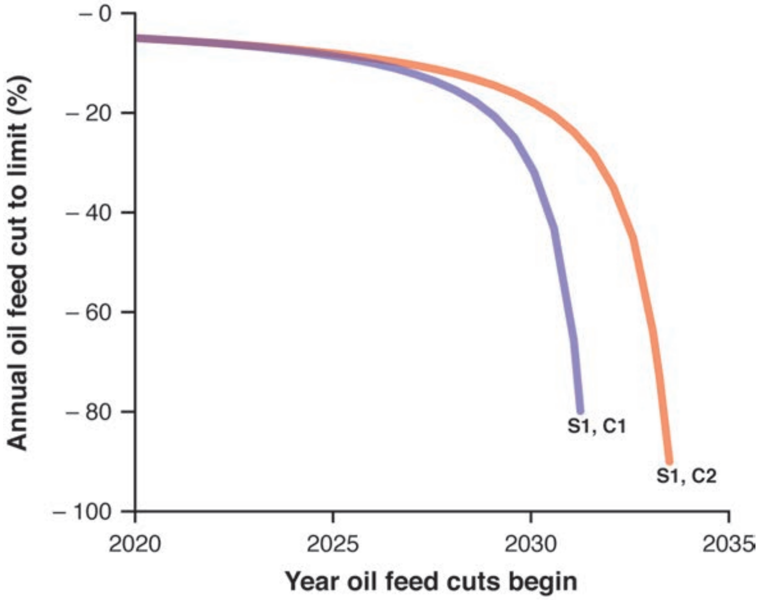
A 20% capacity reserve represents a "safe" case because it exceeds current jet fuel production, leaving room for growth in air travel along with continued use of other small-volume refined products which might prove hard to replace. This is case C1, the blue curve in Chart 9.

Alternatively, only 10% of current refining capacity could be kept in service through 2050 if we blend carbon-neutral biofuels into jet fuel, and curtail air travel in the event that this blending does not prove sufficiently effective. In this case a 10% capacity reserve would be technically feasible—but carry significant risk. This is case C2, the orange curve in Chart 9.

As the closeness of the blue and orange curves in the chart *before* 2025 illustrates, we need not worry about the risk that the 10% capacity reserve case (C2) represents so long as we start to decommission refining capacity right away. And even with delay until it's almost too late, when drastic 80–90% annual feed rate cuts would be needed to meet the climate limit, the 10% capacity reserve case allows only a couple more years of delay. Last chances to meet the limit would come by 2031 in the 20% capacity reserve case (S1,C1), and by 2033 in the 10% capacity reserve case (S1,C2).[1] These results describe all plausible pathways to the 2050 climate limit which do not change the carbon intensity of the petroleum fuel chain (Scenario S1).

The orange curve can meet the climate limit later than the blue curve because its extra emissions during that delay would be offset by extra emission cuts from cutting refinery feed rates by 90% instead of 80% during 2033–2050.

But again, Chart 9 shows only pathways with no change in carbon intensity. Both curves in this chart could shift to the right *or* to the left if the carbon intensity of the petroleum fuel chain changes.



9. Effect of delay on annual refinery feed rate cuts to the 2050 climate limit: Scenario S1, 10–20% capacity reserve. Assumes non-petroleum emission cuts to their share of California's 2050 climate limit.

C1 (C2): 20% (10%) of current refining capacity reserved through 2050.

Leaving less refining capacity in future service allows delaying feed rate cuts to the climate limit in return for more extreme cuts in feed rate and annual emissions later. The chart illustrates this effect for leaving 10% *v.* 20% of capacity in service through 2050. Pathways shown in the chart assume no change in carbon intensity and steady progress to state targets by all non-petroleum emission sources.[1]

TRANSITION IMPACTS

Chart 10 illustrates effects of delay on how deep refinery oil feed-rate cuts must be once they start (left axis) for all plausible paths to the 2050 climate limit. Each black curve shows many paths, which start to decommission refining capacity at different times (bottom axis). And each black curve shows paths for a different combination of carbon intensity (scenario S1, S2, S3 or S4) and capacity reserve (blue or orange shading).

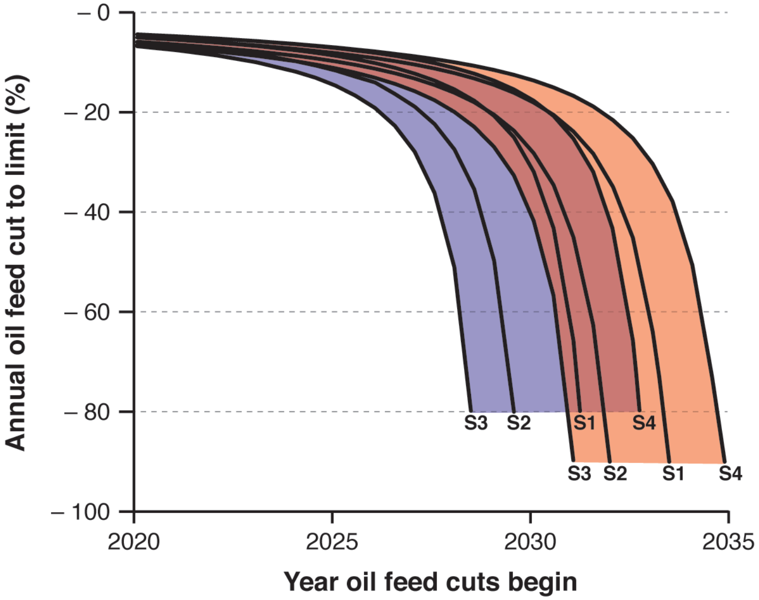
> *Early action to decommission refining capacity is a critical component of the least-impact, most just, most feasible paths to climate stabilization in California.*

This chart reveals that while plausible future changes in carbon intensity and in the refining capacity reserved for future needs matter—shifting the timing by as much as several years—delay really matters. Annual feed rate cuts deepen from 4.4–8.6 % with action before 2023 to 80–90% with delay until 2028–2035.[1]

But even before then, delay could drive us off a climate limit feasibility cliff. The critical period for action before annual cuts to the climate limit dive from ≈ 20% to 80% on paths that avoid air travel curtailment risk (blue shading) ends no later than 2030 and could end as early as 2026.[1] This "cliff" comes when the curves in the chart dive sharply downward from the –20% mark.

These results measure potential transition impacts. It would be harder, and more disruptive to people's lives, especially in low-income communities near refineries, to replace 20% instead of 4.4–8.6 % of the transportation fuels, jobs, and taxes linked to oil in a year—and replacing 80% of them in a single year would be unprecedented. That's a crucial difference between the early action and delayed action paths. Thus, these results show, early action to decommission refining capacity is a critical component of the least-impact, most socially just, most *feasible* paths to climate stabilization in California.

When should the decommissioning start? Right away.



10. Effect of delay on annual refinery feed rate cuts to the 2050 climate limit: Scenarios S1–S4, 10–20% capacity reserve.

Minimum sustained annual oil feed cuts to meet the limit by year the cuts begin,[a] accounting for:

🟪 At least 20% of current refining capacity remaining in service through 2050 for potentially irreplaceable products (e.g., jet fuel).[b]

🟥 At least 10% of current refining capacity remaining in service through 2050 for potentially irreplaceable products.

Petroleum fuel chain carbon intensity scenarios:

S1. No change in current rate of emission per barrel of oil.
S2. Switch to low-quality oil starts 2020, complete by 2031.
S3. Switch to very low-quality oil from 2020–2031.
S4. Switch to lighter U.S. average oil feed quality & install all feasible refining & extraction upgrades, 2020–2026.

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[a] Assumes non-petroleum emission cuts to their share of California's 2050 climate limit. For data and methods details see Supporting Material.[1]

[b] Reserving 20% of existing capacity is consistent with California's 2050 target, which would cut annual emission to 20% of the 2020 rate by 2050.

4. CAN WE WAIT FOR THE REFINERIES TO WEAR OUT?

A decade ago, Davis and colleagues[47] found that if we had stopped building new ones, the fossil fueled power plants already built by then could have worn out fast enough to meet our mid-century climate stabilization goal. Whether or not this is true for oil refineries in California now, a decade later, depends on how long the refining capacity already built here could last—its operable duration.

To answer this question CBE compared actual age and total operating duration data for 1,637 California refining equipment units with standard industry data for the relative capital costs and production values to refiners of the 12 critical process types included in that data sample. *See how refineries wear out* in the last chapter of this report for more detailed background on this analysis; all data and methodological details are given in the Supporting Material tables S20–S23.[1]

These data suggest that the oldest half of existing California refining capacity would not fully wear out for ≈ 21–31 years.[1] This does *not* mean it will run that long, because we could choose to decommission it sooner. It does *not* mean refining capacity will shrink at all, because refiners could continue to rebuild it if we let them. It means that if neither of those things happen, total already-built California refining capacity can be expected to wear out at a rate of ≈ 1.6–2.3 percent per year.[1]

EMISSION CAPACITY GAP

The difference between waiting for refining capacity to wear out and starting to decommission it now on paths to the climate limit is illustrated in Chart 11. The orange band shows the capacity left in service from 2020–2035 if all existing capacity is used for its operable duration with no major rebuild projects. This is the estimate summarized above. The green band shows capacity left in service on paths to the climate limit that start to decommission refining capacity in 2020.

The gap between the green and orange bands is the issue.

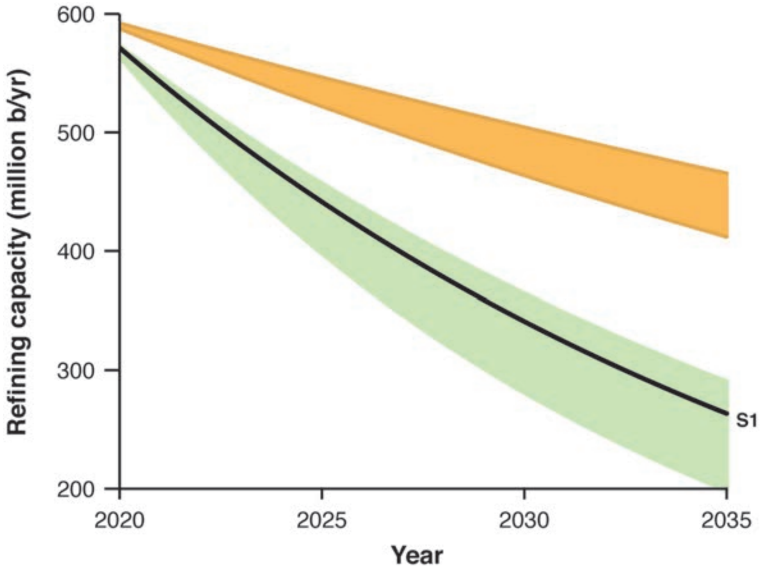
This gap is the difference between operable refining capacity and climate-compatible refining capacity on these paths. It appears right away, and grows over time, representing emissions that could exceed the state's climate limit substantially, because while only ≈ 1.6–2.3 % of existing capacity will wear out each year, ≈ 4.4–6.7 % of it must be decommissioned each year to meet the limit on these early action paths.[1] That's the best-case estimate.

Delay would allow more cumulative emission before cuts start, which must be offset by deeper cuts later on delayed action paths to the climate limit, driving the green band down, and widening the gap, on the right side of Chart 11. And delay allows at least some refining equipment to be rebuilt.

REBUILD IMPACT

Existing, already aging equipment will not run as long as new equipment. Refinery expansions and rebuilds could prolong the operable duration of California refining capacity, raising the orange band in Chart 11 and further widening the gap between operable and climate-compatible capacity. Refiners here plan such projects.[23, 24] Waiting to start decommissioning refineries increases the chances such projects will be built during the delay.

Consider these effects of delay with rebuilds that maintain but do not expand current refining capacity. Delay forces rates of operable capacity loss on paths to the climate limit to increase,



11. Refining capacity left in service from 2020–2035 if the state climate limit will be met *versus* that if the refinery equipment already built is used for its operable duration.[1]

Best case paths. **b:** barrel (oil); 42 U.S. gallons

🟧 Capacity in service assuming use of existing, already-built refining equipment for its operable duration. Orange shading shows the range of 1.59–2.34% annual capacity loss based on California refining equipment data. This estimate applies only if **no** new projects to expand or prolong oil refining will be permitted and built.

🟩 Capacity in service assuming the best-case pathways to the climate limit. Starting in 2020 these pathways decommission 4.4–6.7% of capacity each year to meet the 2050 climate limit. Green shading shows this range for carbon intensity scenarios S1–S4. The black line shows 'existing equipment' scenario S1, which assumes no new projects to expand or prolong refining.

from 2.7–3.4 %/year starting in 2020, to 21–62 %/year starting in 2031, to 62–88 %/year starting in 2033. *See* Table 5. And this example still underestimates potential expansion impacts.

STRANDED ASSETS

A "stranded asset" is an investment or property that has suffered from unanticipated or premature write-down, devaluation or liability or has become subject to impairment, abandonment and financial losses due to diminished expectations of future profitable production. Thus—assuming we expect to ensure the survival of human societies as we know them by acting to meet our climate limit—the gap between operable and climate-compatible capacity measures potentially stranded oil refining assets. And stranded asset potential affects political feasibility.

Refiners seek to protect operable and profitable assets. So this gap between operable and climate-compatible capacity also measures infrastructure inertia, a pillar of carbon lock-in, that represents a commitment by powerful interests and institutions to future emissions.[47–49] How wide this gap gets, how much we let these climate-stranded assets pile up, matters to the political feasibility of meeting our climate limit.

Therefore, the difference between stranding 2.7–3.4 % of otherwise operable refining capacity annually if we start to decommission now, and being forced to strand 62–88 % of it annually if we delay until 2033, indicates a clear difference in the political feasibility of early action *versus* delayed action paths.

CRITICAL TIMING

Can we wait for the refineries to wear out? No. It won't work in the end and will make everything worse along the way. Refiners have invested in carbon lock-in that threatens natural assets the whole economy depends upon.[49] There is no plausible path to the climate limit that avoids taking at least some refining capacity out of service while it is still operable. Instead, climate-stranded refining assets will only pile up if we wait to start decommissioning later, increasing refiners' motivation to protect their assets from imminent losses by resisting the necessary climate stabilization action during our delay. And this worsening vested interest entrenchment would come on top of the potentially traumatic worsening of transition impacts with delay that is described in Chapter 3. Delay would make everything worse for climate stabilization.

Our least-impact, most socially just path to the climate limit also is our path of least resistance—starting now.

5. Effect of delaying decommissioning on climate-stranded assets assuming no change in refinery operable duration.

Climate	Decommission (%/yr)		Operable loss (%/yr)	
path start	Case C1	Case C2	Case C1	Case C2
Jan 2020	5.0 %	5.0 %	2.7–3.4 %	2.7–3.4 %
Jan 2025	8.7 %	8.2 %	6.3–7.1 %	5.8–6.6 %
Jan 2031	64 %	24 %	61–62 %	21–22 %
Jan 2033	100 %*	64 %	100 %*	62 %
Jun 2033	100 %*	90 %	100 %*	88 %

Assumes the current 1.59–2.34 %/year wear-out rate[1] with delay: this underestimates impacts of delay if refining capacity continues to expand. Scenario S1 for both capacity reserve cases, C1 and C2, are shown.[1]
* Values of 100% indicate paths foreclosed before the given start date.

