Achieving Carbon Neutrality in California

PATHWAYS Scenarios Developed for the California Air Resources Board

DRAFT: August 2020

Energy+Environmental Economics

Achieving Carbon Neutrality in California

PATHWAYS Scenarios Developed for the California Air Resources Board

DRAFT: August 2020

Energy and Environmental Economics, Inc.
44 Montgomery Street, Suite 1500
San Francisco, CA 94104
415.391.5100
www.ethree.com

Project Team:
Amber Mahone
Zachary Subin
Gabe Mantegna
Rawley Loken
Clea Kolster
Niki Lintmeijer

Table of Contents

Acronyms

BECCS	Bioenergy with Carbon Capture and Sequestration
BEV	Battery Electric Vehicle
CARB	California Air Resources Board
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide equivalent
DAC	Direct Air Capture
DACCS	Direct Air Capture with Storage
EE	Energy Efficiency
GHG	Greenhouse Gas
GWh	Gigawatt hours
GWP	Global Warming Potential
HFC	Hydrofluorocarbon
HFCV	Hydrogen Fuel Cell Vehicle
LCFS	Low Carbon Fuel Standard
MMT	Million metric tons
NET	Negative Emission Technology
RD&D	Research, Development and Demonstration
VMT	Vehicle Miles Travelled
ZCE	Zero Carbon Energy (scenario)

Executive Summary

Study Purpose and Approach

This study evaluates scenarios that achieve carbon neutrality in California by 2045. Specifically, the scenarios evaluated here achieve at least an 80% reduction in greenhouse gases from 1990 levels by 2045. Carbon neutrality means that all greenhouse gas (GHG) emissions emitted into the atmosphere are balanced in equal measure by GHGs that are removed from the atmosphere, either through carbon sinks or carbon capture and storage. This work specifically focuses on pathways to reduce carbon dioxide emissions from energy use in buildings, transportation, and industry, as well as from other non-combustion and high global warming potential GHGs, including methane, nitrous oxide, and refrigerant gases: hydrofluorocarbons (HFCs), perfluorocarbons, sulfur hexafluoride, and nitrogen trifluoride.

Natural and working lands will also play a pivotal role in addressing climate change. Natural and working lands sequester carbon dioxide in forests, soils, and oceans; these carbon *sinks* can be enhanced through land and ecosystem management practices. Likewise, natural and working lands can also represent a *source* of greenhouse gas emissions, due to land use changes such as deforestation and wildfires. This study does not evaluate the role of natural and working lands as either a net source or a net sink for greenhouse gas emissions in California. The California Air Resources Board and other agencies are continuing to research and collect data on the state's historic and current carbon flux from natural and working lands to help inform a more complete view of the path to carbon neutrality in the state. Future updates of California's Climate Change Scoping Plan will include emissions targets for this sector, considering the role of natural and working lands as an emissions source and as a potential sink alongside the transportation, energy, and industrial sectors.

The purpose of this study is to help to inform considerations for the California Air Resources Board initial development of the 2022 Scoping Plan update. The draft report may be revised based on comments received on the initial scenario results. These scenarios build on Energy and Environmental Economics' (E3's) prior research into deep decarbonization strategies to achieve a 40% reduction in GHG emissions by 2030, and an 80% reduction by 2050 ("80x50"), relative to 1990 levels, as well as a literature review of deep decarbonization studies, including emerging research from European studies.

Key study questions include:

- What are the available energy and non-combustion GHG reduction strategies to help achieve carbon neutrality by 2045?
- How should California consider the tradeoffs between achieving additional energy-sector greenhouse gas reductions versus relying on carbon dioxide removal?
- How do different mitigation strategies compare on the basis of fuel combustion (implying air quality and health impacts), climate change mitigation risk, and technology adoption and implementation risk?
- What are least regrets strategies that are likely to be indispensable in working towards carbon neutrality?

Scenarios

The authors evaluate three scenarios that achieve net zero emissions by 2045, excluding natural and working lands, using the California PATHWAYS model, each with ambitious reductions in fossil fuel-related GHGs and direct emissions of non-energy, non-combustion greenhouse gases. All scenarios include high levels of energy efficiency across all sectors, high levels of renewable electricity generation, high levels of electrification in the transportation and buildings sector, and deep reductions in non-energy, non-combustion greenhouse gas emissions like methane and HFCs. As a result, all scenarios achieve at least an 80% reduction in gross GHG emissions (under AB 32) by 2045 (“80x45”), representing new and ambitious actions and technology deployments to reduce emissions in California.

The scenarios differ in their level of adoption of advanced mitigation measures that result in over 80% reduction in GHG emissions by 2045 and their degree of their reliance on carbon dioxide removal (CDR) to achieve carbon neutrality by 2045.[1]

+ **The High CDR scenario** achieves an 80% reduction in gross greenhouse gas emissions by 2045, and of the scenarios evaluated, relies most heavily on carbon dioxide removal strategies to achieve carbon neutrality by 2045.
+ **The Zero Carbon Energy scenario** achieves zero-fossil fuel emissions by 2045, with some remaining gross emissions from non-combustion and high GWP gases by 2045. CDR strategies are minimized in this scenario.
+ **The Balanced scenario** represents a middle point between the prior two scenarios in terms of energy-related GHG reductions. This scenario includes less CDR than the High CDR scenario, and more CDR than the Zero Carbon Energy scenario.

Scenario Results

The scenarios are ranked based on their performance across key metrics, including health-related air quality impacts (approximated based on combustion of fuels), climate risk, and technology adoption and implementation risk. Carbon abatement cost ranges for the advanced mitigation measures and carbon

[1] Carbon dioxide removal is a term that encompasses many forms of GHG removal from the atmosphere, whether through natural and working lands carbon sequestration (not evaluated here), or through negative emissions technologies that actively pull carbon dioxide out of the atmosphere, such as direct air capture or biomass energy with carbon capture and sequestration.

dioxide removal required for each scenario to go beyond 80x50 and achieve carbon neutrality are also evaluated but the relative cost impact of each scenario is deemed uncertain.

- **The High CDR scenario** achieves approximately an 80% reduction in direct GHG emissions by 2045, with approximately 80 million metric tons (MMT) of CO2e removed from the atmosphere using a combination of CDR strategies. This scenario represents the highest risk scenario, from a climate mitigation perspective, because it has the highest remaining direct GHG emissions, and relies on relatively untested CDR strategies which are not widely commercialized. The scenario also has the highest remaining quantity of fuel combustion, which means the air quality impacts, though far improved relative to today, will likely be highest among the three carbon neutral scenarios evaluated. Both the climate risks and the technology adoption and implementation risks of relying so significantly on CDR are high. Continuing to emit such a large share of gross emissions into the atmosphere through 2045 could result in an overshoot of emissions, with a risk of missing the state's climate goals if CDR options are not implemented early on. Furthermore, many CDR options rely on a significant amount of land and energy resources, rendering the implementation of CDR at scale uncertain. The cost of CDR strategies vary widely, depending on which strategies are deployed. In general, land-based carbon sequestration strategies are estimated to be lower cost than negative emissions technologies (NETs) like bioenergy with carbon dioxide capture and storage (BECCS) or direct air capture of carbon dioxide paired with storage ("DAC with CCS" or "DACCS"), but the land-based CDR solutions in California are likely to be limited. Given the wide range of uncertainties around the costs of CDRs, we cannot conclusively estimate whether the High CDR scenario is lower or higher cost than the other scenarios.
- **The Zero Carbon Energy scenario** represents the other bookend strategy to achieve carbon neutrality in California, whereby all fossil fuel emissions are avoided or mitigated through a combination of advanced (and ambitious) mitigation measures. These measures include earlier, more rapid and more complete deployment of electrification strategies in buildings, transportation and some industrial processes, as well as deployment of more speculative technologies such as electric aviation and hydrogen fuel-cell trains. Hydrogen and synthetic natural gas are deployed in industry and in the natural gas pipeline to fully displace or mitigate all remaining fossil fuel emissions in this scenario by 2045. The remaining gross GHG emissions,

approximately 33 MMT CO_2e by 2045, represent a 92% reduction in gross emissions relative to 1990 levels. These remaining emissions are from non-energy, non-combustion GHG emissions, including methane from agriculture and waste, that appear to be difficult to fully mitigate using today's technology solutions. These remaining direct emissions sources are mitigated with CDR strategies in this scenario. As a result of the rapid deployment of emission reduction strategies and the more limited reliance on CDR, the zero-carbon energy scenario has the lowest climate risk, achieving deeper carbon reductions in 2030 (45% below 1990 levels versus 40% reductions in the other scenarios). While this scenario's limited reliance on CDR helps to reduce the technology adoption and implementation risk along one dimension, the scenario also relies on early deployment of advanced mitigation measures and technologies, some of which are not commercially available today. All of the technologies deployed in this scenario have been demonstrated at a minimum in a lab setting but would require further RD&D to bring to commercial scale. In addition, the scenario relies on fully decarbonizing transportation sector emissions and eliminating all fuel combustion in buildings. Eliminating all transport emissions may be challenging as some of these vehicles may not fall directly under the regulatory authority of state agencies, including interstate trucking, shipping, trains, and aviation. Likewise, eliminating fossil fuel combustion in buildings by 2045 would be particularly challenging as it would require early and rapid deployment of electric end uses in buildings, as well as a plan for how to safely reduce, and eventually eliminate, gas throughput across the substantial retail gas infrastructure in the State. The cost of the scenario, may in fact be comparable to the other scenarios because, while it relies on the least amount of CDR and more rapid deployment of lower cost measures, such as zero-emissions trucks, it also relies on higher cost measures, including synthetic natural gas and industrial uses of hydrogen and electrification. The balance of these lower-cost and higher cost strategies means that the total costs could be within a similar range of the other scenarios. Overall, there are many cost uncertainties in all of these emerging technologies, making it difficult to conclude whether the zero-carbon energy scenario is lower or higher cost than the other scenarios evaluated here.

+ **The Balanced scenario** represents a blend of measures implemented in the other two scenarios. While it still relies on rapid deployment of electrification and other carbon mitigation strategies, the deployment of electrification technologies is not as rapid as in the zero-carbon energy scenario. Further, the balanced scenario includes less reliance on some of the more speculative measures such as electric aviation and fuel-cell trains. This scenario does not include some of the most expensive carbon mitigation measures, such as synthetic natural gas in the pipeline. This scenario includes approximately 56 MMT of CO_2e from CDR strategies in 2045, which is less than the High CDR scenario and more than the zero-carbon energy scenario.

Figure 1 below illustrates California's estimated greenhouse gas emissions by sector in 2020, and that for each of the three scenarios in 2045 as well as the relative amount of carbon dioxide removal needed to negate remaining GHG emissions. Statewide greenhouse gas emissions in 1990 were 431 MMT CO_2e. The High CDR scenario achieves an 80% reduction in gross GHG emissions by 2045, while the Balanced scenario achieves an 87% reduction, and the Zero Carbon Energy scenario achieves a 92% reduction in gross GHG emissions by 2045, relative to 1990 levels.

In the Zero Carbon Energy scenario, energy-related emissions from industrial, transportation, and residential and commercial building sources are eliminated by 2045. The remaining emissions in this scenario are from non-combustion GHGs including methane and other high GWP gases, as well as non-combustion GHG emissions from the recycling and waste and agriculture sectors.