Acting now has opposite climate stabilization feasibility effects. Instead of being forced to shut down refining capacity all at once to meet the climate limit, stranding 62–88 % of it while it's still otherwise operable in 2033, we could gradually decommission less than half as much of that operable capacity by 2033 at a rate of only 2.7–3.4 percent per year.[1] That's if we start to decommission refining capacity now.

In fact, our least-impact, most socially just path to climate stabilization also is the path of least industry resistance—starting to decommission now.


Photo: CBE

5. WHAT DOES THIS SAY ABOUT CARBON TRADING?

Carbon trading is a type of pollution trading—the exchange of money for permits to pollute issued by political authorities that facilitate these transactions—in which permits to emit CO_2e are bought and sold. The carbon trading scheme applied to oil in California has three key elements: Cap-and-trade[50] trades permits to emit called "allowances" or "offsets" under a declining economy-wide mass emissions limit. The Low Carbon Fuel Standard (LCFS)[51] trades permits to emit called "credits" under a declining transportation fuels emission intensity limit. And oil refiners are allowed to acquire these permits to emit *instead of* cutting mass emissions or switching from polluting to clean technology.[52] The scheme has been in place since 2013.[50–52]

This carbon trading-only experiment with oil did not work. Its failure is linked to structural limitations of carbon trading that appear unresolvable. The carbon trading-only policy threatens to foreclose feasible pathways to climate stabilization in California.

CALIFORNIA'S CARBON TRADING EXPERIMENT WITH OIL DID NOT WORK

Carbon trading was an experiment. It had not worked elsewhere. Pollution traders asserted the hypothesis that became its stated objectives: that carbon trading would cut emissions, incentivize switching from inherently polluting to climate-compatible technologies, and be more cost-effective than other ways to do that emission cutting and that technology switching. But exactly the opposite happened with oil. Now, seven years later, the data show that carbon trading has failed to achieve its objectives in the California oil sector.

Increased emissions. Total petroleum fuel chain CO_2e emissions reported in 2017 exceeded those reported in 2013 by some 26 million metric tons (Mt).[1] These emissions continued to increase through 2018 based on estimates using state emission factors for the portion of oil sector emissions associated with

Table 6. Comparison of engine fuels production and petroleum fuel chain CO₂e emissions from oil refined in California since 2013.
Mt: Megaton, 1 million metric tons

	Engine fuels production [a]	Petroleum fuel chain emissions	
	(billions of gallons)	Total [b] (Mt)	Engine fuels [c] (Mt)
2013	25.1	356	308
2014	26.2	369	321
2015	25.3	357	310
2016	27.0	374	321
2017	27.4	382	336
2018	27.9	NA	341

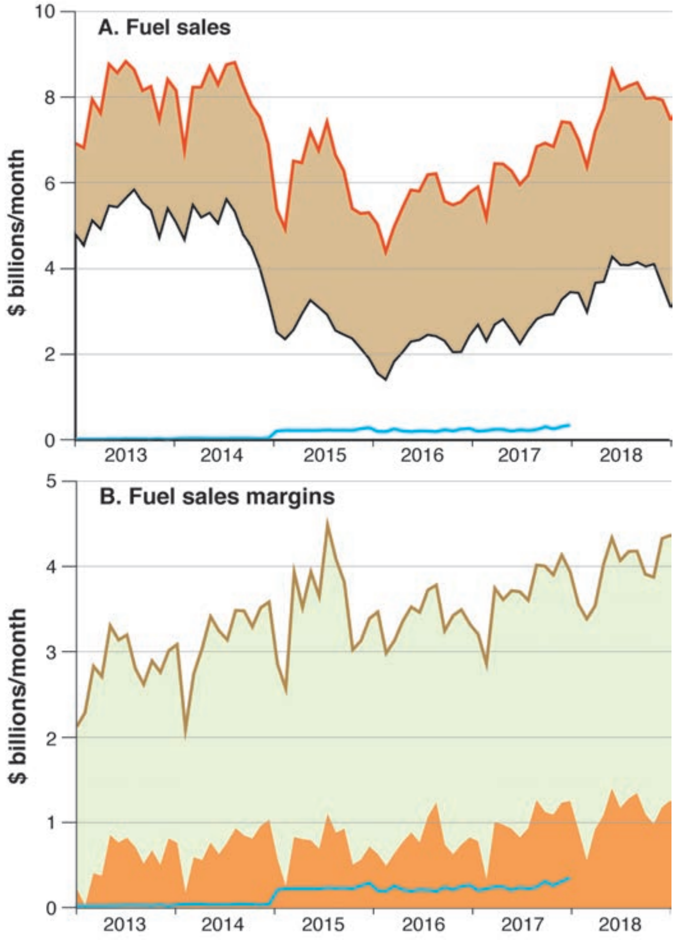
[a] Combined gasoline, distillate-diesel and jet fuel production reported by the state.[1, 70] [b] Total petroleum fuel chain emissions reported.[1] _See_ Chapter 1.
[c] Petroleum fuel chain emissions associated with these engine fuels estimated from LCFS emission factors for CARBOB (100.82 g CO₂e/MJ; 119.53 MJ/gallon), diesel (100.45 g/MJ; 134.37 MJ/gal.) & jet fuel (89.37 g/MJ; 126.37 MJ/gal.).[51]

gasoline, diesel, and jet fuel. _See_ Table 6. Emissions increased as production increased, further supporting the observed and estimated emission increases. Carbon trading did not achieve its objective to cut emissions in the state's oil sector.

Increased production. The fuels production increase that drove increasing petroleum fuel chain emissions since 2013 (Table 6) shows that carbon trading failed to incentivize a switch from inherently polluting oil sector technology.

Monthly sales of transportation fuels refined in California (red, Chart 12A) exceeded the cost of oil industry permits under cap-and-trade and the LCFS ("carbon costs to oil") by 17–360 times. Crude oil sales (black line) and fuel sales margins (brown), not carbon costs to oil (blue line), drove these fuel sales.

Fuel sales margins (brown; the difference between fuel sales and crude sales) exceeded carbon costs to oil by 10–130 times. _See_ Chart 12B. Price margins (green shading) and fuels production (orange), not carbon costs to oil (blue line), drove fuel sales margins. Moreover, increasing refinery production (orange) increased fuel sales margins (brown line). This production effect on fuel sales margins *alone* exceeded carbon costs to oil by a total of 3.8 times from 2013–2017. _See_ Chart 12B.



12. Carbon market data for oil refined in California.
(**A**) fuel sales, and (**B**) fuel sales margins, ***v.*** carbon market costs to oil.

— **Sales of petroleum transportation fuels refined in California.** From refinery production,[70] in-state and export sales[71] and Calif. & West Coast retail prices[72] for gasoline, distillate-diesel and jet fuel.

— **Sales of crude oil refined in California.** From crude inputs[70] and crude aquisition costs to refiners.[9]

— **Carbon market cost to oil.** From cap-and-trade and LCFS allowances, credits and offsets charged to refiners, extractors & fuel suppliers and mean allowance and credit prices.[54, 57, 73–75]

— ■ **Fuel sales margin (fuels–crude sales).**[9, 70–72]

□ **Price margin effect (fuels–crude prices).**[9, 70–72]

■ **Fuels production effect (refining increase).**[70–72]

Carbon trading did not incentivize a switch from oil. It allowed oil companies to make more money from oil technology than it cost them in permits to pollute. They used even more of that polluting technology.

Cost ineffective. Failing to cut oil emissions or incentivize a switch from oil, carbon trading was not effective, so it clearly was not cost-effective, in the state's oil sector.

THIS CLIMATE POLICY FAILURE IS LINKED TO INTRINSIC LIMITATIONS OF CARBON TRADING THAT APPEAR UNRESOLVABLE

As the Green Finance Observatory explains: "Air pollution is not a standardized, clearly delineated and readily tradeable asset. Transforming air pollution into a tradeable asset requires what is called a commoditisation process: ... stipulating that a reduction of a certain number of molecules achieved at one place or time by one technology is climatically 'the same' as a reduction of an equivalent number of molecules of a range of pollutants by another technology at another place or time."[53]

In other words, at least three illusions are essential to the process of turning permits to emit into a pseudo-commodity which can be 'valued' in dollars per ton of CO_2e so that these permitted tons can be bought and sold in a carbon trading market:

> Abstraction from place,[53] the illusion that each ton permitted has the same effect though traders emit in different places. Carbon trading is blind to *where* it permits emissions.
>
> Equivalence between technologies,[53] the illusion that each ton permitted has the same effect though traders use different technologies. Carbon trading is blind to *which polluting technology* it permits.
>
> Abstraction from time,[53] the illusion that each ton permitted has the same effect though traders' investments affect future emissions for different lengths of time. This means the permit price cannot 'see' when trading for the cheapest incremental emission cuts today leaves inherently polluting technologies in place,[53] reinforcing path dependent carbon lock-in over time[48] and threatening to create 'dead ends' along pathways to climate stabilization.[3, 4, 47] Carbon trading is blind to the *commitments to future emissions* it permits.

Since making carbon tradeable requires stipulating to them,[53] these structural illusions or "blinds" appear to be intrinsic limitations of carbon trading. Moreover, that is apparent from the specific mechanisms by which these blinds explain the failure of carbon trading to achieve its objectives in the state's oil sector.

Place matters. Blind to where it permits emissions, carbon trading permits emissions from refining imported crude to produce exported fuels free of charge. Emissions from extracting the imported crude and burning the exported fuels were exempt from cap-and-trade because they occurred outside the state.[50] Total petroleum fuel chain emissions associated with the exported fuels—including all emissions from extraction and refining for the exports—were exempt from the LCFS because those exports were sold outside the state.[51] And instead of limits on the excess refinery emissions from production for export that enabled emissions to shift out of state, cap-and-trade gave refiners here permits for 81 % of their direct emissions free of charge[54] under provisions which were *supposed* to prevent this emission-shifting "leakage."[50]

An environmentally just policy would prohibit excess refinery co-pollutant emissions caused by producing fuels we do not need or use here from worsening disparately severe health risks in low-income communities of color near refineries. This could have cut carbon emissions across the fuel chain of oil refined in the state, since the extraction, refining, and refined fuels combustion emissions associated with the exported fuels would not occur without that excess production.

Instead, blind to where it permits emissions, carbon trading worsened environmental injustice by giving refiners permits to emit from excess production for export free of charge. Further, the state's cap-and-trade program gave away those permits that enabled emission shifting while supposing that it was doing so to prevent emission shifting—again, because carbon trading is blind to *where* it permits emissions.

In effect, this intrinsic limitation of carbon trading alone exempted some 617–813 million metric tons (Mt) of CO$_2$e emissions from 2013–2017. The lower bound of this estimate includes emissions from extracting, refining, and burning exported fuels exempted from the LCFS, while the upper bound reflects all the emissions exempted under either cap-and-trade or the LCFS and includes refining emissions permitted free of charge. See Table S19A for details.[1] This 617–813 Mt was 34–44 % of the total fuel chain emissions from oil refined in California during this period.

Technology matters. California's trading scheme sought cheap incremental emission cuts from other technologies at carbon costs that failed to incentivize a switch from oil because it is blind to which polluting technology it permits to emit. Those cuts could be achieved at carbon costs too low to incentivize a switch from oil by other technologies that earn different sales margins per ton emitted, face different mandates and barriers to technology switching, or achieve only incremental cuts without switching from inherently polluting technology at all. But the uniform carbon cost that the trading market requires is blind to these differences between technologies.

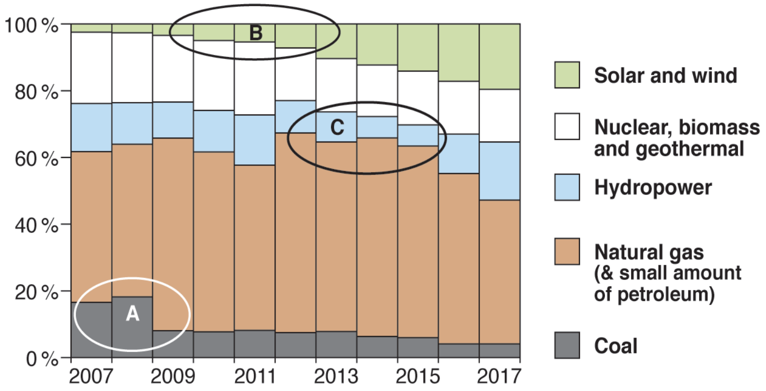
At wholesale fuel and electricity prices, California refineries made approximately 20 times more money per ton of direct CO$_2$e emitted than natural gas-fired power plants and nearly 40 times more than coal-fired plants. See Table 7. Among major energy production technologies, only the suite of cleaner non-fossil generation which is beginning to replace fossil fueled power plants made more. (*Id.*) Thus, carbon trading's uniform cost per ton incentivized refiners to buy permits from other technologies instead of decommissioning refining capacity. Blind to which polluting technology it permits, carbon trading allowed that.

Table 7. Power plant and refinery sales per ton CO$_2$e emitted.
California data, 2013–2017

	Sales/ton CO$_2$e emitted
Electricity generation	
Coal-fired power plants	$ 42
Natural gas power plants	$ 76
Non-fossil generation*	$ 2,550
Oil refining	$ 1,600

* Non-fossil: biomass burning, hydro, geothermal, nuclear, solar and wind power. From wholesale electricity and refined products (gasoline, diesel and jet fuel) prices,[76] electricity generation for California,[77] refinery production,[70] and total direct emissions from electricity generation and refineries.[1, 25, 75]

Different climate protection mandates also applied to electricity. The Renewables Portfolio Standard (RPS) requires switching from fossil-fueled to renewable electricity.[55] Senate Bill 1368 set a CO$_2$ limit on power plants that in effect bans long-term power purchase contracts for coal.[56] No such mandates were applied to the oil sector. After a drought curtailed hydropower and forced more fossil fueled power use from 2012–2015, these mandates began to cut the share of total electricity from fossil fueled power plants during 2016 and 2017. See Chart 13.



13. Fuel shares of electricity used in California, 2007–2017[77]

A. Shift from coal to natural gas begins ≈2008–2009 under SB 1368. **B.** Significant switch to solar and wind begins ≈2009–2013 under RPS. **C.** Drought curtails hydropower from 2012–2015, delaying the shift from fossil fuels despite prior technology switching until 2016–2017, when emission cuts coincide with carbon trading.

During this switch between fundamentally different electricity technologies (Chart 13) with very different sales margins per ton CO_2e (Table 7), already-built transmission technology investments could serve the new electricity. And already built-in home and business appliances used the cleaner electricity. Meanwhile oil faced tougher technology switching barriers.

Locked into their investments in liquid fuels extraction, refining, distribution, and combustion infrastructure, oil companies protected otherwise stranded refining assets by importing crude and exporting refined fuels as in-state extraction and West Coast oil demand declined.[1, 16, 17] But the uniform carbon cost that the trading market required was blind to this difference between electricity and oil technologies. It could not address investment barriers to the switch from oil.