Figure 1. Greenhouse gas emissions by sector in 2020 and 2045, by scenario, including total CDR required to achieve carbon neutrality in 2045 (excluding potential sources from NWL)

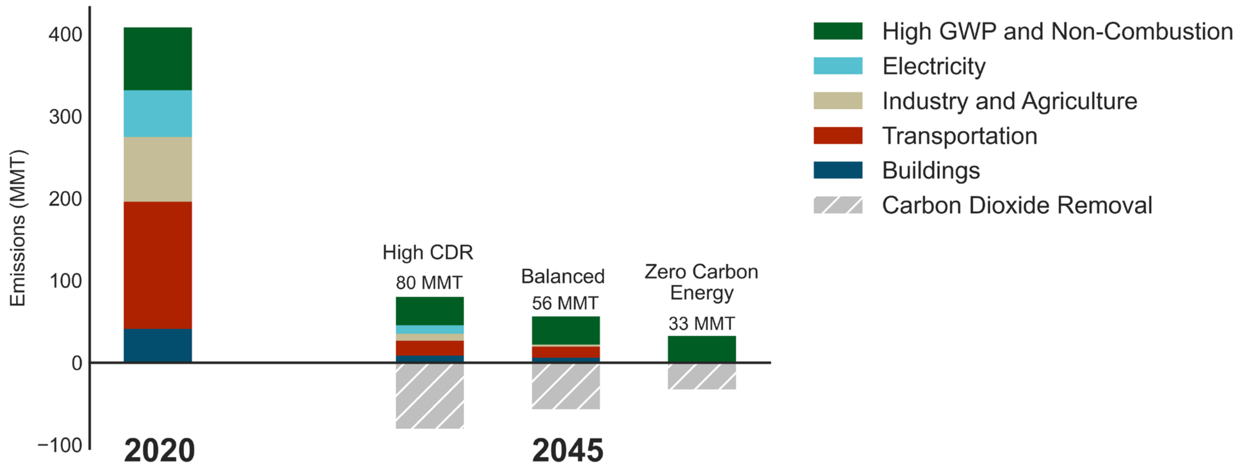


Figure 2 summarizes the relative differences between the three scenarios on the basis of estimated potential health impacts from criteria pollutants (approximated based on the total fuel combustion in 2045 in each scenario), climate change mitigation risk (based on cumulative, gross emission reductions between 2020 and 2045), and the potential for technology adoption and implementation risks. Scenarios with higher fuel combustion are likely to be associated with worse air quality and health impacts, although a more detailed analysis of the air quality impacts of each scenario may be warranted. Scenarios with lower total and cumulative greenhouse gas emissions are associated with lower climate change mitigation risk. Technology and adoption risk are estimated based on the degree of reliance on non-commercialized or technologically challenging mitigation options, such as direct air capture or accelerated electrification in buildings and transportation.

Figure 2. Carbon neutral scenario comparison across key metrics

This summary figure illustrates that among the three scenarios evaluated here, the High CDR scenario faces the highest risks in terms of remaining health impacts, climate change mitigation risk and technological feasibility. The Balanced scenario performs the best on the basis of technological feasibility and implementation risk, while the Zero Carbon Energy scenario performs the best on the basis of reduced health impacts and reduced climate risk.

Key Findings

LEAST-REGRETS OPTIONS

Achieving carbon neutrality by 2045 requires ambitious near-term actions around deployment of energy efficiency, transportation and building electrification, zero-carbon electricity, and reductions in non-energy, non-combustion greenhouse gas emissions. These least-regrets strategies are common across all deep decarbonization strategies.

In addition, achieving carbon neutrality will require scaling up research, development and deployment efforts around CDR strategies, such as land-based carbon sequestration and direct air capture of CO_2.

Achieving the zero-carbon energy scenario requires rapid deployment of electrification in vehicles and buildings achieving 100% electric or zero-carbon energy sales shares by 2030, if expensive early retirement of equipment is to be minimized. Likewise, very low carbon, if not zero-carbon electricity will be needed by 2045 in order to support these high levels of electrification. This will require rapid adoption of renewable generation and renewable integration solutions, at a pace which exceeds recent historical levels of wind and solar adoption. An inter-agency research process is underway to evaluate in more detail the electricity sector implementation strategies and implications of achieving the state's SB 100 goal of meeting 100% of retail sales electricity with zero-carbon electricity.

All carbon neutral scenarios achieve dramatic reductions in fossil fuel combustion and fossil fuel emissions, which will result in global climate change benefits, as well as the potential for improvements in local air quality and associated health impacts. Scenarios with lower fossil fuel combustion will achieve greater improvements in statewide air quality and, likely, local health impacts. However, local health benefits in any specific community will be location and source specific. Although outside the scope of this analysis, properly valuing the local air quality and health benefits associated with reducing fuel combustion is an important consideration in designing California's carbon-neutral future.

CHALLENGES, RISKS, AND OPPORTUNITIES

By any measure, in any scenario, achieving carbon neutrality by 2045 will require a wholesale transformation of California's energy economy. There are numerous technology, policy, and consumer adoption implementation challenges which will need to be overcome across every sector. However, these challenges and risks must be considered within the context of the risk which climate change presents to our collective health and wellbeing. Reducing greenhouse gas emissions presents an opportunity to not only mitigate the worst impacts of climate change, but also to improve local air quality and health outcomes, and to consider new energy solutions that contribute to a higher quality of life and improved energy and public health equity across the state.

All scenarios presented here rely to different degrees on carbon dioxide removal strategies, meaning that RD&D around these options represents a least-regret option. However, it is risky to rely too heavily on CDR strategies as the primary pathway to carbon neutrality. Some CDR strategies carry the risk that they may not permanently sequester carbon, such as wildfire risks associated with forest management, while other CDR strategies, such as direct air capture, rely on continuous energy inputs and maintenance in order to pull carbon dioxide out of the atmosphere. A higher reliance on CDR strategies may mean that achieving carbon neutrality, and net negative emissions post 2045, presents a higher climate risk than scenarios with greater reductions in gross emissions.

The range of emissions quantities evaluated here, and removed with CDR by 2045, is between 33 and 80 MMT CO_2 a year. The total amount of CDR would need to increase over time in order to achieve net negative emissions by mid-century and beyond. For context, the total estimated increase in carbon stock in California's croplands and urban forests, across the time period from 2012 – 2014, is the equivalent of sequestering an average of 19 MMT of CO_2e per year.[2] Likewise, the total carbon stock decrease in California's forests and other natural and working lands between 2001 and 2010 averaged to an equivalent of 63 MMT CO_2e per year during that period.[3] To contextualize the 2045 CDR numbers using an example from the energy sector, total GHG emissions from California's electricity sector in 2017 were a similar order of magnitude, at 62 MMT CO_2e.

Setting in motion the steps necessary to achieve deeper reductions in gross GHG emissions in the 2045 timeline, along the lines of the Zero Carbon Energy scenario, would also necessitate faster and deeper

[2] California Air Resources Board, 2018. "An Inventory of Ecosystem Carbon in California's Natural & Working Lands: 2018 Edition" Page 8 **https://ww3.arb.ca.gov/cc/inventory/pubs/nwl_inventory.pdf**
[3] *Ibid*

GHG reductions in the 2030 timeframe. Early actions taken now to reduce emissions from transportation, vehicles, and buildings, will not only help ensure that the state is on track to meet its ambitious 2030 climate goals, but will also reduce the risk of missing the carbon neutrality target by 2045.

UNCERTAINTIES

Many key uncertainties remain around the achievement of carbon neutrality in California. One of these uncertainties is the optimal use and deployment of zero-carbon fuels in hard-to-electrify sectors, including certain high temperature industrial processes, heavy-duty long-haul trucking, aviation, trains and shipping. These fuel uses may be met with a combination of fossil fuels, hydrogen, synthetic zero-carbon fuels or biofuels. It is still uncertain how the relative costs of these technologies will evolve over time. As the cost of wind and solar decline, the cost of renewable hydrogen production is also falling, making hydrogen a more attractive solution than biofuels for some applications. The market for sustainable biofuels remains nascent, making it uncertain how much sustainable biomass supply will be available, and what the best uses for these biomass resources will be through mid-century.

Introduction

1.1 What Climate Science Tells Us About the Urgency of Reducing Greenhouse Gases

Scientists across the world agree that limiting global warming to 1.5 degrees Celsius (°C) or less is critical to averting the worst impacts of climate change. Limiting global warming to 1.5°C, with high confidence, will require, globally, about a 45% reduction in CO_2 emissions from 2010 levels by 2030 (which is proportionate to the scale of California's goal of a 40% reduction from 1990 levels by 2030), and reaching net zero emissions by mid-century (IPCC, 2018).

The Intergovernmental Panel on Climate Change (IPCC) reports summarize the current state of our scientific understanding of climate change, and the impacts and implications of climate change across the world. California's Fourth Climate Change Assessment compiles the most recent and rigorous research on the impacts of climate change to the state, as well as the benefits of reducing greenhouse gas emissions. Both of these resources clearly indicate that, as a society, we must both lower our greenhouse gas emissions, and deploy carbon dioxide removal strategies including improved carbon sinks in forests, soils and oceans, in order to reduce global temperature increases, and to mitigate the risks of climate-change induced natural disasters such as wildfires, hurricanes, droughts, and flooding.

This research in California, and across the globe, confirms that the impacts of climate change will be felt disproportionately by lower income and vulnerable groups. Lower greenhouse gas emissions thus translate directly to better health, equity, and economic outcomes for Californians and the world. Reducing greenhouse gas emissions is an important form of promoting a more just and equitable future (Kalansky, 2018).

1.2 Motivating Questions and Report Organization

This study seeks to provide insights into what a carbon neutral future for California may look like, from a technology deployment perspective with a focus on strategies to reduce gross emissions from the energy sector. This study is designed as one piece of the puzzle to help inform the California Air Resources Board's development of the 2022 climate change scoping plan. Emissions sources and sinks from natural and working lands, while an important part of achieving carbon neutrality, are outside the scope of this paper. Likewise, additional considerations around social and environmental justice and equity will be considered in the development of the next Scoping Plan. The motivating research questions for this work are more narrow and include:

+ What are the available energy and non-combustion GHG reduction strategies to help achieve carbon neutrality by 2045?
+ How should California consider the tradeoffs between achieving additional energy-sector greenhouse gas reductions versus relying on carbon dioxide removal?
+ How do different mitigation strategies compare on the basis of fuel combustion (implying air quality and health impacts), climate change mitigation risk, and technology adoption and implementation risk?
+ What are least regrets strategies that are likely to be indispensable in working towards carbon neutrality?

The next sections describe California's climate goals, as well as the current state of carbon neutral climate goals and research in other jurisdictions, with a focus on European research into deep decarbonization futures. Chapter 2 describes the modelling approach, the scenarios evaluated, the GHG reduction strategies available within each sector and a summary of key results from each scenario, with a focus on 2045 results. Chapter 3 discusses the implications and overall findings of the study results. Chapter 4 concludes and highlights next steps for further investigation and research.

1.3 California's Carbon Neutral Executive Order and Supporting Policies

Nearly every country has agreed, as part of the 2016 Paris Agreement of the United National Framework Convention on Climate Change (UNFCCC), to significantly reduce and limit the impacts of climate change. The common goal is to limit global warming to no more than 2°C, while working towards a goal of 1.5°C or less. While the United States is currently withdrawing from the global Paris Agreement (expected to be effective in November 2020), California, and many other U.S. states, counties, and cities, remain committed to these climate goals as climate change will have unique and acute impacts at each of these levels.

Consistent with the IPCC Special report, in 2018, Governor Brown signed Executive Order B-55-18 which calls for California to achieve carbon neutrality as soon as possible, and no later than 2045. The state is to maintain net negative emissions after 2045, meaning that GHG sinks must exceed GHG sources. The Executive Order explains that the carbon neutrality goal is layered on top of the state's existing commitments to reduce greenhouse gas emissions 40% below 1990 levels by 2030 (as codified in SB 32), and 80% below 1990 levels by 2050.

The carbon neutrality Executive Order describes other characteristics of the goal, including improving air quality, climate adaptation and biodiversity, and supporting the health and economic resiliency of urban and rural communities, including low-income and disadvantaged communities. The carbon neutral climate goal will also include carbon sequestration targets from natural and working lands, which are still under development. These will be the focus of a separate CARB report and not part of the scope of this analysis. The Order leaves open the question on how far the state will go in decreasing gross GHG emissions beyond 80% by 2050 from 1990 levels compared to how much of the State's gross emissions can be mitigated by carbon dioxide removal options.