Instead, the carbon trading scheme allowed oil companies to avoid any structural switch from their inherently polluting technology by taking emission reduction credit for incremental and ultimately insufficient operating efficiency improvements, refrigerant capture offsets, and tree planting offsets.[57, 58]

The state was warned about these specific problems. The University of California issued one such warning in 2007. It said "uniform carbon costs" might decarbonize electricity but "would not generate a strong enough signal in the transportation sector, either to produce fuel switching," which involves "severe coordination and investment problems" or to reduce fuels demand.[59] Thus measures beyond cap-and-trade and the LCFS "likely will be needed."[59] The Green Finance Observatory reprised another warning, from 2011—"Equating CO_2e reductions that result from different technologies ... makes it possible, indeed necessary to make climatically wrong choices in the name of molecule prices."[53, 60] It explained: "Emission cuts resulting from a switch to renewable technologies and away from fossil fuel dependency is entirely different from emission cuts resulting from routine, low-cost efficiency improvements. The former is a structural change contributing to the overall objective,

whereas the latter entrenches existing practices by delaying long-term non-fossil investments."[53] Despite the warnings, the state's trading scheme still proved unable to solve these problems, further supporting the conclusion that this intrinsic limitation of carbon trading may be unresolvable.

Making the cheapest incremental emission cuts available now is not the same as making the switch from inherently polluting to sustainable technologies needed to stabilize our climate. And yet, because it requires a uniform carbon cost that is blind to which inherently polluting technology it permits, carbon trading seeks easy incremental cuts elsewhere *instead of* incentivizing technology switching from oil to climate-compatible alternatives.

Timing matters. Oil companies protected long-lasting California refining assets by importing oil and exporting refined fuels. They continued to rebuild and expand their refining capacity here. This created climate-stranded assets that are incompatible with pathways to the state's 2050 climate limit. Carbon trading allowed this, not only because it is blind to which technology it permits to emit where, but also because it is blind to the commitments to future emissions it permits.

The 617 Mt of petroleum fuel chain emissions from refining imported oil to export fuels during 2013–2017[1] were driven by past commitments to future refining. As their in-state crude supply[16] and West Coast refined products market[17] both shrank, instead of beginning to switch from oil, refiners protected their investments by importing crude and exporting fuels. The place-based blindness of carbon trading allowed that, but their desire to keep using their refining capacity investments drove it. And blind to those commitments to future emissions, carbon trading allowed oil companies to double down on those commitments.

Oil companies used the opportunity carbon trading created to trade for permits to emit from rebuilt and expanded California refining infrastructure as a way to justify and permit those long-lasting investments in polluting technology. A proposed crude import capacity expansion at Valero's Benicia refinery[61] and a permitted hydroprocessing capacity expansion at Chevron's Richmond refinery[62] are examples of the use of trading to support investments in projects that disincentivize the switch from oil.

Another example: In 2016 Phillips 66 proposed to expand the heavy oil hydrocracking feed rate at its refinery in Rodeo. Producing hydrogen for the project could increase refinery CO_2 emissions significantly. The Bay Area Air Quality Management District approved the project without any new public review in 2018, citing cap-and-trade as part of its rationale.[63]

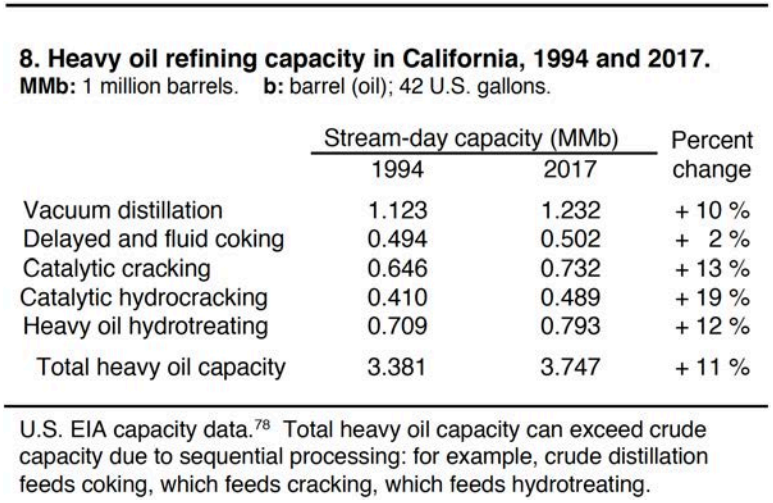
Carbon trading supported such projects in effect, because it is blind to the commitments to future emissions it permits. Tree planting is not the same as replacing fossil fuel technology.

As refiners rebuilt to import more oil and export more refined fuels, their heavy oil refining capacity expanded. *See* Table 8.

Now existing, already-built California refining capacity is wearing out more slowly than it must be retired on paths to the state's 2050 climate limit. Even if no new rebuilds or expansions prolong its operable duration, this already-built capacity wears out at a rate of only 1.6–2.3 percent per year. But in this best-case, it must be decommissioned at a sustained rate of ≈ 5.0 % per year to meet the climate limit. *See* chapters 3 and 4. Thus at least 2.7–3.4 % of statewide refining capacity must be retired while it is still otherwise operable each year—including 44,500 to 56,000 barrels per day of it in 2020 along this best-case 5% per year pathway—to meet our climate limit.[1]

Had the state set carbon limits akin to those that are phasing out coal-fired power, excess refinery production for export might have been phased out by now. This could have avoided any need to retire refining capacity before it wears out along a 2017–2050 pathway to the climate limit. (Supporting Material, Table S19.)[1] Instead, blind to the commitments to future emissions it permits, carbon trading let refiners create climate-stranded assets.

That's a market failure.



8. Heavy oil refining capacity in California, 1994 and 2017.
MMb: 1 million barrels. **b:** barrel (oil); 42 U.S. gallons.

	Stream-day capacity (MMb)		Percent
	1994	2017	change
Vacuum distillation	1.123	1.232	+ 10 %
Delayed and fluid coking	0.494	0.502	+ 2 %
Catalytic cracking	0.646	0.732	+ 13 %
Catalytic hydrocracking	0.410	0.489	+ 19 %
Heavy oil hydrotreating	0.709	0.793	+ 12 %
Total heavy oil capacity	3.381	3.747	+ 11 %

U.S. EIA capacity data.[78] Total heavy oil capacity can exceed crude capacity due to sequential processing: for example, crude distillation feeds coking, which feeds cracking, which feeds hydrotreating.

AB 398 THREATENS TO FORECLOSE FEASIBLE PATHS TO OUR CLIMATE LIMIT.

State Assembly Bill 398, enacted in 2017, extends the state's carbon trading scheme through 2030. It prohibits California's Air Resources Board from using any other measure to limit or cut CO_2e emissions from refineries under cap-and-trade. It prohibits the state's air districts from setting limits intended to cut CO_2 emissions from any refinery under cap-and-trade. And AB 398 provides cap-and-trade allowances free of charge for up to 90 % of refinery emissions through 2030.[52]

This is the same policy for oil that failed since 2013, with the same intrinsic limitations that led to that failure and make it likely to fail again. And by then it could be too late.

Table 9 compares early action and delayed action pathways to the climate limit based on the data and analysis described in Chapter 3. Delaying refining capacity decommissioning until after 2030—what current state policy threatens to do—would make some otherwise plausible pathways to the state's climate limit *technically* infeasible. (Table 9, scenarios S-2 and S-3 in Case C-1.) Worse, it could make all the remaining pathways to the limit less *politically* feasible.

After 2030, all plausible paths to the state's climate limit require refining capacity losses of up to 80–90 % in a single year and, at best, 17–45 % per year, sustained year after year. See Table 9. Replacing that much of the oil-dependent tax and jobs base in communities that host concentrations of oil infrastructure so quickly would take extreme efforts, if it could be done at all.

> *We had better start using all the tools in the toolbox to get out of our crisis with oil.*

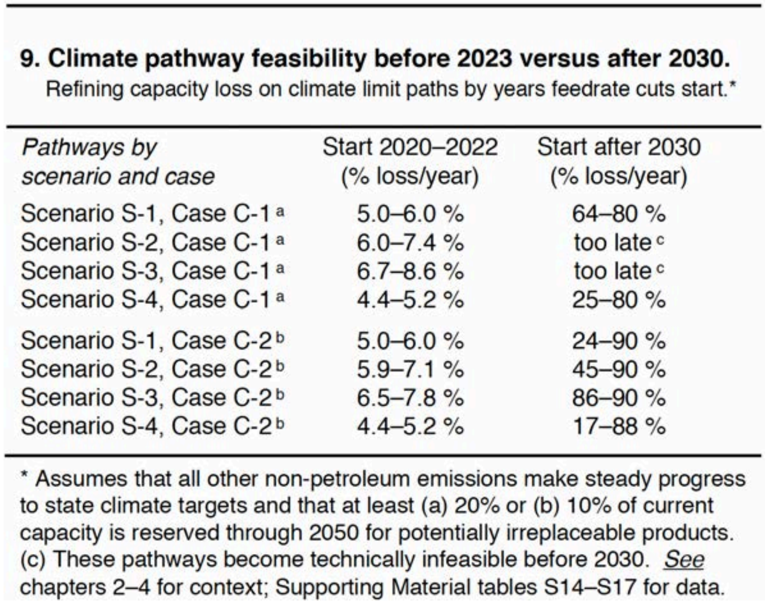
In contrast, we have an opportunity to meet the limit while replacing 4.4–8.6 % of the community's oil-dependent tax and jobs base annually by starting in 2020–2022. (*Id.*) This is much less risky and disruptive for people living and working in and around refineries, and therefore, much more feasible politically.

But this opportunity will be irreversibly lost with further delay.

At the same time, meeting the climate limit after further delay would force us to retire even more refining capacity before it wears out. See Chapter 4. That would predictably increase refiners' incentives to protect their polluting investments by moving even more aggressively in the political arena.

The carbon trading-only policy that the state has applied to oil refining threatens to foreclose feasible paths to our climate limit.

What does all this say about carbon trading? It shows that if we are to have a reasonable chance of protecting our climate and health, the carbon trading-only policy for oil refining must be replaced by effective policy measures. It suggests that these measures could include technology-forcing direct emission limits and mandates that are proving effective in the electricity sector. It says we had better start using all the tools in the toolbox to get out of our crisis with oil.



9. Climate pathway feasibility before 2023 versus after 2030.
Refining capacity loss on climate limit paths by years feedrate cuts start.*

Pathways by scenario and case	Start 2020–2022 (% loss/year)	Start after 2030 (% loss/year)
Scenario S-1, Case C-1 [a]	5.0–6.0 %	64–80 %
Scenario S-2, Case C-1 [a]	6.0–7.4 %	too late [c]
Scenario S-3, Case C-1 [a]	6.7–8.6 %	too late [c]
Scenario S-4, Case C-1 [a]	4.4–5.2 %	25–80 %
Scenario S-1, Case C-2 [b]	5.0–6.0 %	24–90 %
Scenario S-2, Case C-2 [b]	5.9–7.1 %	45–90 %
Scenario S-3, Case C-2 [b]	6.5–7.8 %	86–90 %
Scenario S-4, Case C-2 [b]	4.4–5.2 %	17–88 %

* Assumes that all other non-petroleum emissions make steady progress to state climate targets and that at least (a) 20% or (b) 10% of current capacity is reserved through 2050 for potentially irreplaceable products. (c) These pathways become technically infeasible before 2030. See chapters 2–4 for context; Supporting Material tables S14–S17 for data.

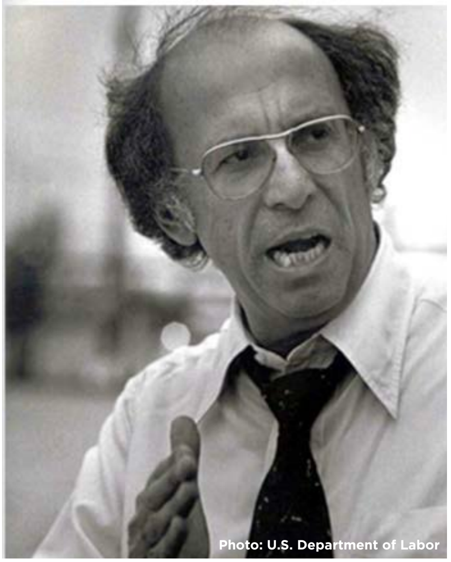


Photo: U.S. Department of Labor

ANTHONY (“TONY”) MAZZOCCHI

Tony Mazzocchi was a labor organizer, health and safety expert, and leader in the Oil, Chemical and Atomic Workers Union (OCAW). In 1991 OCAW called for paying workers to go to college and thus be able to get good jobs when environmental crises eventually force unsustainable industries to close plants.[79] First dubbed a “Superfund for Workers,” Mazzocchi later named this concept a “Just Transition.”

Transition: The process or period of changing from one state or condition to another; to undergo or cause this process or period of change.

Carbon lock-in: Resistance to change of CO_2e-emitting systems which is caused by mutually reinforcing technological, capital, institutional, and social commitments to the polluting system which have become entrenched as it was developed and used. Carbon lock-in is a type of path dependence.

6 BLUEPRINT FOR JUST TRANSITIONS FROM OIL

A just transition is a process or period of intentional change from unsustainable and unjust to sustainable and just energy and social systems that builds societal capacity to break free of carbon lock-in. The term has evolved as the scope and mutually reinforcing nature of social, environmental, and energy crises have become more clear.

Just transitions are possible, necessary, and linked to specific factual and social conditions that define pathways to climate and health protection and erect barriers to these pathways. Indeed, conditions that led to our crisis with oil create opportunities to escape it. Some key opportunities are revealed by the research described in this report.

JUST TRANSITIONS ARE POSSIBLE

Petroleum technology is jobs-poor. It is built for a business model that extracts returns on capital-intensive investment for its owners. Oil refining provides less than 1 % of jobs statewide and employs the fewest people per million dollars revenue of any sector in California's economy.[10] *See* Chart 14.

Alternatives to oil could create more jobs.

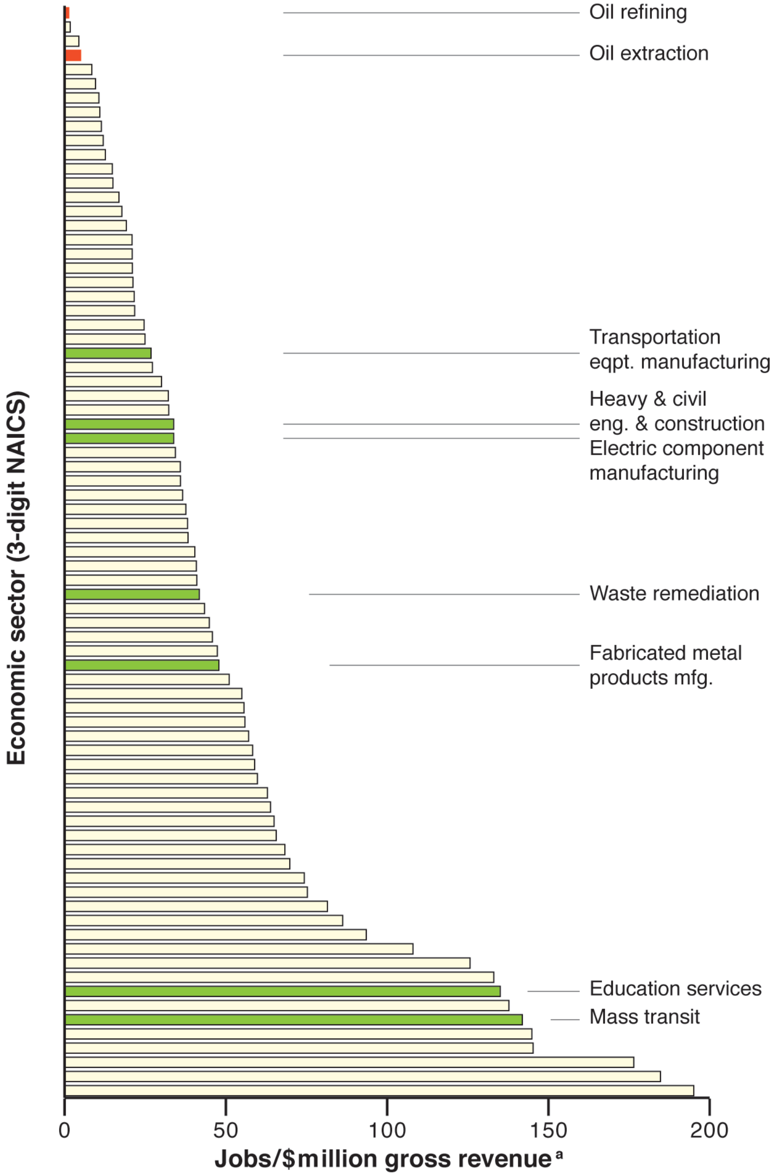
Across all sectors, the state's economy provides ≈ 27 times more jobs/$million revenue than oil refining.[10] (This compares revenue instead of contribution to gross domestic product since continuous, endless growth of extractive economies, an assumption embedded in GDP, is unsustainable.) Sectors likely to be tapped in our transition from oil—to provide renewable energy transportation and mass transit, decontamination and repurposing of oil plant sites, and transition training for workers to move into clean, safe jobs—provide ≈ 20–110 times more jobs/$million revenue than oil refining.[10] *See* green bars, Chart 14.

Since these relatively jobs-rich transition sectors could grow as refining capacity is decommissioned, more jobs could be created statewide. And since any other sector creates more jobs/$million revenue than refining, more jobs could be created in communities that host refineries as the oil-dependent portions of the local tax bases are replaced.

This suggests that the oil sector has contributed to the extractive economics now driving a growing gap between rich and poor in California. More importantly, it shows that our most feasible pathways to the state's climate limit—paths that start to replace refining capacity with sustainable alternatives now—create new opportunities to achieve economic justice.

Health and Energy Savings

Petroleum energy extracts wealth from our communities that it is still possible to redirect toward just transitions. Health cost savings from cutting harmful co-emissions along pathways to the



14. California jobs per $million revenue by economic sector, 2012.

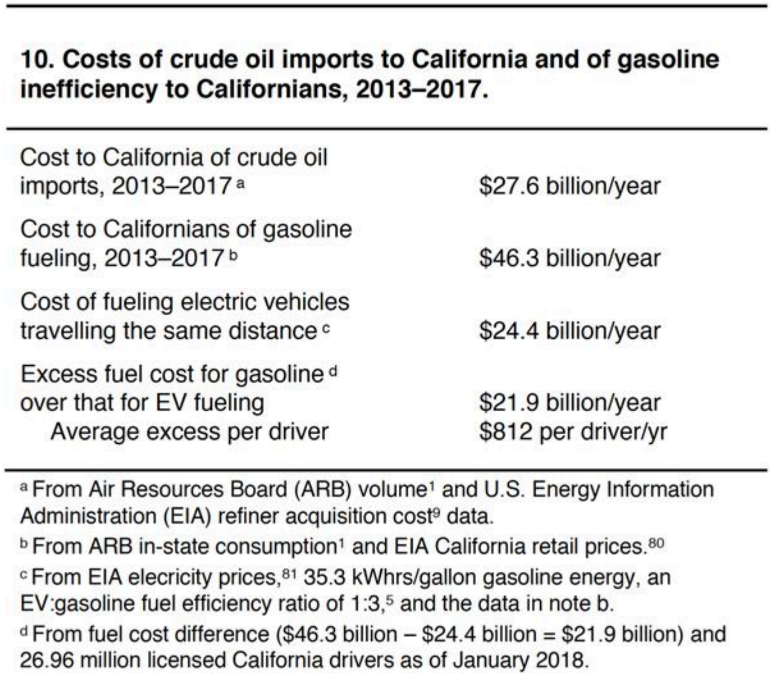
Red bars show oil refining and extraction. Green bars highlight some of the sectors likely to expand in the transition from oil. [a] Employees and "sales, shipments, receipts, revenue, or business done" from the 2012 Economic Census.[10]

state's 2050 climate limit could total more than $197–343 billion ($6.36–11.1 billion/year). This is a conservative estimate, based on premature deaths associated with exposures to petroleum fuel chain $PM_{2.5}$ emissions alone (chapters 1–2) and U.S. EPA's $9MM/death estimate.[1] It may in fact underestimate co-pollutant cost savings significantly. Recent research using more detailed statewide exposure assessment suggests that the difference between co-pollutant emissions from all sources among paths to California's climate targets alone could account for health cost savings of $65.7–101 billion/year.[64]

Meanwhile refiners' growing dependence on imported crude extracts wealth from the state that our transition to sustainable alternatives could invest here instead. Costs of crude imports sent an average of $27.6 billion/year out of California from 2013–2017. See Table 10. Crude import cost savings that could be invested in early transitions[1] could grow from $1.22–2.37 billion per year during 2020–2022 to $22.1–27.6 billion per year by 2038–2050, assuming the same crude prices.[†]

At the same time the outdated, fundamentally inefficient vehicle technology that the petroleum fuel chain relies upon wastes a fortune as heat. Total costs to drivers of battery electric cars are dropping below those of gasoline cars largely because EVs are using only about one-third as much energy as gasoline cars per mile.[5, 7] Switching from gasoline to electric cars could save Californians ≈ $21.9 billion/year in fuel costs at current prices. See Table 10. That's an average of $812/year per driver. (*Id.*) And it's from energy efficiency savings, which means that after spending less to support making clean electricity fuel here than we spent on petrofuels extracted elsewhere, these savings could help with other just transition needs.

[†] In-state extraction also must be phased down.[1] This can be done in a just way; see *Last Chance Alliance* for details.[65] In fact, short sighted plans to double down on the state's dwindling, climate-constrained oil resources risk the future of some communities' entire economies.



10. Costs of crude oil imports to California and of gasoline inefficiency to Californians, 2013–2017.

Cost to California of crude oil imports, 2013–2017 [a]	$27.6 billion/year
Cost to Californians of gasoline fueling, 2013–2017 [b]	$46.3 billion/year
Cost of fueling electric vehicles travelling the same distance [c]	$24.4 billion/year
Excess fuel cost for gasoline [d] over that for EV fueling	$21.9 billion/year
Average excess per driver	$812 per driver/yr

[a] From Air Resources Board (ARB) volume[1] and U.S. Energy Information Administration (EIA) refiner acquisition cost[9] data.

[b] From ARB in-state consumption[1] and EIA California retail prices.[80]

[c] From EIA elecricity prices,[81] 35.3 kWhrs/gallon gasoline energy, an EV:gasoline fuel efficiency ratio of 1:3,[5] and the data in note b.

[d] From fuel cost difference ($46.3 billion – $24.4 billion = $21.9 billion) and 26.96 million licensed California drivers as of January 2018.

From Extractive to Cooperative Economics

Most of us surely would choose these benefits that redirecting money from oil to climate-compatible alternatives could give our families—if we could get them. Fortunately, economic policy tools which our state and local governments can use could do that. We have this collective choice.

Many types of taxes are more just, targeted, and transparent in response to public needs than the carbon trading charges reviewed in Chapter 5, and for these reasons could be more effective at redirecting money from oil to climate-compatible alternatives.

Taxing income, wealth, and oil company profits could be more just than carbon charges refiners pass on at the gas pump, where most of us spend more of our income than the rich just to get to work. Targeting higher taxes at inherently harmful businesses, such as oil as well as tobacco companies, could redirect more money from oil to just transitions than carbon trading, which charges every business under cap-and-trade at the same rate per ton of CO_2e emitted. Spending this money through transparent city, county, and state policy decisions could be more responsive to communities' just transition needs than letting oil and other vested interests decide how to maximize their profits under cover of non-transparent carbon trading markets.

State and local policies also could ensure against community abandonment. Owners of other energy infrastructure have been required to pay up front for closure bonds used to decommission offshore oil platforms and trust funds used to decommission nuclear power plants. Here, the funds could be used to fix the mess the refiner made in the community because its site use and pollution delayed development of economic alternatives in and around the site, its closure requires cleanup before those alternatives can be developed, and at the same time that closure causes local tax and job losses. "Just Transition Bonds" could be site-specific and targeted to each community's unique needs.

These opportunities alone won't stabilize our climate: other taxes have some of the same limitations as carbon trading for making rapid systemic technology change,[53] and closure bonds alone do not require technology switching. We'll need all the tools in the toolbox to transition in time. But these opportunities show it is possible for our transitions to be just. And that's crucial.

JUST TRANSITIONS ARE NECESSARY

In addition to the technology forcing mandate that is working for electricity (*see* Chapter 5), state officials proposed to mandate cutting petroleum use for transportation in half by 2030. But that proposed mandate was stripped from Senate Bill 350 in 2015. Then, in Assembly Bill 398 (2017), the state fell back on its failed carbon trading-only policy. (*Id.*) In both cases state leaders admitted publicly that these 2015 and 2017 actions were affected by calculations about political feasibility. This is why just transitions are necessary: Solving our climate crisis without providing for peoples' needs during the economic transition which the solution will require has not proved feasible.

When we cannot take a collective action we must take to survive only because some of us need help to join in this action that everyone needs, our solution is obvious: help each other.

This is our environmental crisis. We know it is existential. We know it is urgent. We already have the technology to solve it. But not the political will—we are divided by the environmental, economic, and racial injustice that is at the root of this crisis and now threatens to sideline many people we need to help solve it. In our new, more difficult, reality for organizing and sustaining the collective actions necessary to meet our climate limit, how hard and disruptive to people's lives this could become matters.

> *More than anything else, our most feasible pathways to climate and health protection must ensure just transitions.*

State Safety Net

It's no secret that the average "new economy" job now fails to pay for the family's food, housing, health care, college, and retirement costs. People doubt this will change by magic. After all, we see carbon trading prioritize cost-effectiveness for polluters instead of ensuring that people's transition needs will be met. To refinery workers—who have decent pay and benefits because their labor actions won them—saying that we must "make a cost-effective transition" sounds a lot like "you're fired." More precisely, losing the last well-paid job one is trained for usually means earning less for years, and without support, could leave us unable to work for a sustainable future.

A climate policy that unnecessarily forces workers to choose between their family's environmental health and their family's livelihood is unjust at best. At worst it also is self-defeating. Depriving too many of the ability to meet our basic needs, we cannot do all of the work necessary to decarbonize our economy.

A more feasible climate policy would include a social safety net to help people weather the transformative disruption that we know is coming.

Public policies already guarantee health care, college tuition, housing, job transition assistance, and retirement security to *some* of us: an effective just transition policy could extend this safety net to *many more* of us. Strongly perceived needs to extend our safety net now, even before the toughest part of our climate challenge hits, have sparked renewed debate on the national stage. And California has often enacted needed policy change before it has spread nationwide. Now the state must do so to ensure its people will be able to thrive in the hard work of transforming our economy for a liveable future climate.

Targeted Local Support

Where the jobs are will change. Oil extraction and refining technology is concentrated geographically while most renewable energy technologies are distributed. Thus, replacing oil justly means more than making electric cars and buses affordable. It means intimately local, community-specific planning, siting decisions, and building work. It means financing and building a broader range of alternatives to replace disparately oil-dependent tax bases and jobs. And in communities that host refineries, it means substantial work to decommission refining capacity.

All plausible pathways to the state's climate limit retire refining capacity.[1] That means more work to replace oil-dependent taxes and jobs in these communities. It promises net jobs gains if the community has the capacity to build up sustainable economic alternatives on time (Chart 14), and threatens disparately severe tax and job losses if the community lacks this capacity.

Paths to our climate limit also would re-size refining equipment during periodic "turnarounds" because refineries must operate safely as well as efficiently at lower feed rates. *See* Table 11. The additional work to plan, engineer, manufacture, and install

11. Evolution of refinery turnaround work to implement least-impact climate and health pathways.

	What would not change	What would change
Purpose	Continued or upgraded operation within safety & health constraints	Purpose will include upgrades to meet climate constraints
Objectives	Inspect, repair, install, tie-in, or decommission equipment safely while it is not running[a]	Re-size equipment to run efficiently at gradually reduced annual feed rates[b]
Timing	Annually or biennially[c]	No change needed
Work Flow		
Planning *months–years*	Design, engineering & detailed safety analysis	More work to resize for lower feed rate[b]
Procurement *months–years*	Get eqpt., materials, & construction labor	More frequently need resized eqpt.[b]
Site prep *days–months*	Construction & plant-wide rebalance prep.	More work to resize for lower feed rate[b]
Shutdown *days*	Safely shutdown some & rampdown other units	More frequently will involve more units[b]
Inspection *weeks–months*	Find, analyze, & fix all hazards before restart	May involve more work at more units[b]
Construction *weeks–months*	Remove, repair, install, and tie-in equipment	More work to resize for lower feed rate[b]
Startup *days–weeks*	Pre-heat, ramp up, re-balance refinery, debug	More frequently will involve more units[b]

[a] Refining equipment that cannot be accessed while it is operating is shut down for inspection, maintainence, and construction or repair and is re-started afterward. Refiners call this a 'turnaround.'

[b] Gradually cutting feed rates reduces hazardous materials volume and process hazard *and* requires re-sizing refinery equipment to run efficiently at lower rates. Least-impact climate paths thus employ more labor to design, build, and install this re-sized equipment, in turnarounds that would recur as feed rates decline, from 2020–2050.

[c] Turnarounds are essential for maintenance that safety standards *require* for many high-hazard process units each 3–5 years. Refiners prefer to do them in one part of their refinery at a time, while running the rest, and when gasoline prices are seasonally lower. For these reasons California refinery turnarounds occur each Spring and Fall. *See also* references 82–84.

re-sized equipment that could be done each year could create transition jobs for some, but not all, current refinery workers.

This need for community-driven transitions, each tailored to site-specific opportunities and needs, is why a "Just Transition" is really many just transitions. Each community has its own unique constellation of transition opportunities and needs.