California has enacted a suite of carbon mitigation policies designed to move the state towards achieving these climate goals, with the focus to date on meeting the state's 2030 climate goal. These policies include cap-and-trade, the low carbon fuel standard, a requirement for 60% of retail electricity sales to be met by renewables in 2030 followed by zero-carbon retail and state electricity sales by 2045 (SB 100), a doubling in energy efficiency (SB 350), the advanced clean truck standard, as well as reductions in short-lived climate pollutants like methane and HFCs, among many others.

While California is making progress towards reducing greenhouse gas emissions, the pathway to carbon neutrality by 2045 is still under consideration, and many technological, legal, and other research questions remain outstanding about how California will achieve this ambitious goal. This report represents one piece of the puzzle in understanding the clean energy technology deployment pathways that could help inform the state's broader look at carbon neutrality, including natural and working lands and other considerations, which will be reflected in the 2022 Scoping Plan.

1.4 Strategies and Findings Across Carbon Neutral Studies

After reviewing a number of carbon neutrality studies, most of which have been published in Europe to date, we can identify several commonalities across all of these studies which are useful to informing a study of how California may achieve carbon neutrality. Across all studies and jurisdictions, there is a strong reliance on: 1) energy efficiency, 2) electrification, 2) low-carbon fuels, including low-carbon electricity and some reliance on low-carbon liquid and gaseous fuels, such as hydrogen, for hard-to-electrify sectors, and 4) carbon dioxide removal (CDR), including carbon sinks in natural and working lands and negative emissions technologies (NETs). All of these studies highlight the importance of maximizing available land sinks and, as a necessity, generally have some reliance on negative emissions technologies.

Nearly all studies and jurisdictions agree that there is no silver bullet solution towards deep decarbonization. A mix of all options and available technologies is necessary to meet carbon neutrality, with a common goal among European studies of achieving at least a 90% reduction in economy-wide gross emissions by 2050. While some pathways have a strong reliance on technology and innovation to fill this mix, others lean towards societal disruptions and consumer behavioral changes (Tsiropoulos, Nijs, Tarvydas, & Ruiz, 2020).

Key areas of uncertainty and differences between these studies include: 1) types and level of zero-carbon fuel use (e.g. hydrogen vs. biofuels vs. carbon capture and sequestration (CCS)), 2) the level of electrification across sectors and the absolute growth of the power sector, 3) the emphasis on behavior change and disruptive societal/economic changes, and 4) the reliance on different forms of negative emissions technologies.

All global or national deep decarbonization pathways that limit global warming to 1.5°C use CDR technologies to some extent to neutralize emissions from sources for which mitigation is challenging, and to achieve net negative emissions after mid-century (Rogelj, et al., 2018). However, as IPCC notes, the reliance on such technologies is risky as most CDR deployment options are unproven.

Decarbonization studies are often paired with some form of carbon price, either in the form of a carbon tax or cap-and-trade system, or as a societal shadow price (Lempert, et al., 2019). According to the IPCC Special Report, policies reflecting a high price on carbon emissions coupled with complementary policy instruments will minimize overall decarbonization costs (Rogelj, et al., 2018)

1.4.1 EUROPEAN DEEP DECARBONIZATION STUDIES

The European Union countries and the United Kingdom (UK) have become national-level leaders in deep decarbonization in particular in their development of policies and plans for decarbonization options across the economy. A few European decarbonization studies and plans are highlighted throughout this study to provide broader context for comparing with this work’s sub-national California-based decarbonization measures across all sectors and emissions sources.

European deep decarbonization studies have reached a consensus on the level of fossil phase-out: all scenarios phase down the use of coal by 70% by 2030 (almost 100% for electricity generation) and phase out coal 100% by 2050, with a decline in oil and natural gas use of at least 75% by 2050. In each of the studies reviewed here, the use of natural gas in Europe declines sharply towards 2050, but natural gas still has a significant role to play towards 2030 (the majority of the fossil natural gas phase-out thus takes place between 2030-2050). Countries with a strong reliance on natural gas infrastructure, such as the UK and the Netherlands, focus on hybrid electrification with some continued use of fossil and renewable natural gas options (using a mix of natural gas, biomethane and blended hydrogen) towards 2030 to ensure that peak heat demands in cold winter-time periods are met at least cost, using a mix of electricity and gas pipeline infrastructure, as well the potential for a new dedicated hydrogen pipeline backbone. A recent report from eleven gas infrastructure companies in Europe presents a vision for a dedicated hydrogen pipeline that would initially serve clustered industrial facilities in Northern Europe, and which could expand to provide green hydrogen to a broader range of industrial, transport and some building heating loads by 2040 (Wang, van der Leun, Peters, & Buseman, 2020).

A review of 16 European scenarios by the European Commission that reach economy-wide emission reductions by at least 90% in 2050 analyzes the differentiation in the final energy mix among 2050 scenarios. All European scenarios forecast a significant reduction in final energy consumption due to a combination of energy efficiency and electrification, though the range of reductions differs by 30-60%. Moreover, all scenarios generally rely on around 10-15% of (partly imported) biomass in the final energy mix (Tsiropoulos, Nijs, Tarvydas, & Ruiz, 2020).

A commonality across jurisdictions is the uncertainty on the deployment and application of hydrogen. Many jurisdictions recognize a role for hydrogen in deep decarbonization pathways in the long term, but the technologies used to deploy hydrogen and the sectors in which it adds most value are uncertain. Recently announced plans by the European Union and Germany place strong emphasis on the future deployment of green hydrogen and its application mostly for industrial and transportation purposes. In existing scenario studies however, the level of hydrogen consumption is one important factor in explaining the variance across electricity production.

Nearly all existing European scenarios still rely on fossil fuels (mostly natural gas) with CCS and/or hydrogen by 2050 to provide flexibility in the electricity sector and for high-temperature applications in industry. In particular, these studies find that CCS plays a key role in heavy industrial sectors (cement, iron and steel) and for some flexible electricity production. In the context of these European deep decarbonization scenarios, CCS technologies store between 0.1 and 0.45 GtCO2/year underground towards 2050, most of which is in offshore fields (Tsiropoulos, Nijs, Tarvydas, & Ruiz, 2020). This does not include the amount of CO_2 storage that might be needed for negative emissions technologies such as direct air capture and bioenergy with CCS.

2 Modeling Approach, Scenario Design and Greenhouse Gas Reduction Strategies

2.1 About the California PATHWAYS Model

This study builds on prior research into scenarios that achieve California's 2030 and 2050 (80x50) climate goals, using E3's California PATHWAYS model (Williams, et al., 2012); (CARB, 2017); (Mahone, 2018); (Aas, 2020)). The California PATHWAYS model is a "techno-economic" scenario-based model representing energy consumption and greenhouse gas emissions in California through 2050. Energy consumption in the residential, commercial and transportation sectors are represented at the end use level, including for lighting, space heating, water heating, cooking, and different vehicle types, among other end uses. Energy consumption in the industrial, oil and gas, petroleum and agriculture sectors are represented at the fuel-use level. Non-energy, non-combustion greenhouse gas emissions are also represented, based on GHG accounting protocols from the California greenhouse gas emissions inventory. As previously discussed, this study does not include GHG emission sources or sinks from natural and working lands in California, which are being separately evaluated by state agencies.

As a technology-based, economy-wide, greenhouse gas emissions accounting model, the scenarios developed in the tool reflect key interactions between sectors. For example, electrification in buildings and transportation results in higher electricity demands and greater generation capacity needs, reflected in the electricity sector. Renewable fuel demands, including for hydrogen, synthetic gas and biofuels, are represented in a fuels supply module, which accounts for the resource potential and cost of available biomass feedstocks.

The scenarios developed here are tailored to reflect different worldviews and assumptions about the future pace of technology and policy deployment. Apart from the biofuels supply module, which includes a least-cost optimization selection process, the scenarios do not reflect an economy-wide, least-cost optimization. The authors, rather than the model, “pick” the pace of technology deployment and the technology mix for each scenario, constrained by the goal of achieving the state’s 2030 and 2045 carbon neutrality climate goal using a stock-roll over model to reflect a realistic turn-over timeline for end use equipment. For more information about the California PATHWAYS model, see the CARB 2017 Scoping Plan modeling information for PATHWAYS (CARB, 2017) and the model description and appendices in Mahone, 2018.

2.2 Greenhouse Gas Emissions Accounting and Boundary Conditions

The California Air Resources Board 2019 Greenhouse Gas Emission Inventory is used as the basis for GHG accounting in this analysis, and for drawing the boundaries around which sources of emissions are counted in these scenarios. The GHG inventory is used because it is the basis for the state’s 2030 climate change law, SB 32, which sets the state’s 2030 target of 40% GHG reduction relative to 1990 levels. Emissions from natural and working lands will be included in the updated 2022 Scoping Plan evaluation of carbon neutrality by 2045 but are not part of the scope of this analysis.

The inventory, and the PATHWAYS model GHG accounting, are both designed to align with guidance from the IPCC’s Fourth Assessment report, applying 100-year global warming potential factors when comparing emissions from carbon dioxide to other global warming gases, including methane, nitrous oxide and other fluorinated gases such as hydrofluorocarbons (HFCs). California’s emissions accounting approach includes an estimate of in-state anthropogenic greenhouse gases, as well as emissions from imported electricity. Emissions from in-state aviation and shipping within 24 nautical miles of the state’s coastline are included, but emissions from interstate and international aviation and shipping outside of the state’s coastal boundaries are excluded. Biofuels are treated as zero-carbon fuels in this accounting approach, following IPCC GHG inventory guidance.

The potential for California's natural and working lands to serve as an emissions sink in the future remains an on-going area of research in the state. Greenhouse gas emissions and carbon sinks from natural and working lands are not currently included in the CARB AB 32 Annual GHG inventory or in the PATHWAYS model. Land-based and natural ecosystem carbon sinks are likely to play an important role in meeting the state's long-term climate goals, as is controlling emissions from wildfires and other lands. Given the ongoing research into this topic, the scenarios developed here do not explicitly include land-based emissions, either sources or sinks, in the 1990 GHG baseline or in the emissions reduction scenarios. Rather, the total amount of CDR needed in each scenario to achieve carbon neutrality by 2045 is specified. The CDR in each scenario could come from a range of solutions, including carbon sinks from natural and working lands, or from NETs such as direct air capture.

2.3 Carbon Neutral Scenarios

In this report, we evaluate three different scenarios that achieve carbon neutrality by 2045 (excluding sources from NWL), distinguished by their degree of reductions from fossil fuel-based greenhouse gas emissions versus CDR strategies, including land-based carbon sinks and NETs. All of the scenarios achieve at least a 40% reduction in GHG emissions by 2030 and an 80% reduction in GHGs by 2045, relative to 1990 levels, without any reliance on CDR. The three scenarios are evaluated based on the potential costs, fuel combustion (used as a proxy for air quality-related health impacts), climate change mitigation risk and technology and implementation risk and feasibility of each scenario. A "reference" or "counterfactual" scenario is not evaluated in this study but will be an important focus of CARB's next Scoping Plan.

- **The "High Carbon Dioxide Removal" scenario** includes a broad range of deep decarbonization strategies, which are similar to E3's prior "high electrification" scenario, including energy efficiency, electrification, low-carbon fuels, zero-carbon electricity, and reductions in non-energy GHG emissions. In addition, off-road transportation electrification is accelerated and industrial carbon capture and sequestration (CCS) is assumed, in order to achieve just over 80% reductions in direct GHG emissions by 2045. In this scenario, 80 million metric tons (MMT) of CO2e from fossil fuel combustion and non-energy GHGs in 2045 remain. These gross emissions net to zero by applying 80 MMT of carbon dioxide removal strategies, including sinks from natural and working lands and negative emissions technologies like direct air capture.
- **The "Zero-Carbon Energy" scenario** includes a similar set of decarbonization strategies as the High CDR scenario, but these strategies are deployed earlier and more deeply. As a result, 2030 GHG emissions are lower in this scenario, achieving a 45% reduction in GHGs by 2030, relative to 1990 levels. In addition, emerging emission reduction technologies, including synthetic natural gas in the gas pipeline, electric aviation, and fuel-cell trains in off-road transportation are applied, in order to eliminate all fossil fuel emissions by 2045. In the zero-carbon energy scenario there are zero fossil fuel emissions by 2045. The remaining 33 MMT of CO2e in 2045 in this scenario come from non-energy sources of GHGs, including methane from agriculture. These gross emissions are mitigated using CDR strategies to achieve carbon neutrality.
- **The "Balanced" scenario** represents a balance between the measures in the High CDR scenario and the zero-carbon energy scenario, which each represent a bookend approach towards achieving carbon neutrality. The balanced scenario includes less reliance on CDR strategies, compared to the High CDR scenario, but also has less reliance on the more speculative emission reductions technologies included in the Zero-Carbon Energy scenario, like electric aviation and hydrogen fuel-cell trains. In addition, the pace of electrification is somewhat slower in the balanced scenario compared to the zero-carbon energy scenario. This scenario results in 56 MMT of CO_2e in 2045, about half of which is from fossil fuel emissions and half of which is from non-energy GHG emissions, which must be reduced with CDR strategies.

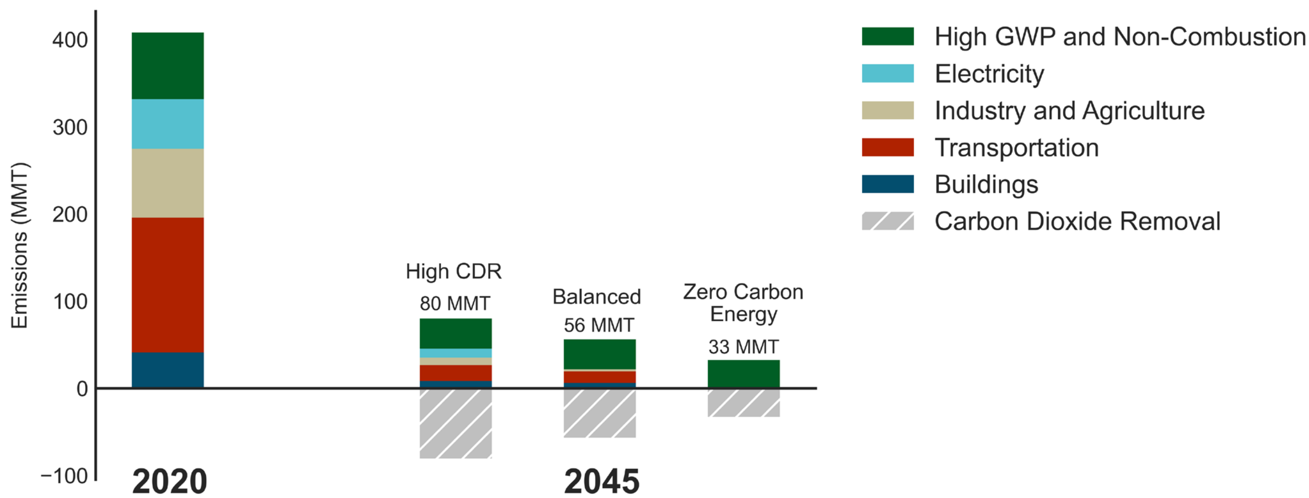
A summary of the key emission reduction strategies applied in each scenario are summarized in Table 1 below. More details about the sector-by-sector assumptions in each scenario are described in Section 2 below, including a discussion of the carbon mitigation strategies evaluated in each sector.

Table 1. Summary of emission reduction strategies by scenario (measures that are the same across all scenarios are shown in grey font)[4]

Sector	High CDR Scenario	Balanced Scenario	Zero Carbon Energy Scenario
Low-Carbon Fuels	**0.4 Exajoules (EJ)** of **advanced biofuels** for: on & off-road ground transportation pipeline gas demand (12% biomethane) **0.1 EJ** of **hydrogen** for: pipeline gas demand (5% H_2 blend)	**0.4 EJ** of **advanced biofuels** for: on & off-road ground transportation renewable aviation fuel biomethane for electricity generation **0.3 EJ** of **hydrogen** for: pipeline gas demand (5% H_2 blend) direct H_2 combustion in industry HDV fuel cell transportation	**0.4 EJ** of **advanced biofuels** for: on & off-road ground transportation renewable aviation fuel biomethane for electricity generation **0.3 EJ** of **hydrogen** for: pipeline gas demand (5% H_2 blend) direct H_2 combustion in industry HDV fuel cell transportation **0.04 EJ** of **synthetic natural gas** for: industry gas demand (10% blend)
Buildings	**100%** sales of electric appliances by **2040** **High** energy efficiency: • *SB 350 **doubling of AAEE** is met by 2030* • *46 TWh of electric EE in 2030 relative to 2015* • *67 TWh of electric EE in 2045 relative to 2015*	**100%** sales of electric appliances by **2035** **High** energy efficiency: • *SB 350 **doubling of AAEE** is met by 2030* • *46 TWh of electric EE in 2030 relative to 2015* • *67 TWh of electric EE in 2045 relative to 2015*	**100%** sales of electric appliances by **2030** **All** gas end uses retired by **2045** **High** energy efficiency: • *SB 350 **doubling of AAEE** is met by 2030* • *46 TWh of electric EE in 2030 relative to 2015* • *67 TWh of electric EE in 2045 relative to 2015*
Transportation	**100%** BEV sales for LDV by **2035** **100%** BEV sales for MDV by **2040** **45%/48%** BEV/CNG sales for HDV by **2035** **50%** rail electrification **No** aviation electrification	**100%** BEV sales for LDV by **2035** **100%** BEV sales for MDV by **2035** **45%/48%** BEV/HFCV sales of HDV by **2035** **75%** rail electrification **No** aviation electrification	**100%** BEV sales for LDV by **2030** **100%** BEV sales for MDV by **2030** **50%/50%** BEV/HFCV sales for HDV by **2035** **75%/25%** rail electrification/hydrogen **50%** of in-state aviation electrified
Industry & Agriculture	**No** incremental industry electrification **No** direct hydrogen combustion **17 MMT** CCS for cement, glass, oil & gas **~80%** reduction in ag. energy emissions **90%** reduction in energy demand from oil & gas extraction and petroleum refining	**44%** of energy demand met with electricity **16%** of energy demand met with hydrogen **18 MMT** CCS for cement, glass, oil & gas **~90%** reduction in ag. energy emissions **90%** reduction in energy demand from oil & gas extraction and petroleum refining	**53%** of energy demand met with electricity **19%** of energy demand met with hydrogen **14 MMT** CCS for cement and glass **100%** reduction in ag. energy emissions **100%** reduction in energy demand from oil & gas extraction and petroleum refining
Electricity	Remaining dispatchable gas capacity is fueled with **natural gas** **95%** zero carbon generation	Remaining dispatchable gas capacity is fueled with **biomethane** **100%** zero carbon generation	Remaining dispatchable gas capacity is fueled with **biomethane** **100%** zero carbon generation
High GWP & Non-Combustion	Emissions reductions relative to 2020: **23%** for landfill & wastewater methane; **72%** for pipeline fugitive methane; **41%** for agricultural methane/N_2O; **75%** for HFCs/refrigerants		Same as other scenarios, but with **100%** reduction in gas distribution pipeline fugitive methane due to gas distribution grid retirement
Carbon Dioxide Removal	**80 million metric tons/year** of carbon dioxide removal needed in 2045	**57 million metric tons/year** of carbon dioxide removal needed in 2045	**32 million metric tons/year** of carbon dioxide removal needed in 2045

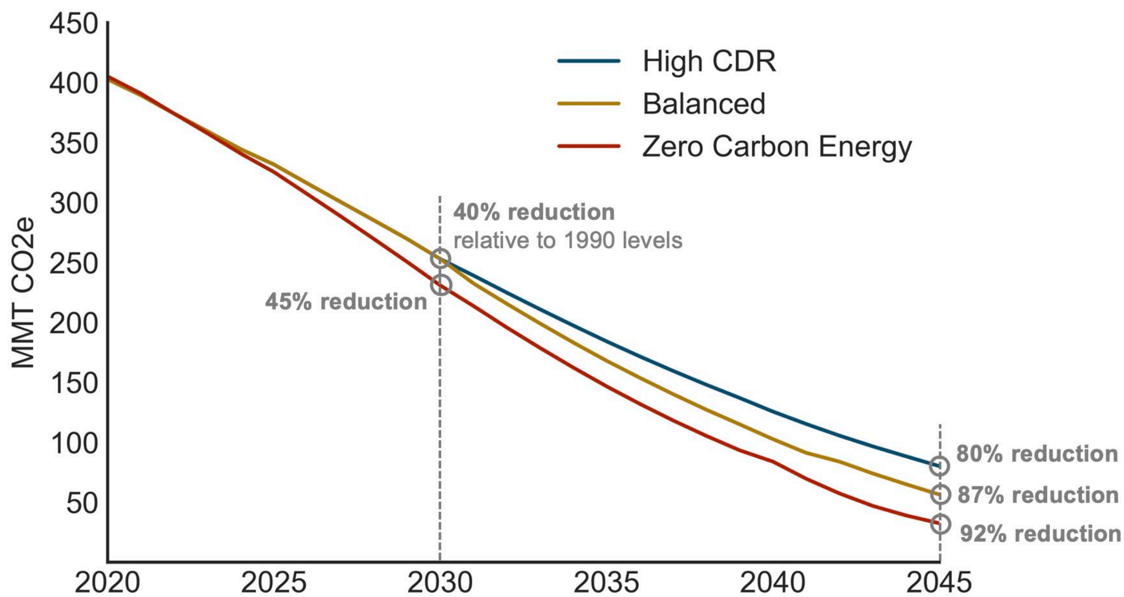
Figure 3 below illustrates the gross greenhouse gas emissions in 2020 and 2045 for each of the three scenarios, and the magnitude of carbon dioxide removal that would be needed to achieve carbon neutrality in each scenario. Figure 4 illustrates the trajectory of gross greenhouse gas emissions in each scenario, between 2020 and 2045, prior to the application of CDR strategies.

Figure 3. Greenhouse gas emissions sources and sinks by sector in 2020 and 2045, by scenario



[4] Percentage hydrogen blend is given as a % of energy input

Figure 4. California statewide gross greenhouse gas emissions by scenario (2020 – 2045), excluding the impacts of carbon dioxide removal (CDR) strategies



2.4 GHG Reduction Strategies by Sector

The following section dives into the specific measures adopted, results across each sector, and gross emissions sources for all three scenarios. These sectors include:

- Low Carbon Fuels
- Buildings
- Transportation
- Industry and Agriculture
- Electricity

- High GWP Resources
- Carbon Dioxide Removal

Each of these subsections includes an initial overview of the sector's decarbonization challenges as discussed in the broader global literature, often using European studies as examples, followed by a deeper dive into the California context of decarbonization measures and policies for that sector and finally providing a specific breakdown of the measures applied in each scenario for that sector or group of emissions.

2.4.1 LOW-CARBON LIQUID AND GASEOUS FUELS

Most decarbonization pathways show a significant reliance on low-carbon (or zero carbon) liquid and/or gaseous fuels across all sectors of the economy (buildings, industry, transportation, and electricity) in order to meet climate goals, and in particular when targeting net zero emissions. The low carbon liquid and gaseous fuels most often referred to in these studies include, but are not limited to, hydrogen, synthetic fuels, and biofuels (including biomethane). These fuels can satisfy the same energy services as their fossil counterparts but are instead produced from renewable resources, or require carbon capture and sequestration. The renewable resources used to produce such low carbon fuels typically fall in two categories: biomass or electricity from renewable energy resources (direct use of low-carbon and zero-carbon electricity is discussed in a subsequent section).