Ignoring site-specific transition needs could be a grave mistake. Oil refining accounts for less than 1 % of jobs statewide,[10] yet that's thousands of jobs for people who live in the regions around refineries. Worse, while figures range among communities and estimates vary, refining accounts for some 10–30 % of the local tax base in some California communities.[66–69] The same injustice that has concentrated polluting oil infrastructure in low-income communities of color has made us disparately dependent on oil for local taxes that support schools, fire fighting, public safety and other basic community needs—and the jobs doing that work.

Yet, in part because local governments lack funding, information about why this is a priority, or both, publicly reported analysis of tax-linked local jobs transition needs remains incomplete.[69] An effective just transition policy could prioritize this readily doable analysis and use it to support Just Transition bonds and targeted state safety net spending, among other means to direct transition support where it is needed most.

Just, politically feasible climate policy must get transition support to where it is needed most.

The alternative—forcing communities and workers to choose between our livelihood and our environmental health in the transition everyone needs—would do an injustice that risks everyone's future.

BREAKING THE CHAIN

The same factors that make oil inherently polluting across the inter-dependent links in its fuel chain (chapters 1–3) *also* create a key opportunity. Any of these inter-dependent links can become a bottleneck in the polluting fuel chain. Oil technology is inherently polluting, or more precisely, it is not technically feasible to reduce the carbon intensity of the technology enough to decouple oil emissions from oil flows sufficiently. (Chapter 2.) Thus, restricting oil flow at one link in the chain cuts emissions across the fuel chain. This is crucial in California's setting.

Place-based factors

The same conditions that put emissions from extracting imported oil and burning exported fuels refined here beyond the state's reach (chapters 1, 5) create another key opportunity. These same conditions place all the direct emissions from refineries here squarely within the state's reach—and that of our communities hosting refineries. Together with the technology factors that are reviewed above, this means we can cut emissions across the fuel chain of oil refined here by using our state and local authority to cut oil flow by decommissioning refining capacity.

Technology-forcing mandates like in the electricity sector

Similar logic led to the plant-specific emission limits and fossil fuel energy delivery limits that have begun to replace fossil fuels and cut emissions in California's electricity sector. (Chapter 5.) Following this logic, the state applied these power plant limits and fossil fuel energy delivery limits to the link in that fuel chain it controls; utilities.[55, 56] A similar combination of technology-forcing limits, tailored to refineries and coordinated to ensure that transportation here will not need the refining capacity it decommissions, can decarbonize transportation in California, and cut emissions across the fuel chain of oil refined here.

The same limitations that make refining technology inherently polluting mean that limiting refinery feed rates can cut mass emissions from refineries. Indeed, oil feed rate "throughput" limits on emissions of combustion co-pollutants of CO_2—$PM_{2.5}$, oxides of nitrogen and sulfur, and others—are widely used and proven in practice at California refineries.

Gradually declining mass and feed rate limits on CO_2e and combustion co-pollutant emissions from each refinery can ensure an emission trajectory to climate and health protection will be achieved in the state's oil sector. On paths without new projects to expand or prolong refinery operation, for example, these limits achieve the oil sector's share of emission cuts to the state's 2050 climate limit by cutting each refinery's feed rate 5.0 % per year starting in 2020, 5.5 %/year starting in 2021, or 6.0 %/year starting in 2022. (*See* Supporting Material[1] Table S14 for data.)

Refining is the critical link in the petroleum fuel chain for climate and health protection in California.

All of these refinery limits could be set now using the same land use authority communities are using to stop refinery expansions. The state's air districts and Air Resources Board can set these limits on CO_2e co-pollutants now using their health protection authority. And the districts and ARB could set these limits based on health *and* climate protection authority—if the state rescinds the exemptions it gave refiners from carbon-cutting limits set by air districts or ARB under its carbon trading scheme (Chapter 5).

Coordinating this timed oil phase-down with existing plans to increase the share of zero emission vehicles in transportation could then complete an effective technology-switching policy across the petroleum fuel chain in California.

Despite the built-in efficiency advantage (Table 10) and current subsidies favoring electric vehicles, federal interference threatens to trump effective vehicle efficiency standards, and automakers still focus on selling petroleum-fueled cars here. An alternative backstop to vehicle technology-switching incentives may be needed to ensure that we meet our climate limit. California has opportunities to set up this alternative backstop. For example, it might set gradually declining limits on new petroleum fuel vehicle registrations that ensure our transportation technology shift is coordinated with the refining capacity decommissioning needed along paths to our climate limit. That would limit fossil fuel energy delivery in our transportation system, much like the state's successful Renewables Portfolio Standard limits fossil fuel energy delivery in our electricity system. It won't solve our crisis with oil by itself—unlike the state's utilities, refiners here export a large and growing portion of the fossil fuel energy they produce. But it could backstop incentive policies to make sustainable mobility affordable and protect low-income drivers from unnecessary gas price spikes as we decommission refining capacity on otherwise feasible paths to our climate limit.

TIMING

Time is of the essence, as shown in chapters 2–4. Confusing the timing of causes and effects is a mistake: we don't have until 2030 or 2050 to wait for irreversible effects that we can prevent by addressing their causes now. Moreover, the fallacy that we have more time than we really do leads to false solutions. Now, waiting for more study of unproven technologies (Chapter 2), or for more experiments with carbon trading schemes that failed, are likely to fail again, and literally prohibit using all the tools in the policy toolbox (Chapter 5) could wait until it's too late.

Chapter 3 documents a crucial difference in potential transition impacts between early action and delayed action pathways to the state's climate limit. Starting in 2020–2022, the limit can be met by decommissioning 4.4–8.6 % of refinery capacity annually.[1] This would challenge communities that host refineries to replace ≈ 0.44–2.6 % of the local tax base annually, assuming currently available data suggesting oil pays 10–30 % of the local taxes.[66–69] That's hard work, but doable with transition support and, since refining is jobs-poor (Chart 14), should create *more* jobs locally.

In contrast, waiting until June 2033 could make most currently feasible paths to the limit impossible and force as much as 90 % of all refining capacity—and 27 % of the community's tax base and the local jobs it supports—to be lost in only 1–3 years.[1, 66–69] For the feasibility of meeting our climate limit, this difference between transition benefits along early action paths and severe community impacts on delayed action paths could be pivotal.

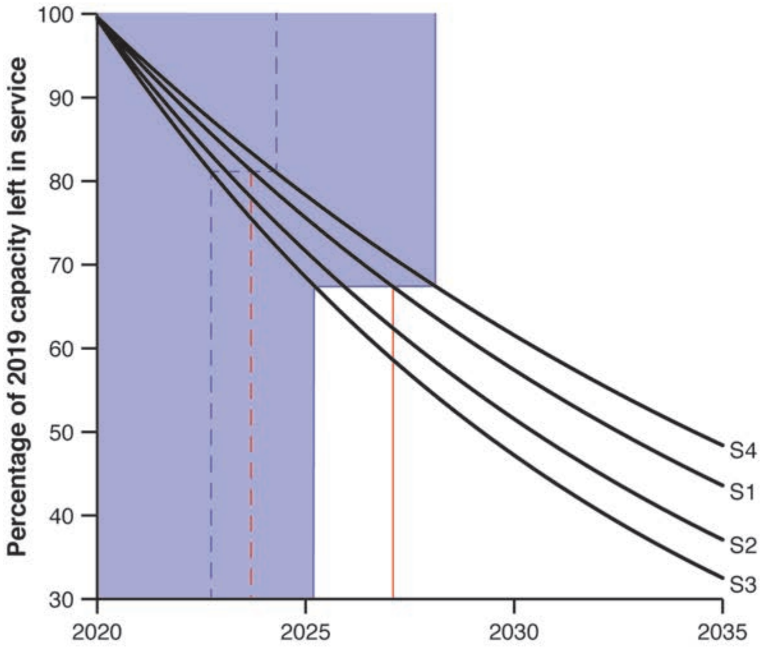
Early action pathways to the state's climate limit also minimize climate-stranded assets (Chapter 4) and the risk that too little refining capacity might be reserved for potentially irreplaceable products (Chapter 3). Early action thus limits refiners' incentives to protect their assets as well as risks that future activities such as air travel might be curtailed. This remarkable alignment of transition, asset, and risk reduction benefits further reveals the greater feasibility of early action paths.

Justice now

Refining imported oil to export fuels Californians don't need or use causes excess pollution of disparately-exposed nearby communities. (Chapter 5.) This *also* reveals that an action for climate justice need not pose any risk to California fuel supplies.

Nearly 19 % of gasoline and diesel production and 33 % of total fuels production by California refineries was exported to other states and nations from 2013–2017.[1] Along all plausible paths to the climate limit that start to decommission this export capacity first in 2020, all refining capacity for fuels used in California can stay in place for at least 3–9 years (2020 through 2022 to 2028; *see* blue shading and lines in Chart 15). And it can stay in place for at least 4–8 years (red lines) in likely scenario S1. (*Id.*)

Chart 15 illustrates the likely 4–8 year range and plausible 3–9 year range of this estimate as the horizontal distance between data for gasoline and diesel exports only (dashed red/blue lines) and data for all refined fuels exports (solid red/blue lines). Since some of the other fuel exports are byproducts of gasoline and diesel refining, the true value will fall within this range.



15. Effect of decommissioning refinery export capacity first along early action pathways to the state's climate limit [a]

╲ **Pathway to 2050 climate limit starting in 2020 by scenario**

▨ **Period when decommissioning export capacity (dashed line: gasoline & diesel export capacity) can achieve path. Red lines: period if carbon intensity does not change**

Scenarios

S1. No change in current rate of emission per barrel of oil.
S2. Switch to low-quality oil starts 2020; complete by 2031.
S3. Switch to very low-quality oil from 2020–2031.
S4. Switch to lighter U.S. average oil feed quality and install all feasible refining and extraction upgrades, 2020–2026.

[a] Assumes all other (non-petroleum) emissions make steady progress to the state's 2030 and 2050 climate targets and ≥ 20 % of 2019 refining capacity is reserved through 2050 for production of potentially irreplaceable products. Recent and planned future switching to renewable fuel vehicles would extend the red and blue lines shown even farther toward the right in this chart. See Supporting Material[1] tables S1, S14–S17, and S19 for data.

Thus the state's ongoing effort to reduce its dependence on petroleum transportation already is at least 3–9 years ahead of our need to decommission refining capacity—so long as we do that gradually by starting to do it now.

During the same 3–9 years harmful co-pollutant emissions from refineries could be cut along with their feed rates, by more than 19 %.

This means that over the next few years, our most feasible, early action, paths to the state's climate limit could eliminate at least one-fifth of all the health impacts from refinery air pollution in nearby low-income communities of color without posing any risk to California's fuel supply. The best time to start to decommission oil refining capacity in California is now.

SOME STARTING POINTS

This research suggests some immediate, technically feasible and mutually-reinforcing actions which, taken together, would help to ensure that achieving climate and health protection could be economically sustainable for all Californians—and thus, more likely to prove feasible *politically*. Communities could organize to hold our public officials accountable for these actions:

Support just transitions

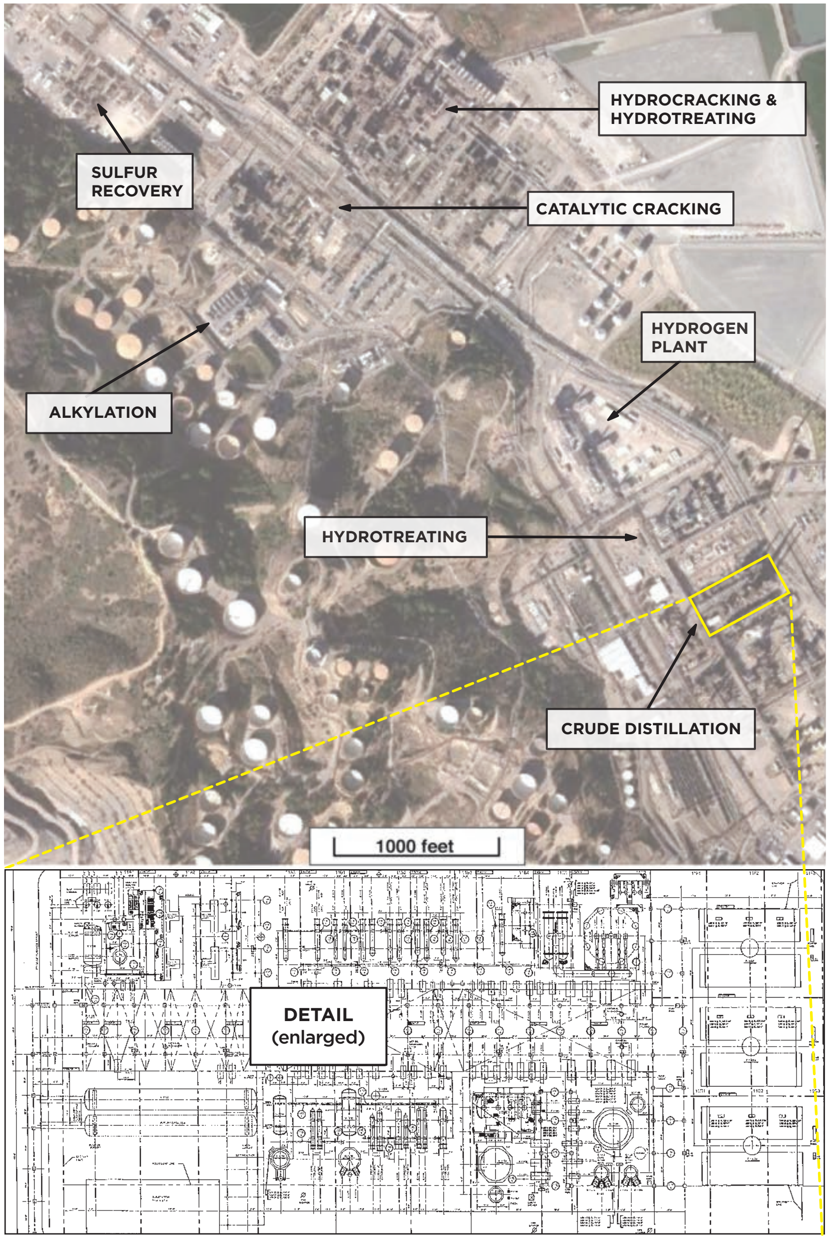
1. Extend our social safety net so that all those whose jobs or communities are now dependent on oil are guaranteed support for job transition, health care, college tuition, housing, and retirement security. *State* officials could take this action.
2. Establish Just Transition Bonds to remedy site-specific legacy impacts, including pollution and deferred development of sustainable economic alternatives. Secure a Bond from each refiner up front to ensure against abandonment upon closure. *City, county,* and *state* officials could take this action.
3. Quantify local taxes and fees paid by oil companies and develop sustainable alternatives to replace these revenues locally as refineries decommission. *City* and *county* officials could take this action.

Decommission refining capacity

4. Acknowledge that quickly starting a gradual decommissioning of refining capacity is an essential part of the most feasible paths to achieving state climate goals with proven technology. The state's *Air Resources Board* could take this action.
5. Set facility-specific refinery combustion emission limits on pollutant mass and oil feed throughput which decrease at rates needed to ensure that state climate and health protection goals are met (e.g., –5 % and –6 % per year starting in 2020 and 2022, respectively, assuming action number 9 below). *City, county, regional* and *state* officials could take this action.
6. Ensure that California's transportation fuel-switching effort outpaces its need to decommission refining capacity through aggressive measures to ensure clean mobility for all people. *State* officials could take this action.

Change the rules

7. Challenge the environmental injustice of permitting harmful refinery emissions solely to export fuels that Californians do not use or need. *City, county, regional* and *state* officials can take this action.
8. Revise state law to rescind the exemption from carbon-cutting emission limits on refineries and the carbon trading-only policy for oil refining enacted by Assembly Bill 398 in 2017. *State* legislators and *Governor Newsom* could take this action.
9. Reject new construction projects that would expand or prolong the operable duration of oil refining capacity. *Governor Newsom* could take this "moratorium" action by executive order. Alternatively, *communities* can continue to hold public officials accountable for rejecting these projects.



A refinery's processing equipment viewed from the sky. Chevron Richmond processing yards. Detail: Crude distillation unit schematic illustrates equipment components in a refinery process unit. Images from City of Richmond permit files and EIR SCH #2011062042.

Photo: CBE

BACKGROUND:
REFINING TECHNOLOGY, SYSTEM BOUNDARY

HOW REFINERIES WORK

Crude oils are complex, widely-ranging mixtures. Depending on the crude oil, much or most of the hydrocarbons—compounds of hydrogen and carbon—in it will have too many carbon atoms bonded together, too few hydrogen atoms per carbon, or too many contaminants, to burn them in gasoline, diesel or jet engines.

To make more of the crude into engine fuels refiners break carbon bonds in those hydrocarbons, add hydrogen, remove contaminants, and reformulate (rebuild) the hydrocarbons. They do each of these things to an extent that varies with the specific properties of the oils they buy and the fuels they want to sell. All this requires processing different components of the crude fed into the refinery in different ways. To do that, they must separate one component from another.

This separation is done by boiling the oil (distillation). Carbon bonds are broken (cracked) in catalytic cracking, coking, and hydrocracking units. Hydrocracking is hydrogen addition cracking and also removes contaminants—but it requires lots of hydrogen, which refiners make from fossil fuels by steam reforming. Hydrotreating adds hydrogen and removes contaminants. Contaminants removed are handled by processes such as sulfur recovery. Hydrotreating, catalytic reforming, alkylation, and isomerization are reformulation processes. Blending outputs of all these process steps yields gasoline, diesel and jet fuel.

Oil refining is this sequence of processing steps and a refinery is the collection of interconnected equipment that performs them. See an example of what this looks like on page 84.

The same carbon rich, hydrogen-poor, contaminated hydrocarbons that require cracking, coking, and hydroprocessing to make engine fuels make crude oils in which such compounds are more abundant denser (heavier), dirtier (e.g., higher-sulfur), lower quality oils.

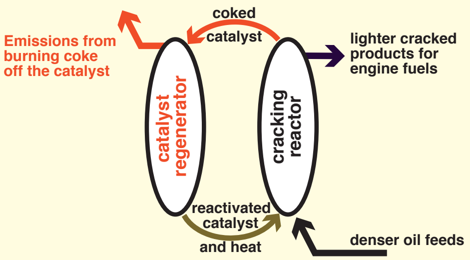
Side effects of making engine fuels from lower quality oils affect petroleum fuel chain emissions in at least six ways.

First, this makes fuels refiners burn dirtier. For example, petroleum coke—a dense, carbon rich, highly contaminated solid or semi-solid cake, powder or deposit that burns roughly as dirty as coal—forms as a byproduct and is burned in catalytic cracking. This unavoidable side effect is built into its process design. It makes cat cracking the major emitter of $PM_{2.5}$ in many refineries. Petroleum coke formation, burning, and emissions increase as cat cracking oil feed rates increase.

Second, making engine fuels from lower quality oil adds dirty-burning byproducts to the refined fuels mix. For example, petroleum coke formed as a byproduct of boosting engine fuels production by coking is removed from this process—again as part of its intrinsic design—and is sent to be used elsewhere. This “marketable” coke is typically burned in power, cement, and smelting plants. Petroleum coke accounted for ≈ 16% of total California refined fuels exports from 2013–2017.[1]

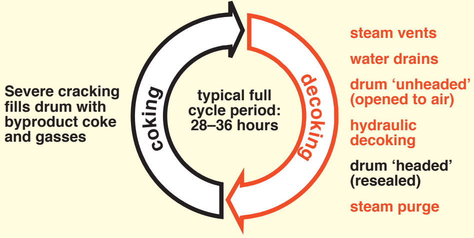
SIDE-EFFECTS OF REFINERY PROCESSING: THREE EXAMPLES.

CCU PROCESS FLOW



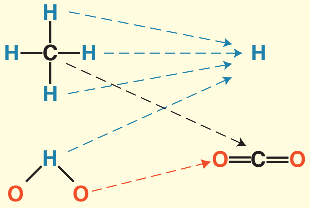
Petroleum coke, an extremely dirty-burning fuel, forms as a by-product and is burned in catalytic cracking units (CCUs).

DCU DRUM CYCLE



The petroleum coke byproduct formed in delayed coking units (DCUs) is removed from them and sent to be burned elsewhere.

SMR SHIFT REACTION



Hydrogen (H) production by steam methane reforming (SMR) creates and emits approximately ten tons of CO_2 for each ton of hydrogen produced.

Third, it emits huge amounts of carbon dioxide (CO_2) as a process reaction byproduct. Hydrocracking denser oils to make engine fuels typically consumes hydrogen at ≈ 300 times its oil feed volume.[18] The steam reforming shift reaction that makes this hydrogen strips it from fossil fuel feedstocks. The carbon from those hydrocarbon feedstocks then bonds with oxygen as CO_2. Even with the lowest-carbon feed, methane steam reforming emits ten tons of CO_2 per ton of hydrogen produced. *See* side effects diagram, above. Hydrogen production increases along with hydrocracking capacity and crude feed density across the U.S. industry[18] and can account for more than 30 % of total direct CO_2e emissions from refineries processing very dense oil feeds.[1]

Fourth, it increases the likelihood of higher emissions over time by doubling down on long-lasting capital infrastructure. The oldest half of California refining capacity today has an operable duration of 21–31 years.[1] And the part of this capacity built to make engine fuels from as much of the crude barrel as possible represents high value assets. For example, the capacity-weighted values of cat cracking, coking, hydrocracking, and alkylation are 6–10 times that of crude distillation, based on capital cost and production value as measured by the Nelson Index.[1] This capital infrastructure represents a commitment to future emissions.[19] Such capital asset commitments can be broken, but make it harder to break out of carbon lock-in.

Fifth, it facilitates higher-carbon, higher emitting oil extraction. Refineries buy the grades of crude they are built to process. Those built to make engine fuels from denser crude oils buy more of these oils. So more of these oils get extracted. These denser, more viscous oils are generally more difficult and higher-emitting to extract.[19–21] Refining the densest crude feed of any major U.S. refining region on average,[22] California refiners support high-emitting extraction here[13] and are seeking to import more oil from the notoriously polluting Canadian tar sands.[23]

Sixth, it increases combustion emissions per barrel of oil refined. Making engine fuels from denser, more contaminated crude takes more work, which takes more energy. It increases the processing and energy intensities of oil refining.[18] Burning more fuel per barrel for that energy, refiners emit more combustion pollutants.

The quality of crude refined can affect refinery emissions of carbon dioxide equivalents (CO_2e) dramatically.[18–24] Refining the densest crude feed on average, California refineries emit more CO_2e, as measured in kilograms emitted per barrel of crude refined, than those in any other major U.S. refining region.[18,22–24]

The importance of these considerations—and especially their implications for the plausible range of future petroleum fuel chain carbon intensities—is described in chapters 1–4.

HOW REFINERIES WEAR OUT

There are many data to describe the operable duration (OD) of oil refining equipment—and, for some of the same reasons, several categories of these data.

Hundreds of interconnected equipment "units" perform various functions to process crude in a refinery.[1] The various types of units have different capital costs and production values to the refiner. They run under often-severe but different operating conditions, wear at different rates, and must be repaired, rebuilt, or replaced at different times. And the various processes have often-severe but different pollution and safety hazards, which require unit-specific environmental and safety permits that are meant to—and often do—record startup, rebuild, and replacement data.

The operable duration (OD) estimate reported here is based on these data for 1,637 California refinery equipment units.

CBE used the California Public Records Act to query air districts and land use authorities for the dates of initial startup, major rebuild, permanent shutdown, and the operating status, of process units at California refineries. All data found were analyzed for 12 process types—atmospheric crude distillation, coking, catalytic cracking, hydrocracking, hydrotreating, hydrogen production, catalytic reforming, alkylation, sulfur recovery, marine ship loading, storage tanks, and heat/steam/power (furnace, heater, boiler and turbine) units. This data sample[1] includes direct observations of 1,637 equipment units in real-world operation.

Current process *unit* age is the time from initial startup, or major rebuild, if any, to May 2018, for each unit. Process *type* age is the median age of the units of each process type. Process *unit* operable duration (OD) is the time from initial startup or major rebuild to retirement or, if the unit is still operating, to May 2018.

This May 2018 cutoff provides a data-driven minimum OD estimate, but since many newer units will run long after 2018, it underestimates their OD. Due in part to this, process *type* OD is estimated as the minimum time that the longest-lasting 5–30% of equipment has been in service. At the upper bound this estimate includes less new equipment that will run long after 2018 but is based on fewer data. At the lower bound, the time that the oldest 30% of the equipment has been in service, it is based on more data but includes more equipment that could run beyond 2018. Overall this results in a conservative, likely underestimate, of OD.

As expected given their differing functions, operating conditions, wear rates and replacement rates, the process types have different ages and ODs. Median age ranges across process types from 21.4–49.3 years.[1] OD ranges from 49.3–69.3 years at the lower bound (upper bound: 54.1–90.3 yrs) across these process types.[1] And as these expected differences should remind us, processes also have different capital costs and production (profits) values to refiners.[1] Based on the industry standard "Nelson" weighting factors and statewide refining capacities as of 2018,[1] those values vary across the processes built here by a factor of ≈ 2.5 times.

Accounting for all of these data and differences between process types, the process-level data are weighted by the Nelson factors to estimate the as-built operable duration of statewide refining capacity (57.7–67.8 years) and its median age now (36.4 years).[1] Subtracting this median age from this as-built OD, the oldest half of existing California refining capacity would not fully wear out for ≈ 21–31 years. These results give an initial capacity loss of ≈ 1.59–2.34% per year.[1] Finally, to account at least in part for potential reductions in processing severity and wear at lower rates, these percentage losses are applied sequentially, to the remaining capacity in each prior year of the estimate trajectory.

Factors affecting the operable duration of refining capacity.

Inside the refinery—its equipment units

1. Projects to add or replace equipment
2. Maintenance including temporary shutdown 'turnarounds'
3. Operable durations of critical equipment types in the refinery
4. The age of each critical equipment unit in the refinery
5. Capital invested in critical equipment units in the refinery
6. Production value to the refinery of each critical equipment unit
7. Changes in the severity of operating conditions in the refinery

Outside the refinery—its position and setting

8. Public acceptance, permits and permit conditions
9. Access to oil of the grades it is designed to process
10. Access to refined products markets
11. Relative size (returns to scale) of competing refineries
12. Relative productivity of competing refineries
13. Relative operating costs of competing refineries
14. Subsidies, tax breaks and other externalized costs

This estimate accounts directly for factors 2–7 in the box above: *Factors affecting the operable duration of refining capacity*. And California refiners' access to global crude and refined products markets[13–15] and competitive capacities for high-value products, low-cost crude, and returns to scale[1] (factors 9–13) further suggest that this estimate is reliable and conservative. But this OD estimate does not speculate about factors 1, 8 and 14. That's crucial: We *could* allow new projects to increase refining capacity—*or* stop accepting unsustainable externalized costs by starting to decommission refining capacity instead of letting it pollute until it wears out.

All of these data are given along with details of the methods used to analyze them in Supporting Material tables S20–23.[1] Chapter 4 describes the importance of these operable duration considerations to identifying the least-impact, most just, most *feasible* pathways to climate and health protection.

SYSTEM BOUNDARY

All CO_2e emissions associated with activities in the state were included in this analysis—including those from producing imported electricity used in the state, extracting imported oil refined in the state and burning exported fuels refined here. This is a consistent and inclusive "system boundary." In contrast, an exclusive system boundary could exclude all of those import/export emissions, and an inconsistent system boundary could exclude import/export emissions associated with oil but include those associated with electricity. The system boundary chosen has no direct effect on the timing or pace of emission cutting trajectories to state climate targets: The timed percentage cuts targeted define a cumulative limit that is proportionate to the current emissions included in the system boundary. However, the choice of system boundary affects the accuracy of pathway feasibility analyses in other ways.

Inconsistent system boundaries can lead to false conclusions about pathways' climate impacts. For example, import/export emissions associated with oil refined in-state increased by a greater amount (≈ 20 Mt/yr)[1] than those associated with electricity used in the state decreased (≈ 16 Mt/yr)[25] from 2013–2017. By excluding these oil emissions while including these electricity emissions in their GHG Inventory[25] state officials could wrongly conclude that their current path is shrinking the global carbon footprint of energy systems here when, in fact, it could be expanding.

Excluding both oil and electricity import/export emissions from the analysis doesn't solve this problem—the global footprint of energy fuel chains here could still expand undetected.

Moreover, an exclusive system boundary obscures interactions of fuel chain components that affect the feasibility of pathways to climate stabilization. For example, had the state ignored electricity import emissions it may not have taken actions that cut them, such as its emission standard[56] which, in effect, bans longterm power purchase contracts with coal-fired power plants in western North America.

Similarly, environmental health and justice impacts from refining imported oil to export fuels also represent a post-tax subsidy to extract and burn that oil elsewhere, which could be reversed by actions within the jurisdiction of communities here.

Another example: California's GHG Inventory excludes emissions from burning jet fuel that is refined here in cross-border flights.[25] That obscures the magnitude of emission cuts from potentially feasible alternatives to petroleum jet fuel, such as developing jet biofuel production capacity here, cooperating with other states to expand high speed rail networks, or both.

Finally, export accounting problems make exclusive system boundaries unstable. For example, until in-state alternatives like those mentioned above are in place, state and federal political boundaries put most jet fuel emissions beyond California's jurisdiction. Thus, in a crucial sense—what we can do about it here and now—CO_2e from burning ≈ 91 % of California refinery jet fuel production[1] is exported.[††] But that could change if in-state alternatives to petroleum jet fuel prove feasible. Then, these "political boundary" exports could jump the boundary to become emission-cutting targets for fuel-switching and transportation mode-switching within the state's jurisdiction. An exclusive system boundary could either wrongly include these exported jet fuel emissions now, or wrongly exclude them later.

Indirect effects of this jet fuel accounting problem include significant uncertainty in the timing and pace of emission trajectories to state climate targets. (*See* Chapter 3.) This uncertainty was identifiable and quantifiable (*Id*.) only by analysis of an inclusive system boundary.