Biomass can be used to produce biomethane, biofuels or hydrogen. Thermochemical conversion processes such as gasification or pyrolysis are usually assumed in producing such fuels. The process itself however does require a significant source of energy and heat to process the biomass and conduct gasification. In the case of biofuel production some further processing is required to produce specific hydrocarbons such as renewable diesel or renewable jet kerosene (Bui, Fajardy, Zhang, & Mac Dowell, 2020). Biological processes, such as anaerobic digestion, are also considered promising in converting biomass to biomethane. These conversion processes, however, are limited by the availability of digestible biomass feedstocks.

Liquid and gaseous fuels produced via electricity powered by renewables are mainly discussed as being hydrogen and synthetic fuels (in the EU studies also referred to as “e-fuels”). Most of the hydrogen produced today (about 97%) comes from fossil fuels typically using a process called steam methane reforming (IEA 2019) and is referred to as “grey hydrogen”. A low carbon version of this process exists, combining steam methane reforming with CCS to capture the carbon dioxide from the natural gas reforming process, referred to as “blue hydrogen”. Decarbonization studies and regional investment plans for the EU and Germany, however, are focusing increasingly on “green hydrogen”: hydrogen produced via electrolysis and powered by renewable energy (European Commission, 2020) (Federal Government of Germany, 2020). Combined with a push to move away from fossil fuels, the appeal of water electrolysis powered by renewables to produce hydrogen is driven by decreasing costs in wind and solar generation and a projected increase in commercialization of electrolyzers such as Alkaline Electrolysis Cells and Solid Oxide Electrolysis Cells (UCI 2018). Today the cost of “green hydrogen” is two to seven times greater than the cost of “grey hydrogen”, depending on the renewable energy resource available, but the cost is expected to decline substantially (IEA, 2019); (Schmidt, et al., 2017).

There is an increasing consensus around the potential for “off-grid” renewables to power electrolysis energy needs to avoid additional transmission and grid infrastructure. In Europe, limited land availability is also driving a trend towards offshore wind powering electrolysis for hydrogen production (Philibert, 2018). Hydrogen is a high energy density fuel by weight but low energy density fuel by volume and can easily leak from pipelines and valves. Hence, well-designed gas storage and compression are critical in being able to handle and transport hydrogen from its production site to its end user. These hydrogen-specific infrastructure requirements add to the cost of delivering hydrogen and sometimes serve as an argument for promoting synthetic fuel use instead, which can be transported with existing infrastructure. Synthetic fuels have the advantage of being able to directly displace fossil fuel use without the burner tip conversion, pipeline and turbine upgrades required with displacing fossil fuels with hydrogen, but come at a considerable cost premium over hydrogen fuels.

Synthetic fuels are typically produced via two types of processes: the Fischer-Tropsch process or the Sabatier process. Each of these require a hydrogen and a carbon dioxide input stream. While these processes are well known and proven, the cost of acquiring the hydrogen and the carbon dioxide remain high. To minimize net GHG emissions on a lifecycle basis, carbon dioxide is typically assumed to be obtained either via biomass waste processing or via direct air capture. The cost of synthetic fuels is likely to remain high, at about double that of hydrogen (Aas, 2020).

Measures to incentivize the development of the hydrogen and synthetic fuels and benefits from economies of scale could help reduce the cost of production.

2.4.1.1 The California context

In California, measures such as the Cap-and-Trade program and the Low Carbon Fuel Standard help to incentivize the development and deployment of low carbon fuels. Measures specific to each sector such as the ZEV Memorandum of Understanding ("ZEV MOU") on passenger vehicles and California's latest Advanced Clean Trucks regulation also further spur the development of such low carbon fuels.

The ability to produce biogas, biofuels and hydrogen from biomass waste is limited by the availability of waste biomass available to California. In this study we assume that California has access to its population weighted share of national waste biomass production, based on estimates from the US Department of Energy biomass potential study, known as the Billion Ton Study (U.S. Department of Energy, 2016), amounting to 40 million bone dry tons (BDT) in 2045. The amount of biomass available for conversion to fuels will be subject to its use in other parts of the economy and can vary year on year based on changes in forest management and agricultural practices (i.e. agricultural residues). This study does not assume that purpose-grown biomass (such as switchgrass) or biomass from petrochemical waste is used for biofuel production.

Furthermore, large amounts of solar and wind in California and in neighboring regions can provide an excellent source of renewable energy for electrolysis to produce hydrogen. The West is also endowed with salt caverns and geological storage that can serve to store hydrogen in interim periods when renewable energy production and demand are not temporally aligned. This can be done at a very low cost compared to above-ground compression tanks (Mahone, Mettetal, & Stevens, 2020). Earlier studies have also investigated the potential for synthetic natural gas production in the region and using it to serve gas demand in local distribution networks (Aas, 2020).

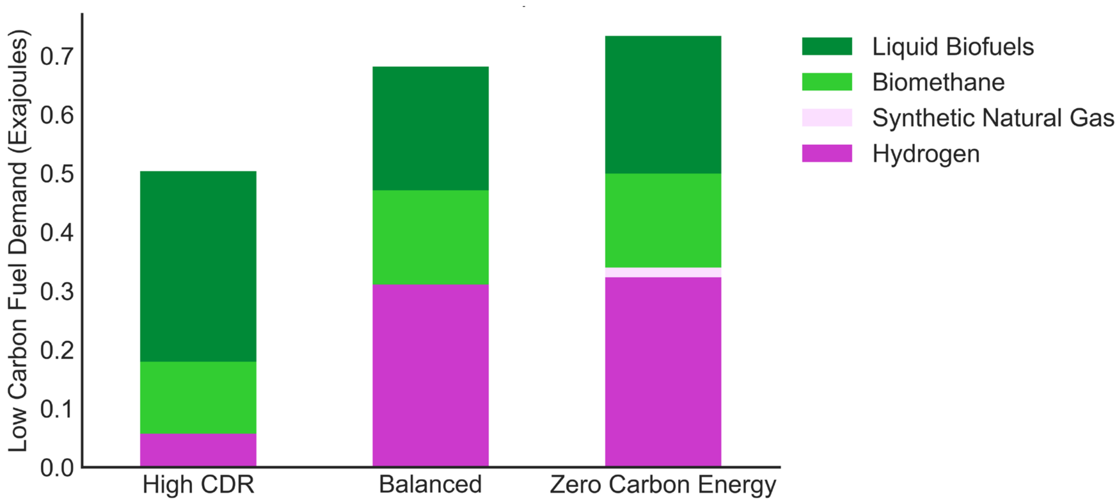
2.4.1.2 Scenario comparison

Figure 5 shows how low-carbon fuels are used in each of the scenarios in this study. All scenarios are assumed to have the same amount of biomass availability, and all scenarios use the total amount of biomass available. However, the allocation of biomass to fuel production pathways differs somewhat by scenario. In the High CDR scenario, biomass is allocated more or less evenly to produce renewable gasoline, renewable diesel, and biomethane. In the Balanced scenario, biomass is allocated mainly to produce renewable jet fuel and renewable diesel, as well as to biomethane in electricity to provide the ~5% of electricity demand that is met with biomethane. In the Zero Carbon Energy scenario, biomass is allocated to renewable gasoline, renewable diesel, and renewable jet fuel, as well as to biomethane for electricity, as in the Balanced scenario.

The use of biomethane to decarbonize the electricity sector is one option among several, and there is still uncertainty around what technologies will ultimately provide the best form of firm, zero-carbon capacity to the grid. This need for firm capacity could also be served, in part or in full, by other zero carbon fuels such as hydrogen and synthetic natural gas, or via other, emerging long-duration energy storage technologies. If these alternative technologies were available to help decarbonize the electricity sector, the biomass allocated to biomethane production in these scenarios could be made available to help decarbonize other sectors.

It is also important to note that there is significant uncertainty regarding the potential for a biofuels production and distribution industry to be sustained for sectors that are rapidly electrifying - meaning the demand for biofuels could eventually reach zero over time. This situation of declining demands for liquid fuels, leading to an uncertain long-term investment environment, exists for renewable gasoline and some renewable diesel in the Zero Carbon Energy scenario. In the other two scenarios, demand for biofuels would be more or less sustained over time.

Figure 5: Low-carbon fuel demand in 2045 by scenario in EJ



2.4.2 BUILDINGS

Increased reliance on energy efficiency and electricity in buildings for heating and water heating is common across all jurisdictions and scenarios in the literature that we reviewed. European scenarios for 2050 show that the building sector could consume 20-55% less energy than it does today, partly by renovations of the building stock (Tsiropoulos, Nijs, Tarvydas, & Ruiz, 2020). For instance, the World Energy Outlook's "Sustainable Development" scenario from the International Energy Agency assumes a 4% annual renovation rate post-2025 and scenarios by the European Climate Foundation assume 96% of the EU building stock are renovated by 2050 (European Climate Foundation, 2018) (International Energy Agency, 2019). With a relatively old building stock, the Buildings Performance Institute Europe calculates that over 97% of the European building stock must be upgraded to achieve 2050 decarbonization (Buildings Performance Institute Europe, 2017). The World Green Building Council recommends increasing renovation rates in industrialized countries to an average of 2% of existing stock per year by 2025, and 3% by 2040 (GlobalABC & International Energy Agency, 2019).

In 2050, the use of natural gas in the European building stock is almost completely eliminated in deep decarbonization scenarios. The building sector increases its reliance on electricity across all jurisdictions and scenarios. In European studies, 37% to 62% of final energy demand is based on direct electricity consumption by 2050. Areas of difference across jurisdictions include the degree to which electrification is relied on to meet winter heating needs. Colder climates assume partial electrification and greater reliance on zero-carbon fuels.

Most jurisdictions and scenarios agree that there is not sufficient biomethane/biofuels to replace natural gas use in buildings. Some natural gas heavy jurisdictions, such as the Netherlands, rely partly on the deployment of hybrid electrification (installing small electric heat pumps combined with high efficiency boilers) in which the winter peak is supplied by biomethane (The Oxford Institute for Energy Studies, 2019), although green hydrogen could also meet these winter peak demands. Unlike in the U.S., European scenarios see an additional role for district heating networks in building heat supply. Across European studies, the building sector covers up to 30% of its heating needs through district heating, growing 2.5 times higher than today (Tsiropoulos, Nijs, Tarvydas, & Ruiz, 2020).

Building energy codes play an important role in setting standards for building construction that will reduce the long-term energy demands of the buildings sector. In the U.S., energy intensity in residential buildings decreased 19% from 2007 to 2017 as a result of efficiency standards for equipment and appliances and stronger building codes (Leung, 2018). Across the world, 73 countries have mandatory or voluntary building codes in place or are developing them (GlobalABC & International Energy Agency, 2019).

Most European studies consider the use of hydrogen in buildings, but only very few assume relatively high volumes (higher than 10% of final energy demand) (Tsiropoulos, Nijs, Tarvydas, & Ruiz, 2020). The Hydrogen Council states that the use of hydrogen in buildings is most attractive in countries generally with cold winters that already have extensive natural gas infrastructure in place, such as the UK, Canada and countries in continental Europe (Hydrogen Council, 2017). In their view, hydrogen could meet up to 18% of heat-related energy demand, by either blending with natural gas, methanization or in pure form.

The IPCC notes that while the technology solutions to realize building decarbonization exist today, barriers such as split incentives[5], lack of awareness, and low access to finance, hinder the market uptake of cost-effective opportunities in the sector (Lucon, et al., 2014). Moreover, behavior, lifestyle, and culture have a major effect on buildings' energy use, further complicating the building stock transition.

2.4.2.1 The California Context

Buildings in California are characterized by a high reliance on natural gas for space heating and water heating. Moreover, buildings in California have a relatively high share of space cooling demand compared to heating demands. The relatively mild winter climate makes building electrification more economically attractive and universally applicable than in colder climates. The absence of a significant winter peak

[5] "Split incentives" refers to situations where the party paying for energy (e.g. a tenant of a rental property) is different from the party paying for appliances that use energy (e.g. the landlord of a rental property). In these situations, the building owner has no incentive to pay more for an energy efficient appliance that would save money for the tenant over time.

suggests a heavier reliance on electrification in buildings may be feasible compared to jurisdictions with colder climates.