[††] In this crucial analysis, from 2013–2017 ≈ 33 % of all fuels refined here were exported.[1] This compares with refined fuels exports of ≈ 20 % if jet fuel burned in cross-border flights is excluded from those exports.

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Air districts (California): Regional agencies charged with controlling emissions from industrial facilities and other buildings. The South Coast Air Quality Management District, Bay Area Air Quality Management District, San Joaquin Valley Air Pollution Control District, and San Luis Obispo County Air Pollution Control District each has one or more oil refineries in its jurisdiction.

Air Resources Board (ARB): the California agency charged with controlling emissions from cars, trucks, buses, and boats, and charged with leading statewide climate protection efforts.

API Gravity (°API): A measurement of the density ("heaviness") of oil promulgated by the American Petroleum Institute (API). °API expresses Specific Gravity (SG) on reverse scale, so that oils with higher SG have lower °API. To convert between API Gravity (°API) and Specific Gravity (SG), use these equations:
$°\text{API} = (141.5 \div \text{SG}) - 131.5$; and
$\text{SG} = 141.5 \div (°\ \text{API} + 131.5)$.

Atmospheric crude distillation: A refining process that separates the mixtures of hydrocarbons in crude oils into their component oil streams, each of which has different properties, for subsequent component-specific processing in other refining units. Atmospheric distillation operates at atmospheric pressure and temperatures up to 350°C, and is the first major step refiners use to make crude oil into useful products. *See* also *distillation, vacuum distillation.*

Barrel (oil): 42 U.S. gallons; one cubic meter contains 6.29 barrels.

Bitumen: Natural bitumen. A very dense, viscous, contaminated portion of the spectrum of petroleum that has fundamentally different extraction and refining properties than conventional crude. Bitumen typically must be heated, mixed with lighter oils in diluted bitumen "dilbit" or pre-processed to convert it into less viscous "synthetic" crude oil for transport to refineries. *See* also *tar sands.*

Butane: A hydrocarbon gas produced in oil refining that is burned as fuel and used to make petrochemicals. California refiners typically burn butane as process fuel or blend it into gasoline or LPG. See also *liquified petroleum gas (LPG).*

Capacity (oil refining): The volume of oil that a refinery process unit, a refinery, or a refining fleet is capable of processing under specified conditions. The conditions are specified as barrels per stream day (b/sd), the maximum volume under ideal theoretical conditions; ***or*** barrels per calendar day (b/cd), the maximum volume accounting for bottlenecks in refineries, environmental constraints, and downtime for maintenance and repair; ***or*** capacity utilized, based on the actual oil feed rate. The actual feed rate accounts for all constraints inside and outside the refinery, is observed rather than predicted, and is the baseline measurement for the analyses of capacity to be used or decommissioned through 2050 in this report. See also *feed rate, process unit.*

Carbon dioxide equivalents (CO_2e): A measurement of the global warming potential (GWP) associated with mixtures of chemicals, where carbon dioxide (CO_2) has a GWP value of 1, other chemicals' GWP values are scaled relative to CO_2, and CO_2e is the sum of these chemicals' GWP values. Because different chemicals have different potencies and persist in the atmosphere for different periods, this measurement includes a time horizon, expressed as GWP over a specified number of years. The most commonly used horizon, 100-year GWP, is used in this report. *See* the 4th Assessment Report of the Intergovernmental Panel on Climate Change for more details.

Carbon intensity (CI): The amount of climate emission caused by a given amount of activity at a particular emission source. The CI of oil can be measured per barrel of oil used. In this report, CI is measured as the mass of CO_2e emitted from oil extraction, refining, and end use of refined products per barrel of oil refined in California.

Carbon lock-in: Resistance to change of CO_2e-emitting systems, which is caused by mutually reinforcing technological, capital, institutional, and social commitments to the polluting system which have become entrenched as it was developed and used. Carbon lock-in is a type of path dependance. See also *infrastructure inertia, operable duration, path dependence, social inertia, stranded asset.*

Catalyst: A substance that facilitates a chemical reaction without being consumed in the reaction.

Catalytic cracking: A carbon rejection cracking process that uses a catalyst and temperatures up to 500–600 °C to convert heavy gas oil into engine fuel feedstocks, gases, and a type of petroleum coke that deposits on and deactivates its catalyst. The catalyst is reactivated continuously by burning off the coke, which also supplies most of the process heat, and makes this an exceptionally polluting refining process. See also *catalyst, cracking, petroleum coke.*

Celsius (°C): A scale for measuring temperature in which water freezes at zero degrees and boils at 100 degrees. Centigrade. A 2°C increase in average global surface temperature is an increase of 3.6 degrees Fahrenheit (°F). To convert from °C to °F use this equation: $^{\circ}F = (^{\circ}C \bullet 1.8) + 32$.

Climate: Atmospheric conditions over years to centuries, including average conditions and the extent of variability in those conditions, such as the frequency, severity, and impact zones of droughts, floods, heat waves, cold snaps and storms.

Climate limit: The maximum amount that human activity can change the climate without unacceptable harm. This limit has been expressed by international consensus as interrelated limits on global temperature rise, CO_2e accumulation in the upper atmosphere, and cumulative emission. The climate limit defined by the emission targets California has adopted, approximately 10.5 Gt from 2017 to 2050 as shown in this report, is consistent with the state's share of the global emission cuts that give a 67 % chance of holding the rise in average global surface temperature to between 1.5°C and 2°C above pre-industrial levels. Deeper cuts could be needed here for a better than 67 % chance, for achieving 1.5ºC, for California's *per capita* share of effort, or if unproven and limited carbon sequestration technologies cannot get the rest of the way to "carbon neutrality" for climate stabilization. See also *climate targets (California), Gigaton (Gt), Paris Accord.*

Climate targets (California): The sequence of continuous and progressively deeper emission cuts, expressed as annual statewide emission levels in executive orders and laws. These levels target cuts to the 1990 emission rate by 2020, 40% below the 1990 rate by 2030, and 80% below the 1990 rate by 2050. This sequence of cuts defines a cumulative limit on statewide CO_2e emission from 2017–2050 of approximately 10.5 Gt. See also *climate limit, Gigaton (Gt), Paris Accord.*

Co-emission: The release of more than one type of pollutant from a single source, activity, or root cause. Particulate aerosols, oxides of nitrogen, and oxides of sulfur are among the toxic and smog-forming combustion products that co-emit with CO_2 from burning fuels to extract and refine oil. See also *co-pollutant.*

Co-pollutant: A pollutant that co-emits from a specific source, activity, or root cause along with another, referenced, pollutant. Particulate aerosol $PM_{2.5}$ is a CO_2e co-pollutant from fuel combustion in oil refining. See also *co-emission.*

Coking: A refining process that uses carbon rejection cracking of "resid" exposed to temperatures up to 565ºC for hours to convert it into engine fuel feedstocks (e.g., naphtha), catalytic cracking and hydrocracking feedstocks (e.g., gas oils), gases to be burned as refinery fuel or used as LPG feedstock (e.g., butane, propane), and a dirty byproduct, petroleum coke. Delayed coking is a batch process because the reaction vessel must be cooled and opened to remove the coke before the next coking cycle; fluidized coking is a continuous process. Gases produced in coking are dirtier-burning than other types of refinery fuel gas. See also *cracking, petroleum coke, resid.*

Cracking (refining): Breaking the bonds between carbon atoms in the hydrocarbons of an oil stream under severe reaction conditions that either reject carbon atoms or add hydrogen atoms, and thereby converting the oil into a mixture of lower-boiling and lighter oils. Refiners use carbon rejection cracking, such as coking and catalytic cracking, and hydrogen addition cracking, such as hydrocracking, to make more gasoline, diesel, and juet fuel from each barrel of crude.

Crude oil: Petroleum after extraction and before refining, crude oils are complex, widely-ranging mixtures of hydrocarbons, heteroatoms (e.g., sulfur, nitrogen), and toxic or potentially toxic trace elements. Crude oil accounts for more than 90% of the operating cost of an oil refinery. See also *oil quality, petroleum.*

Cumulative emission: The total mass of pollutants emitted from one or more sources during a specified period. For example, 0.356 Gt of CO_2e was emitted from oil refined in California in 2013, 0.369 Gt in 2014, 0.357 Gt in 2015, 0.374 Gt in 2016 and 0.381 Gt in 2017, so the cumulative emission from oil refined in California from 2013–2017 was 1.837 Gt.

Decommission: To retire and restore or replace the function of something that has been built and used. In energy industries, to plan and implement removal from service, dismantling, site clean up for reuse, and replacement (as needed) of energy production from the facility being retired. In these respects decommissioning is the opposite of abandonment. For example, to decommission nuclear plants, utilities built up alternative electricity resources and set up trust funds in advance to pay for radioactive site cleanups.

Deep Decarbonization Pathways Project: A collaborative global inititative to explore how individual countries can reduce emissions consistent with the goals of the Paris Accord.

Distillate oils: A mixture of petroleum hydrocarbons including diesel fuels that boils in the range of approximately 200–315 ºC. Distillate oils other than kerosene accounted for approximately 19.7 % of California refinery production from 2013–2017.

Distillation (oil): The separation of an oil mixture into two or more component oil streams based on the temperatures at which the components of the oil mixture boil. Also called fractionation. Distillation of crude oil separates higher-boiling, denser oils from lower-boiling, lighter oils so that the denser oils can be fed to cracking processes, further boosting engine fuels production.

Efficiency (energy): The consumption of less energy to do the same amount of useful work. Examples: Electric cars are more efficient than gasoline cars, which convert more of their fuel energy to heat. Insulated buildings stay comfortably warm in cold weather while burning less natural gas for heating. Refining higher quality oil burns less fuel to make the same types and volumes of engine fuels from the same volume of refinery oil feed. See also *renewable energy, thermodynamics.*

End use (petroleum): The final use of petroleum after it is extracted and refined, including all uses of petroleum products that are not consumed in extraction or refining.

Engine fuels (petroleum): As used in this report, engine fuels means traditional engine fuels: gasoline, jet fuel, and distillate and diesel oils of all types and grades.

Environmental justice: Clean air, water, and soil, and healthy, safe, livable communities are human rights. Environmental justice is the condition of achieving this, and the process of achieving it, which is grounded in the interdependence of all life and the fundamental right to self-determination for all peoples. Environmental justice opposes racism, sexism, and economic injustice in our total environment. For more detail *see* The Principles of Environmental Justice adopted by the First National People of Color Environmental Leadership Summit held on 24–27 October 1991 in Washington, D.C.

Equipment (refining): Any and all built appurtenances that are used directly or indirectly to facilitate the refining of oil, including but not limited to the delivery of oil at the refining site and of refined products from the site. Some examples of refining equipment include reactor vessels, pipes, furnaces, power turbines, boilers, distillation towers, valves, pumps, compressors, heat exchangers, emission stacks, safety flares, storage tanks, and rail, truck, and ship terminals. See also *process unit.*

Export (refined product): The shipment of a refined product to another political jurisdiction; and the product that is shipped. In this report the political boundary is the California state border (except where noted). California refineries exported 20-33% of their refined fuels production from 2013–2017.

Extraction (oil): Accessing and lifting petroleum from a naturally occuring deposit in the Earth to obtain crude oil by any means, such as drilling, digging, steam injection, hydraulic fracturing ("fracking") and pumping. Extraction by drilling, strip mining, steam injection and fracking feed crude to refineries in California.

Feasible: Capable of being accomplished in a successful manner within a reasonable period of time, taking into account economic, environmental, legal, social, and technological factors. Since proven alternatives to oil are now known to be reasonably economical, social factors—societal capacity—may determine whether it is feasible to protect our climate and health by limiting cumulative emission before potentially catastrophic climate impacts become irreversible.

Feed rate (oil refining): The volume of oil fed to a refinery process unit, refinery, or refining fleet during a specified period. From 2013–2017 the crude feed rate of the refining fleet in California averaged 602 million barrels per year.

Fuel chain: The sequence of interdependent steps in the acquisition, conversion, and use of a particular type of fuel energy. For example, the petroleum fuel chain requires oil extraction and refining as well as vehicle engines and industrial devices to burn refined fuels for energy. The solar-electric car fuel chain requires solar energy collection and conversion to electricity as well as cars with electric motors. Both require energy to move from each link in its fuel chain to the next.

Fuel chain emissions: The sum total of emissions from each step or link in the fuel chain of a particular type of fuel. Petroleum fuel chain emissions assessed in this report include extraction emissions, refining emissions, and refined products emissions associated with oil refined in California. See also *refinery fuel chain (California).*

Gas oil: The relatively dense and contaminated mixture of petroleum hydrocarbons that boils within an atmospheric-equivalent temperature range of approximately 315–600 °C. Gas oil is produced in distillation and coking units and subsequently fed to catalytic cracking and hydrocracking units in substantially larger volumes as refineries process lower quality, denser oils.

Gasoline: The relatively low-density mixture of hydrocarbons that is the primary California ground transportation fuel today. There are many types and grades of gasoline, including exports that may not always meet state fuel specifications and smaller volumes burned in aviation. Gasoline accounted for approximately 57.3% of California refinery production from 2013–2017. See also *naphtha.*

Gigaton (Gt): A unit of mass equivalent to one billion metric tons.

Ground transportation: Transportation on the ground of all types. Car, truck, bus, and train ground transportation accounts for the predominant use of gasoline and distillate-diesel fuels in California.

Heavy oil: A dense form of petroleum. In petroleum extraction, a dense portion of the spectrum of crude oil that has fundamentally different extraction and refining properties from conventional crude. In refining, the relatively denser components of crude oil, such as gas oil and "resid," which are processed more intensively than lighter oils. Heavy oil is a significant portion of the crude oils extracted in California and a growing portion of California refinery oil imports.

Hydrogen steam reforming: A fossil fuel hydrogen production process supporting hydrocracking and hydrotreating of denser and lower quality oils in refining, this process uses a catalyst at extreme temperatures up to 845°C to harvest hydrogen from its feedstock. The carbon from that hydrocarbon feedstock then bonds to oxygen. Hydrogen steam reforming of methane creates approximately ten tons of CO_2 for each ton of hydrogen it produces.

Hydrocarbon: A compound of hydrogen and carbon. Crude oils and refined fuels are predominantly comprised of various hydrocarbons.

Hydrocracking: A hydrogen addition cracking process that uses heat, a catalyst, large amounts of hydrogen and extreme pressure to convert heavier oils into engine fuel feedstocks and gases and to remove contaminants (e.g., sulfur, nitrogen, vanadium, nickel) from those oil feeds. The reaction occurs at pressures as high as 3,000 pounds per square inch and temperatures up to 425°C, and can consume as much as 2,250 cubic feet of hydrogen per barrel of oil feed. Hydrocracking can shift quickly between gasoline and diesel production, and is prone to runaway reactions that cause air pollution incidents. See also *cracking, hydrogen steam reforming.*

Hydrotreating: A process that acts on the hydrocarbons in gasoline, diesel, jet fuel, LPG, or catalytic cracking feedstocks to add hydrogen to and remove contaminants (e.g., sulfur, nitrogen, vanadium, nickel) from those hydrocarbon feedstocks using a catalyst and pressure at temperatures of 270–345°C. Hydrotreating of heavy oil, such as gas oil to be fed into catalytic cracking units, requires several times more hydrogen per barrel of oil feed than hydrotreating of light oils. See also *hydrogen steam reforming, hydrocracking.*

Import (oil): The receipt of oil extracted in another political jurisdiction; and the oil that is received. In this report the political boundary is California's border. Imports accounted for two-thirds of the crude oil refined in California from 2013–2017.

Inertia: Resistance to change. At least three types of resistance to change affect the Earth's climate—geophysical, technological, and social inertia. See also *carbon lock-in, climate limit, infrastructure inertia, social inertia.*

Infrastructure: The basic physical and organizational structures and facilities, such as buildings, roads, and energy systems, needed for the operation of a society or enterprise. Oil infrastructure includes the physical network of equipment needed to extract, refine, transport, store and use petroleum and petroleum products. See also *equipment, infrastructure inertia, operable duration, stranded asset.*

Infrastructure inertia: The resistance of a technology's basic organizational structures to systemic changes in its basic physical structures which is motivated by the expectation of benefits from the continued use of technology-specific capital equipment investments. Infrastructure inertia involves mutually reinforcing types of social and technological inertia. Organizing to decommission expensive and long-lasting oil refining capacity early could prevent oil infrastructure inertia from causing future emissions that exceed California's climate limit. See also *carbon lock-in, equipment, operable duration.*

Intergovernmental Panel on Climate Change (IPCC): The international body for assessing the science related to climate change that was established by the World Meteorological Organization and the United Nations Environment Programme in 1988.

Jet fuel: Fuel burned in jet engine combustion turbines. Jet fuel and kerosene accounted for approximately 15.5% of California refinery production from 2013–2017. See also *kerosene, naphtha.*

Just transition: A process or period of intentional change from unsustainable and unjust to sustainable and just energy and social systems that builds societal capacity to break free of carbon lock-in. In this report, this definition is applied to replacing oil with proven alternatives, and is sharpened to stress the place-based, community-driven, tangible, and time-bound systemic change needed to build capacity for climate and health protection in California. The term has evolved as the scope and mutually reinforcing nature of social, environmental, and energy crises have become more clear. See also *carbon lock-in, climate limit, decommission, environmental justice, feasible, infrastructure inertia, pathway (climate), proven technology, social inertia, societal capacity, stranded asset, transition.*

Kerosene: Hydrocarbons that boil in the range of approximately 200–250 °C, produced by California refineries mainly for jet fuel. See also *jet fuel.*

Kilogram (kg): one thousand grams; approximately 2.205 pounds.

Liquified petroleum gas (LPG): Propane, butane, or commonly a mixture sometimes including other gases, that is liquified by pressure or refrigeration and burned as fuel mainly for heating and cooking in non-urban areas, among other uses. See also *butane, propane.*

Megaton (Mt): A unit of mass equivalent to one million metric tons.

Metric ton (ton): One thousand kilograms. See also *ton.*

Naphtha: A mixture of hydrocarbons that boils in the range of approximately 30–200 °C and is produced in oil refining primarily for gasoline production. Naphtha also is used in smaller volumes as a minor component of total jet fuel combustion. Some refineries, primarily in petrochemical regions such as the U.S. Gulf Coast, make significant amounts of naphtha for use as petrochemical feedstock.

Nelson Complexity: Nelson index. A widely used measurement for the value of oil refining capacity based on the relative capital cost and production value to refiners of the processing equipment in a refinery or refining fleet, originally developed by W. L. Nelson. Nelson complexity is the sum of the products of process-specific capacities and process-specific values relative to atmospheric crude distillation, divided by atmospheric crude distillation capacity.

Oil: In this report, petroleum and petroleum products.

Oil quality: The chemical and physical characteristics of an oil deposit or oil stream that affect the capital, energy, and pollution costs of extracting that oil, refining it, or both. Lower quality oils are more expensive and polluting to extract and refine, and sell at lower prices relative to higher-quality oils. For example, peer reviewed research by CBE found that oil quality is the main driver of substantial differences in the energy intensity and carbon intensity of oil refining observed among U.S. oil refining regions.

Oil state: Petrostate. In common usage, a derogatory term for a political jurisdiction with a socioeconomic system that is dependent on oil, typically applied by people in one such state to others but not to their own, and consequently lacking a stable universal definition. In this report, a political jurisdiction hosting a concentration of oil infrastructure that has allowed a critical component of its economy to remain dependent on oil unnecessarily and permits the prolonged operation of oil infrastructure despite more sustainable alternatives. California is an oil state.

Operable duration (equipment): The length of time over which a particular unit, type, or collection of equipment is physically capable of functioning effectively to perform the work it is designed to do. The period from a specified time, such as from when it was built and first used or from the present day, before the equipment wears out. The commissioning and decommissioning dates of refining equipment and the ages and relative value to refiners of the equipment mix now operating in these refineries indicate that the oldest half of California refining capacity today has an operable duration of 21–31 years. *See* also *equipment, infrastructure inertia, process unit, stranded asset.*

Paris Accord: The consensus of nations on climate reached at the United Nations' 21st Conference of the Parties at Paris, France in December 2015 that set a goal of limiting the rise in average global surface temperature to an increment to well below 2°C while striving to limit this increment to 1.5°C, relative to pre-industrial levels. *See* also *climate limit.*

Path dependence: The resistance to large-scale systemic shifts in the development path of complex technological, socioeconomic, and institutional systems that is driven by favorable initial social and economic conditions and the momentum of increasing returns to scale. For example, if we had solar energy, charging stations and electric vehicles instead of oil refineries, gas stations, gasoline cars and diesel trucks, it would be hard to switch to oil now—even if oil didn't pollute too much. *See* also *carbon lock-in, infrastructure inertia, operable duration, pathway (climate), social inertia.*

Pathway (climate): A road map for the array of technologies and measures to be deployed over time, and for the cumulative climate emission trajectory associated with this sequence of actions. Path. This report compares proven technology pathways to a cumulative emission limit defined by state climate targets. *See climate limit.* Multiple paths to the climate limit remain plausible globally, but which path is most feasible depends on place-based conditions and social choices—and paths that delay low-carbon transition make meeting the limit more difficult. *See* also *carbon lock-in, feasible, path-dependance.*

Permit: Approval—limited, conditioned, or revoked. Three types of permits govern emission-related refining activities in California: Local land use authorities grant permits for the construction and use of refining equipment and may condition those permits to limit a range of potential impacts including emissions. Air districts grant permits for the construction and use of emitting equipment and may condition those permits to limit emissions. The Air Resources Board grants permits authorizing CO_2e emissions through its cap-and-trade and Low Carbon Fuel Standard pollution trading schemes.

Petroleum: Latin for rock oil; oil. Liquid or tar-like mixtures of hydrocarbons that are present in certain rock strata and can be extracted and refined to produce gasoline, kerosene, diesel oil, and other products. Earth holds far more petroleum than we can burn without severe climate destabilization. *See* also *crude oil.*

Petroleum coke: A dense, carbon rich, extremely contaminated solid or semi-solid cake, powder, or deposit that forms as a byproduct of refining denser oils. Pet coke. Pet coke includes catalyst coke that forms and is burned in catalytic cracking units, and marketable coke that forms in coking units and is removed from them for use elsewhere. Pet coke is an extremely dirty fuel, roughly as dirty as coal, and the vast majority of this dirty-burning byproduct is burned as fuel. Pet coke accounts for approximately 16 % of total California refined products exports.

Petroleum fuel chain: The sequence of interdependent steps in the acquisition (extraction), conversion (refining) and use (in transport and industry) of petroleum fuel. See *fuel chain; refinery fuel chain.*

Pollution trading: The exchange of money for permits to pollute issued by political authorities that facilitate these transactions.

Process unit: A co-located, interconnected collection of equipment, such as vessels, pipes, compressors, pumps and heaters, that performs a specific task in a manufacturing facility or system. Crude oil is refined by a series of separate processing steps wherein a refinery's multiple process units each perform one or another of the steps. Among other process units in the Phillips 66 refinery at Rodeo, for example, U267 is a crude distillation unit, U200 is a coking unit, and units 240 and 246 are hydrocracking units. See also *equipment.*

Processing intensity (*PI*): The ratio by volume of the combined capacity for vacuum distillation, catalytic cracking, hydrocracking, coking, and heavy oil (gas oil, "resid") hytrotreating to atmospheric crude distillation capacity. ***PI*** is directly related to the capacity to maintain engine fuels production while refining lower quality and denser crude oils, and to increased fuel combustion in refining.

Propane: A hydrocarbon gas produced in oil refining that is burned as fuel and used in chemical manufacturing. In California, propane is typically burned in refining or is converted to liquid form by pressure or refrigeration for sale as a component of liquified petroleum gas.

Proven technology: In this report, proven technology has been demonstrated in practice. Solar panels, wind turbines, and electric cars are examples of proven technology. See also *feasible.*

Refinery fuel chain (California): The extraction, refining, and end use of oil refined in California. See also *fuel chain, fuel chain emissions, and end use (petroleum).*

Refining (oil): Making crude into useable products. The sequence of hydrocarbon mixture separation, carbon rejection, hydrogen addition, reformulation, contaminant removal and blending, performed in multiple interconnected process units, that makes crude oils into useable products. The dominant refining center in western North America, refining in California anchors a larger fuel chain that causes more air pollution from extracting, refining, and burning the oil refined here than all other activities in the state combined.

Renewable energy: Energy that is harnessed for useful work from a primary energy source that is infinitely sustainable on relevant time scales, such as the sun and wind, rather than from a primary energy source that is extracted, finite, and unsustainable, such as oil. For example, in California renewable energy for electric power generation includes solar, wind, geothermal, biomass, small-scale hydroelectric, digester gas, non-combustion conversion of municipal solid waste to clean-burning fuel, landfill gas, and ocean wave, thermal or tidal energy. See also *efficiency (energy).*

Renewables portfolio standard (RPS): A requirement applied to electricity in California for renewable energy to supply growing percentages of total retail end-use sales of electricity by December 31st of specific years. As strengthened in 2018 by Senate Bill 100, these percentages are 25% by 2016, 33% by 2020, 44% by 2024, 50% by 2026, 52% by 2027, and 60% by 2030. SB 100 also establishes the goal of supplying 100% zero-carbon electricity to retail end-use customers in California by December 31, 2045.

Resid: A mixture of hydrocarbons that does not boil, vaporize, or distill in crude oil distillation, resid is the densest, most contaminated separation product from crude distillation. Also known as residual oil, residuum, and vacuum column bottoms. Resid is fed mainly to coking units, and sometimes to other cracking units, to boost refinery engine fuels production, or, in smaller amounts, resid may be processed for asphalt production or blended into heavy fuel oils. Lower quality and denser oil feeds can increase the volume of resid that refineries process dramatically.

Root cause: A basic cause of something; one of the fundamental underlying factors that leads to an event, condition or other effect, which may be obscured by secondary causes or symptoms. An effect can have more than one root cause. In the investigation of industrial chemical spills, fires, and explosions, root causes are management system failures, such as faulty design and unsafe inspection and repair procedures, that led to a condition resulting in the particular incident. If the root causes were removed the incident would not have recurred.

Shutdown (oil refining): The transition of a process unit or units from operation to cessation of operation; and the condition of those units or refineries when operation has ceased. Safe shutdown requires careful management of steps that, depending on the specific process unit or units being shutdown, may include cutting feed, isolation from any units still operating, vessel depressurization, cooling and purging, and adjusting plant-wide operations to keep the refinery in balance. A shutdown may be planned, or unplanned in an emergency, and may be temporary or permanent. See also *turnaround.*

Social inertia: The resistance of social systems to change. Social inertia can be beneficial or harmful, depending on the context. Harmful social inertia emerges from pervasive social injustice and other conditions that impair societal cohesion, as powerful interests influence socioeconomic and political institutions to shape rules, practices and norms, which in turn shape people's habits, beliefs and values, and is reinforced by bureaucratic protection of the status quo. Political resistance to change. Political inertia has emerged as the primary barrier to climate and health protection. See also *carbon lock-in, feasible, infrastructure inertia, societal capacity.*

Societal capacity: The capability of a group of people to organize and sustain the collective actions necessary for the group to thrive. Our need to replace fossil fuels with proven, less polluting alternatives before worsening environmental conditions can no longer sustain our societies' social, economic and political systems is an existential question of societal capacity. See also *carbon lock-in, climate limit, environmental justice, feasible, infrastructure inertia, just transition, social inertia.*

Specific Gravity (SG): The ratio of the density of a substance to the density of another substance that is taken as a standard, when both are weighed in air. The standard for measuring the Specific Gravity of an oil is water, which has an SG value of 1.000. Thus, an oil that is 85.5% as dense as pure water has an SG of 0.855.

Stranded asset: An investment or property that has suffered from unanticipated or premature write-down, devaluation or liability or has become subject to impairment, abondonment, and financial losses due to dimished expectations of future profitable production. Otherwise operable California refining capacity must be retired during the period from 2020–2035 to meet state climate goals consistent with limiting the average global surface temperature rise to between 1.5°C and 2°C above pre-industrial levels, and, from this perspective, is a stranded asset. See also *carbon lock-in, infrastructure inertia, operable duration.*

Tar sands: Geologic formations that contain extractable amounts of bitumen interspersed in or adhered to rock, sand, clay, or other components of the formation. Oil sands. The Western Canadian Sedimentary Basin is one of more than 30 geologic basins on at least four continents that contain tar sands bitumen deposits.

Thermodynamics (laws): Natural laws describing the relationship between heat and other forms of energy. The first, second, and third laws of thermodynamics can be summarized as follows: (1) Energy cannot be created or destroyed. (2) Entropy—heat that is not available for useful work—always increases. (3) Entropy approaches a constant value as the temperature of a system approaches absolute zero.

Ton (metric): 1 thousand kilograms; approximately 2,205 pounds. This report quantifies mass using the international standard for measurement units, the metric system.

Toxic: Generally, poisonous, noxious, injurious, harmful. Environmenally, causing or capable of causing an adverse biological effect at an observed or potential exposure; and the adverse biological effect observed or threatened. Toxic effects of respiratory exposures to the criteria air pollutant $PM_{2.5}$ include, among others, an estimated 2,000–3,000 premature deaths in the San Francisco Bay Area annually.

Transition: The process or period of changing from one state or condition to another; to undergo or cause this process or period of change. *See* also *decommission, just transition.*

Turnaround (oil refining): A planned, periodic, and temporary shutdown of a refinery process unit or plant to perform maintenance, overhaul and repair operations and to inspect, test, and replace process materials and equipment. *See* also *shutdown (oil refining).*

Vacuum distillation: A process using a vacuum and atmospheric-equivalent temperatures up to 600ºC to separate the residual oils from atmospheric crude distillation into gas oil and vacuum "resid." *See* also *atmospheric crude distillation, distillation, gas oil, resid.*

Western Canadian Sedimentary Basin: The geologic formation centered in Alberta, Canada and extending into U.S. Rocky Mountain states that contains petroleum resources including vast amounts of extractable bitumen. *See* also *bitumen, tar sands.*