The relatively new building stock in California, compared to Europe and the Eastern U.S., puts less emphasis on building renovations compared to jurisdictions where old, poorly insulated homes are the norm. In addition, these conditions make hybrid or district heating solutions, that are often considered for hard-to-renovate homes, less relevant. The California residential building stock is dominated by low and mid-rise buildings, facilitating the use of air source heat pump installations.

2.4.2.2 Scenario comparison

In all scenarios, the SB 350 goal of doubling Additional Achievable Energy Efficiency (AAEE) by 2030 is met, as measured by a “combined” doubling metric where gas and electric EE are considered in aggregate. Electric EE savings come from a shift to selling only LED light bulbs by 2030 and increased efficiency for refrigerators, HVAC, and other plug load appliances, while gas EE savings come from more efficient furnaces, ovens/cooktops, and water heaters. Building envelope improvements contribute to EE savings for both fuels, with 24% of the building stock assumed to either be retrofit or constructed with a high efficiency shell by 2030 (this increases to 52% by 2045). Finally, energy savings resulting from fuel substitution are also responsible for a portion of meeting this goal. All scenarios achieve 46 TWh of electric energy efficiency in buildings in 2030 relative to a 2015 baseline, and 67 TWh in 2045.

All scenarios involve a transition to all-electric end uses in buildings (for heating and HVAC, water heating, cooking and clothes drying), with the date of 100% sales share varying by scenario, as detailed below in Table 2. This transition towards building electrification involves substituting gas end uses for high efficiency electric end uses, such as heat pumps, at the end of their useful life (this is known as “replace on burnout”) as well as in newly constructed buildings. No early retirement of gas appliances is assumed in the High CDR and Balanced scenarios, while the Zero Carbon Energy scenario assumes early retirement of all remaining gas appliances in 2045. The transition to all-electric HVAC also has the potential to provide cooling for households that do not currently have air conditioning (since heat pumps provide both heat and cooling), which could help Californians cope with increasing temperatures due to climate change.

Table 2. Building sector assumptions which differ by scenario

Scenario	Sources of differences among scenario assumptions
High CDR	100% sales of electric appliances by **2040,** 5% hydrogen in the gas pipeline by 2045, 12% biomethane in the pipeline by 2045
Balanced	100% sales of electric appliances by **2035**, 5% hydrogen in the gas pipeline by 2045
Zero-Carbon Energy	100% sales of electric appliances by **2030,** with a complete retirement of the low-pressure gas distribution system in **2045**.

Figure 6 shows how energy demand is met for buildings across the three scenarios in 2045, as well as a comparison to 2020 for reference. Note that the "electricity" bar is only showing demand for electricity and does not reflect the difference in electricity emissions between scenarios (the High CDR scenario assumes 95% zero carbon electricity, whereas the other two scenarios assume 100% zero carbon electricity by 2045). The reduction in final energy demand in all scenarios in 2045 occurs primarily due to fuel substitution, since heat pumps are, on average, 3-4 times more efficient than their gas counterparts. The high building efficiency assumptions also contribute to the reduction in final energy demand.

Figure 6. Final energy demand in buildings in 2020, and in 2045 across the three scenarios

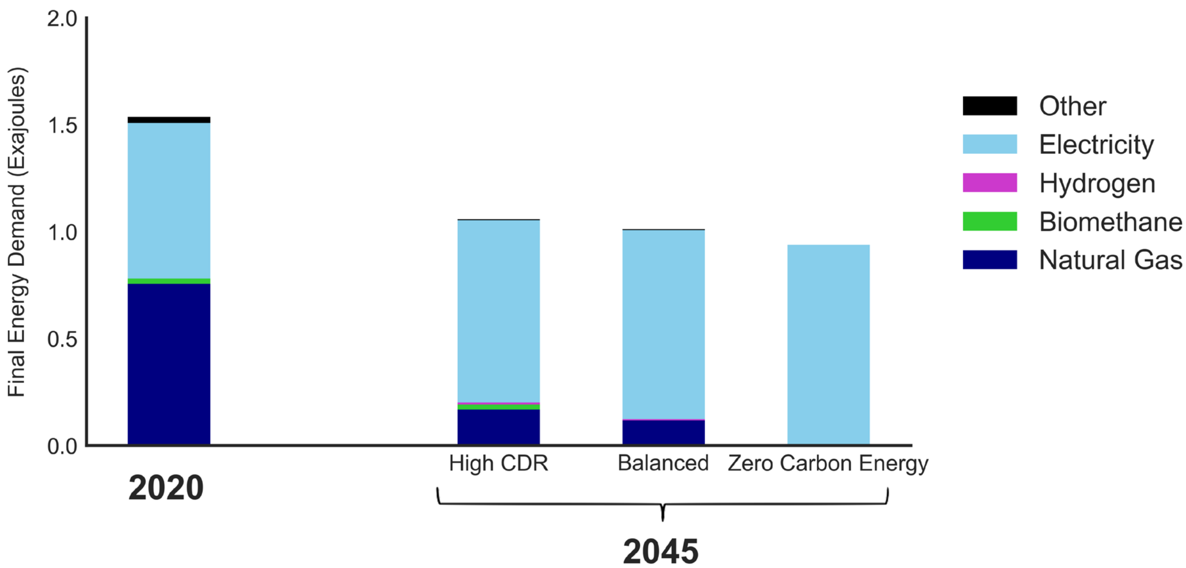
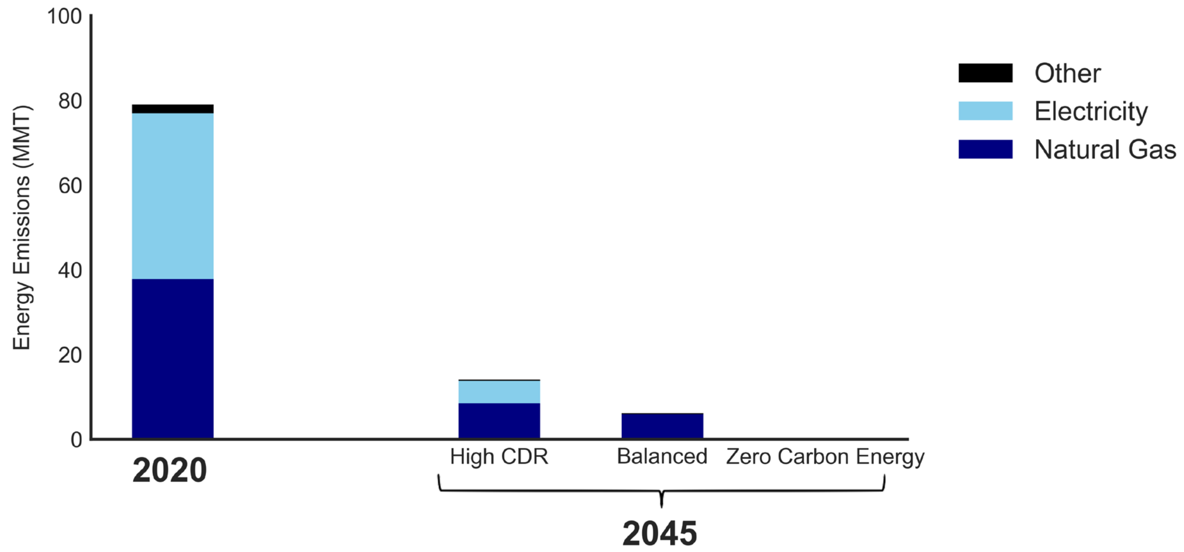


Figure 7 shows the emissions resulting from energy consumption in buildings across the three scenarios, as well as in 2020 for reference. Non-energy emissions such as those from HFCs are not shown here, but rather discussed separately in the non-energy emissions section below.

Figure 7: Energy emissions from buildings in 2020, and in 2045 across the three scenarios



2.4.3 TRANSPORTATION

Most deep decarbonization studies align on the deployment of battery-electric vehicles for passenger transport, and show varying amounts of reliance on hydrogen fuel cell vehicles for some medium and heavy-duty road transport. Overall, deep decarbonization pathways see an important role for electrification, hydrogen, biofuels and synthetic fuels across all parts of transportation, but the mix between these energy carriers is still highly uncertain.

The UK's Committee on Climate Change "Net Zero UK" study (CCC, 2019), for example, highlights the need for all passenger vehicles to be electric by 2050 and the majority of heavy-duty vehicle transportation to be either electric or fueled by hydrogen by 2050. Similarly, the EU's Net Zero study aggregating results from 14 decarbonization focused scenarios, show that by 2050, 65% - 90% of the total vehicle stock should be zero-emissions vehicles comprised of a combination of mostly battery electric vehicles and hydrogen fuel cell vehicles as well as e-fuels or synthetic fuels and biofuels. The UK's Net Zero study assumes some aircraft to be hybrid-electric by 2040.

A commonality amongst most decarbonization studies is the focus on decreasing energy consumption across all transportation modes. This is projected to take place as a result of adopting carbon fuel standards with the deployment of more efficient fuels (e.g. electricity) and engines or fuel cells, as well as smart growth. Some amount of behavior change and commuting options made available via shared economy solutions also play a key role in reducing energy consumption and are particularly important in cities (Carbon Neutral Cities Alliance, 2018). Such measures are expected to significantly reduce total vehicle miles travelled (VMT). In the EU's "Towards Net Zero" study, all scenarios evaluated decrease final energy consumption by at least 50% from 2017 levels (Tsiropoulos, Nijs, Tarvydas, & Ruiz, 2020). And in the most extreme scenarios, a decline of up to 80% in final energy consumption (excluding international aviation and maritime bunker fuels). Driving this decline in energy consumption is the switch from ICEs to electric or hydrogen fuel cell vehicles, which results in very significant energy efficiency gain and aggressive assumptions on VMT reduction as a result of "smart" growth.

2.4.3.1 The California Context

The transportation sector is the largest source of emissions in California, with GHG emissions increasing every year between 2013 and 2017. This corresponds with an increase in annual average VMT/capita over the same period, although annual emissions rose at a slightly slower rate due to the decreasing carbon intensity of transportation fuels in the state and the growing market share for hybrid and battery-electric vehicles. While VMT has dropped sharply in the wake of the COVID-19 pandemic, it remains too early to predict how quickly VMT will return to pre-pandemic levels, if at all.

California has enacted multiple policies to support transportation decarbonization. As of mid-2020, the state has in place regulations requiring manufacturers to sell an increasing number of zero-emission passenger vehicles, medium and heavy-duty trucks, and buses through CARB's Advanced Clean Cars, Advanced Clean Trucks, and Innovative Clean Transit programs. The existing regulations would see ZEVs reach 22% of passenger car sales by 2025, 40% - 75% of medium and heavy-duty truck sales by 2035 (depending on vehicle class), and 100% of sales for transit buses by 2029.

CARB's Low-Emission Vehicle (LEV) III regulation and Low-Carbon Fuel Standard (LCFS) program are both designed to reduce emissions from conventional internal combustion engine vehicles in addition to stimulating ZEV adoption. The LEV III regulation includes increasingly stringent greenhouse gas emission standards for passenger vehicles through the 2025 model year, while the LCFS program uses a credit system to financially incentivize a shift to less carbon intense transportation fuels like biofuels, compressed natural gas (CNG), electricity, and hydrogen.

Federal preemption rules for California provide the state the unique ability to regulate tailpipe emissions, but emissions from international shipping and interstate trucking are harder to regulate. A significant fraction of energy consumption associated with interstate and international aviation and shipping are not included in the state's emission inventory and thus are not considered here – but will need to be mitigated to achieve national and global emissions reductions.

2.4.3.2 Scenario comparison

Across all scenarios, we assume an increase in fuel economy standards for internal combustion engine vehicles (from 45 MPG in 2020 to ~70 MPG in 2045 for passenger vehicles) and a 17% reduction in per capita LDV VMT relative to 2020 by 2045. For off-road transportation, we assume that shore power is used for 80% of hoteling ships by 2030 and that 70% of harbor craft are electrified by 2045. The use of fossil natural gas and biomethane for CNG trucks is phased out in the Balanced scenario and the Zero Carbon Energy scenario. The Balanced scenario assumes a complete transition to hydrogen fuel cell and electric truck sales by 2035. In the Zero Carbon Energy scenario, this transition to 100% hydrogen fuel cell and electric truck sales occurs by 2030.

Table 3. Transportation sector mitigation measures by scenario

Scenario	Assumptions
High CDR	100% BEV sales for LDV by 2035 100% BEV sales for MDV by 2040 45%/48% BEV/CNG sales for HDV by 2040, 7% diesel sales remaining for long-haul 50% rail electrification, no aviation electrification
Balanced	100% BEV sales for LDV by 2035 100% BEV sales for MDV by 2035 45%/48% BEV/HFCV sales for HDV by 2035, 7% diesel sales remaining for long-haul 75% rail electrification, no aviation electrification
Zero-Carbon Energy	100% BEV sales for LDV by 2030 100% BEV sales for MDV by 2030 50%/50% BEV/HFCV sales for HDV by 2030 75%/25% rail electrification/hydrogen, 50% of in-state aviation electrified

Figure 8 shows how energy demand is met across the three scenarios in 2045, as well as how demand is met today for reference. The significant decrease in energy demand by 2045 occurs because electric vehicles are about 3 times more efficient than internal combustion engine vehicles, in terms of source energy, and, to a lesser extent, due to assumed reductions in VMT.

Figure 8: Final energy demand in transportation in 2020, and in 2045 across the three scenarios

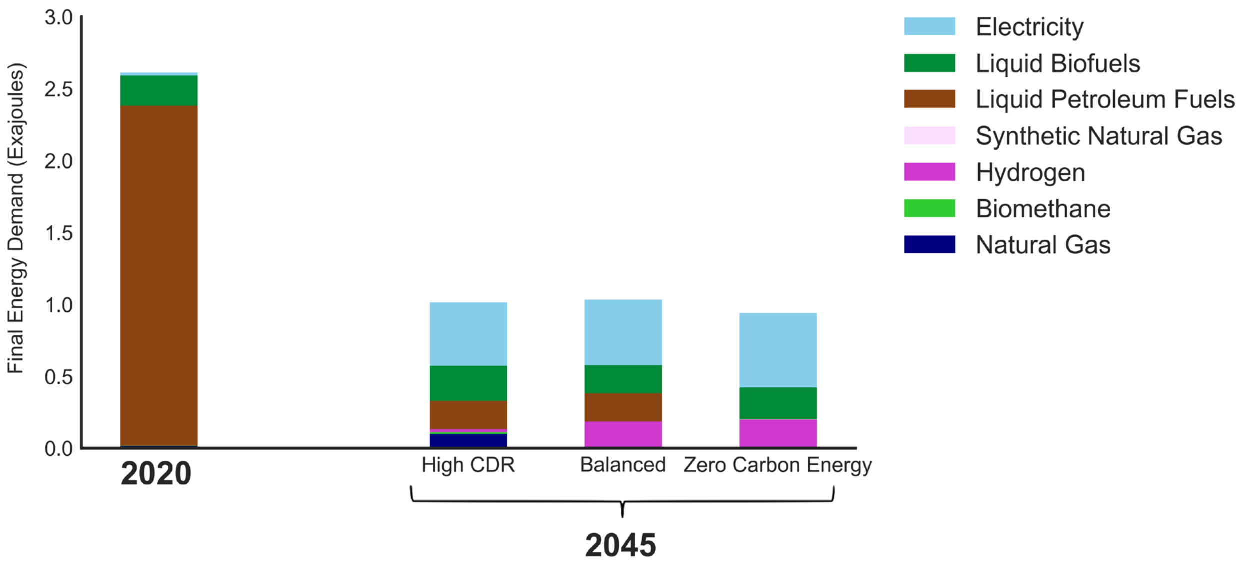


Figure 9 shows the emissions resulting from energy consumption in transportation, both in 2020 and in 2045 across the three scenarios. Note that emissions associated with electricity consumption are included here, whereas in the CARB AB 32 Annual GHG inventory they are accounted for separately. Also note that the Zero Carbon Energy scenario achieves a carbon-neutral transportation sector because biofuels are assumed to fulfill remaining fossil fuel demands.

The remaining emissions from transportation in the High CDR and Balanced scenarios can be expected to decrease over time post-2045 as the stock share of electric vehicles catches up with the sales share. However, both of these scenarios (and in particular the High CDR scenario) include a small amount of ongoing demand for liquid and gaseous fuels, as they do not fully reach 100% electric vehicles.

Figure 9: Energy emissions from transportation in 2020, and in 2045 across the three scenarios

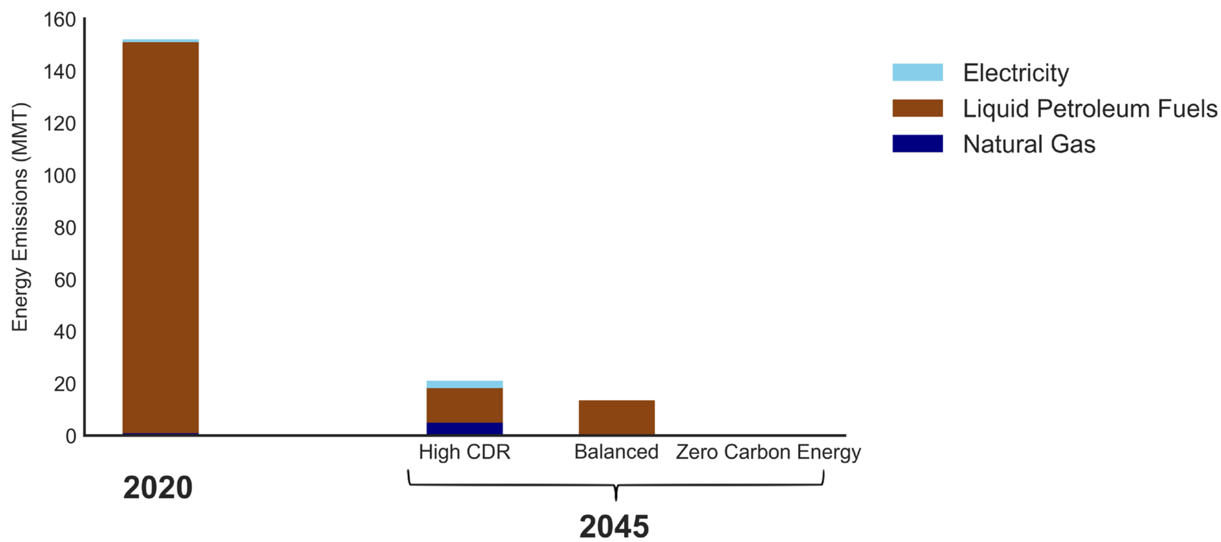


Figure 10, Figure 11, and Figure 12 show the stocks of LDVs, MDVs, and HDVs over time, respectively, for the Balanced Scenario. This scenario represents a widespread transition to zero-emission vehicles for the transportation sector, across all vehicle types. The other two scenarios assume a slightly different pace of transition, as detailed in the table above, but the story remains similar for these other two scenarios.

Figure 10: Light Duty Vehicle Stocks in the Balanced Scenario

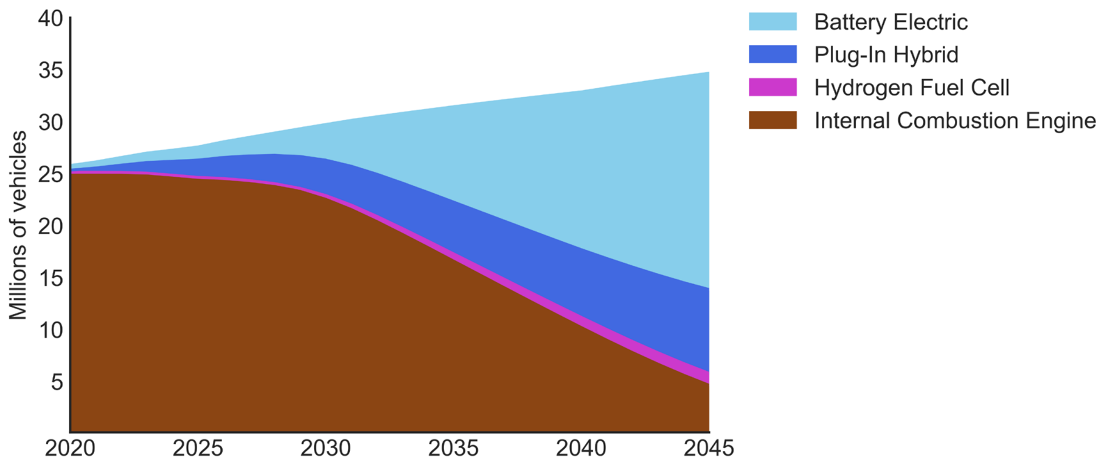


Figure 11: Medium Duty Vehicle Stocks in the Balanced Scenario

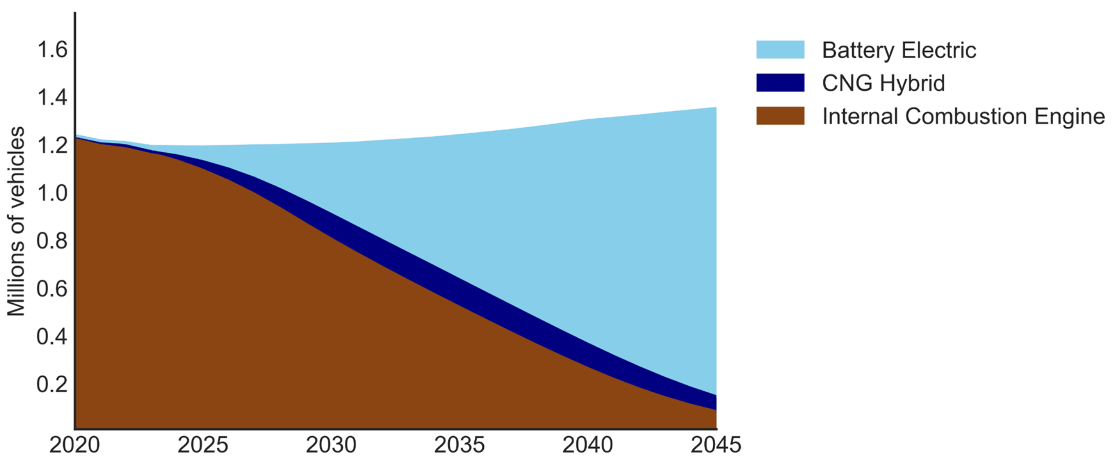
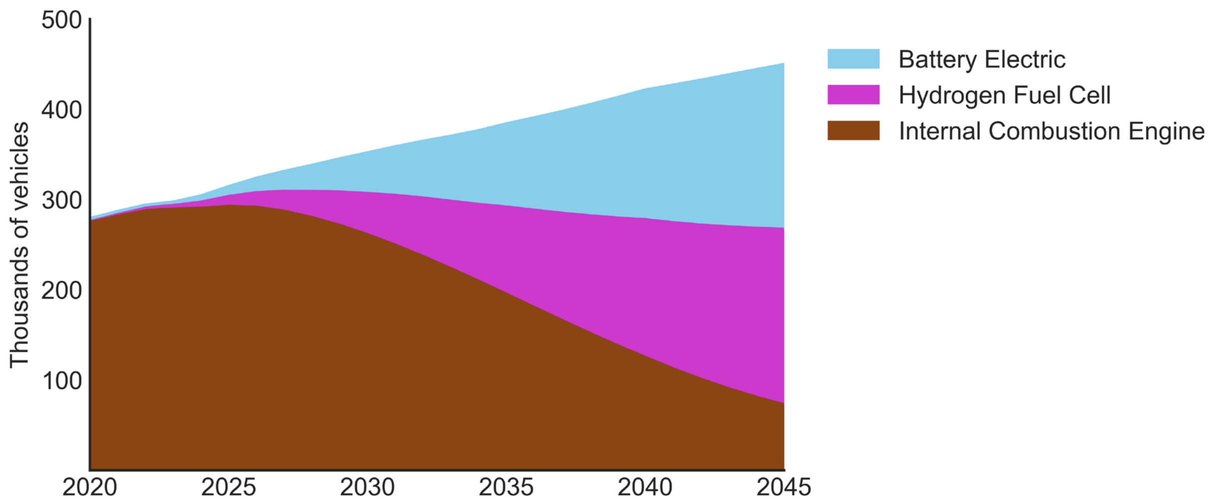


Figure 12: Heavy Duty Vehicle Stocks in the Balanced Scenario



2.4.4 INDUSTRY AND AGRICULTURE

The Industry and Agriculture sectors include manufacturing, cement, oil and gas extraction, petroleum refining and fuel use in agriculture processes.

Across jurisdictions, one of the general uncertainties in the industrial sector is to what degree current demand for manufactured goods and refined petroleum products, for example, persist through 2045 (Tsiropoulos, Nijs, Tarvydas, & Ruiz, 2020). While some studies expect energy demand in the oil and gas sector to decline with the energy transition, other studies assume a global demand for such products will continue to exist. Overall, the role of consumers and consumer behavior is important in these underlying assumptions.

In European deep decarbonization studies, the industrial sector reaches widespread electrification (around 40-60% in most scenarios), combined with the consumption of hydrogen, biofuels, and CCS. In most scenarios 70% to 100% of the energy use in industry is decarbonized by 2050 (Tsiropoulos, Nijs, Tarvydas, & Ruiz, 2020).

The common challenge in the decarbonization of (heavy) industrial sectors is finding suitable alternatives for the application of high temperature heating and process emissions. While electrification is a relatively feasible option for manufacturing sectors, more energy-intense sectors such as steel, chemicals and cement generally require high temperatures and have process emissions that are not linked to energy consumption. Hence, for these industries, strategies relying on electrification or decarbonized fuels are either prohibitively expensive, not available or not sufficient in reducing all emissions. Therefore, these sectors are either reliant on the application of CCS or on heavy process-related innovations. For instance, R&D options in the steel industry exist that produce steel entirely from (carbon free) hydrogen, though this process requires a complete transformation of existing facilities (Eurofer, 2050). California's industrial sector does not include steel production, easing some of the challenges around decarbonization in the sector for the state.

In many European countries, industrial sectors are geographically clustered. This means that they currently share common pipelines for natural gas, which have the potential to be converted to dedicated hydrogen pipelines. In the Netherlands for instance, a hydrogen roll-out proposal already exists that plans to supply hydrogen to industrial sectors through the conversion of one dedicated pipeline that connects all industrial sectors (Gasunie, 2020). Moreover, many European industrial sectors have published sectoral studies that lay out the potential pathways towards decarbonization in 2050. Apart from technological challenges, these studies stress the importance of a global level playing field in implementing carbon-reduction measures (Eurofer, 2050) (Cefic, 2013) (Cembureau, 2020).

In the agricultural sector, uncertainties exist around technology developments related to land use practices, fertilizers, indoor cultivation, etc. As the agricultural sector's largest emissions are methane and nitrous oxide, the biggest challenges in this sector are non-energy related.

2.4.4.1 The California Context

Industry is a large source of emissions in California relative to other states and parts of Europe that have committed to carbon neutral goals. Agriculture, oil & gas extraction, and petroleum refining are all sectors with significant energy demands and emissions in the state—California produces more agricultural products than any other state and is the seventh largest oil producing state in the country, according to the US EIA.

The geology of California's Central Valley is suitable to carbon storage, meaning CCS for some industrial processes is feasible, such as cement production and process heating.

Oil and gas extraction and petroleum refining are currently the largest sources of industrial emissions. However, the role of these industries in a carbon-neutral future is uncertain, particularly if California's oil and gas demand were to decline significantly due to reduced demand.

2.4.4.2 Scenario comparison

In all scenarios, biofuels are used to fulfill liquid fuel demands that are remaining after other decarbonization strategies (mainly in agriculture and off-road equipment). An unspecified 10% reduction in demand due to energy efficiency is assumed for all fuels in industrial and agriculture energy use, consistent with estimates of the achievable potential of energy efficiency in these sectors across a variety of strategies, including more efficient motors, lighting, and process heating improvements. CCS is assumed to be applied in the cement, glass, and primary metal subsectors.

The manufacturing sector in California is comprised of a wide array of industries with highly diverse production processes and energy demands. Because of this, we include a mix of industry decarbonization technologies in our Balanced and Zero-Carbon Energy scenarios that includes electrification, hydrogen combustion, biofuels, and CCS. We assigned these decarbonization technologies to certain industry subsectors and end-uses based on high level assumptions of their relative feasibility, with the understanding that there is a high degree of uncertainty around which technologies will be the lowest cost options in 2045.

Due to the high cost of replacing conventional gas-fired boilers with electric resistance boilers, we chose to replace natural gas with hydrogen combustion for conventional boilers. For process heating, we assumed CCS would be adopted for cement, glass, and primary metal manufacturing, as these subsectors have many characteristics that would lead to CCS being a relatively low cost decarbonization option (e.g. large plant size, high temperature heat requirement, high annual CO_2 throughput, and/or significant process emissions). We assumed that the remaining process heat in industries with lower temperature heating requirements would be met with electric heating technologies. Hydrogen combustion could also be a suitable decarbonization option for many process heating applications, but this was not examined in depth as part of this analysis. Finally, energy demand for the "Other" end-use, which encompasses all industrial end uses that do not fall into categories specified in the table below as well as some off-road transportation fuel demand, was assumed to be evenly split between CCS, electricity, and hydrogen, with a small amount of renewable diesel to replace some of the existing diesel consumption for that end-use.

Table 4. Share of final energy demand by end use for the industrial manufacturing sector in the Balanced and Zero Carbon Energy scenarios in 2045

End-Use	Renewable Diesel	Natural Gas with CCS	Electricity	Hydrogen
Conventional Boiler Use	*0%*	*0%*	*0%*	**100%**
Lighting	*0%*	*0%*	**100%**	*0%*
HVAC	*0%*	*0%*	**100%**	*0%*
Machine Drive	*0%*	*0%*	**100%**	*0%*
Process Heating	*0%*	**53%**	**47%**	*0%*

Process Cooling & Refrigeration	*0%*	*0%*	**100%**	*0%*
Other	**7%**	**31%**	**31%**	**31%**

Table 5. Scenario-specific assumptions for the industry manufacturing, agriculture, and oil & gas extraction / petroleum refining sectors in 2045 across the three scenarios

Scenario	Assumptions
High CDR	No incremental industry electrification ~80% reduction in energy emissions from agriculture (mainly due to electricity decarbonization; renewable diesel used to fulfill diesel demand) 90% reduction in energy demand from oil & gas extraction and petroleum refining due to decreased demand for fossil fuels
Balanced	High industry electrification, direct hydrogen combustion, and CCS (see above table) ~100% reduction in energy emissions from agriculture (remaining diesel demand is transitioned to electricity) 90% reduction in energy demand from oil & gas extraction and petroleum refining due to decreased demand for fossil fuels
Zero-Carbon Energy	High industry electrification, direct hydrogen combustion, and CCS (see above table) 100% reduction in energy emissions from agriculture (remaining diesel demand is transitioned to electricity) 100% reduction in energy demand from oil & gas extraction and petroleum refining due to zero remaining liquid fossil fuel demand due to eliminated demand for fossil fuels

Figure 13, Figure 14, and Figure 15 show how energy demand in the Industry, Agriculture, and Oil & Gas sectors is met in 2020, as well as in 2045 across the three scenarios.

Figure 13: Final energy demand in Industry in 2020, and in 2045 across the three scenarios

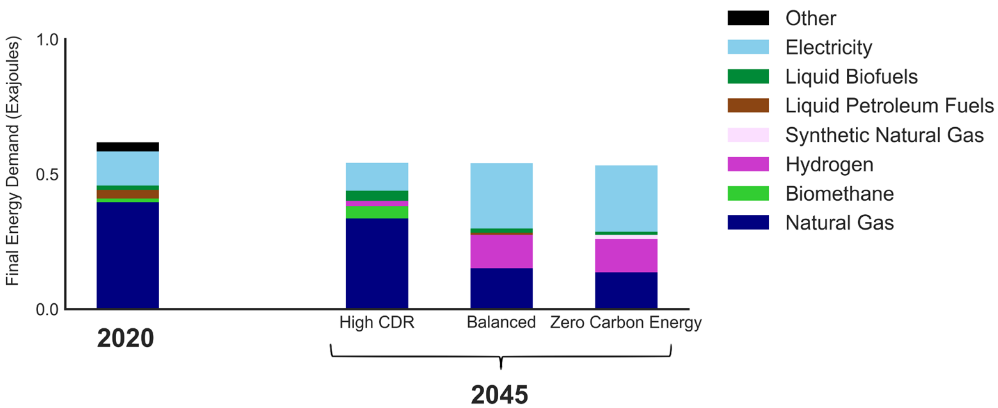


Figure 14: Final energy demand in Agriculture in 2020, and in 2045 across the three scenarios

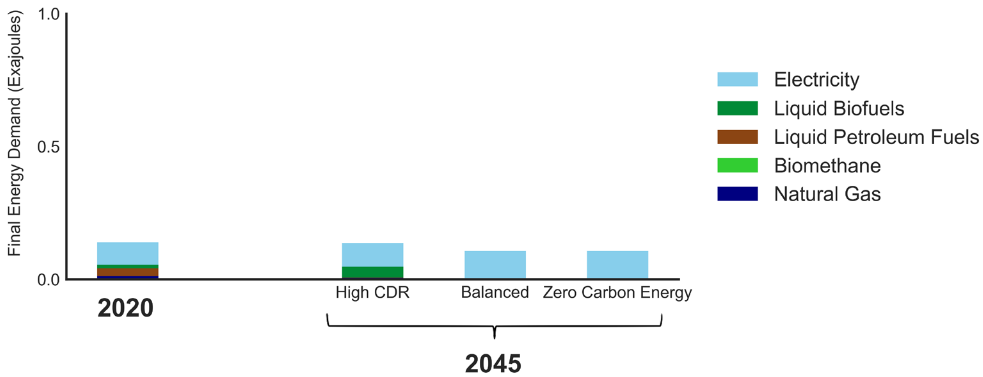


Figure 15: Final energy demand in Petroleum Refining and Oil & Gas Extraction in 2020, and in 2045 across the three scenarios

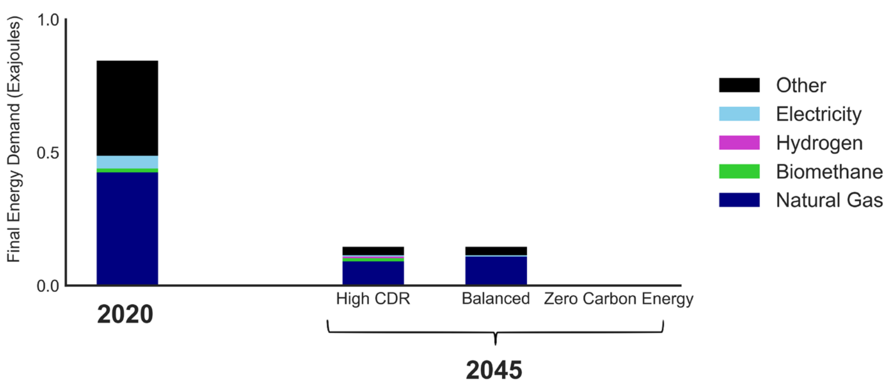


Figure 16, Figure 17, and Figure 18 show the energy and process emissions from the Industry, Agriculture, and Oil & Gas sectors in 2020, as well as in 2045 across the three scenarios. “Other” refers mainly to petroleum coke, as well as refinery & process gas. Also shown here are the emissions that are abated with CCS.

Figure 16: Energy and process emissions in Industry in 2020, and in 2045 across the three scenarios

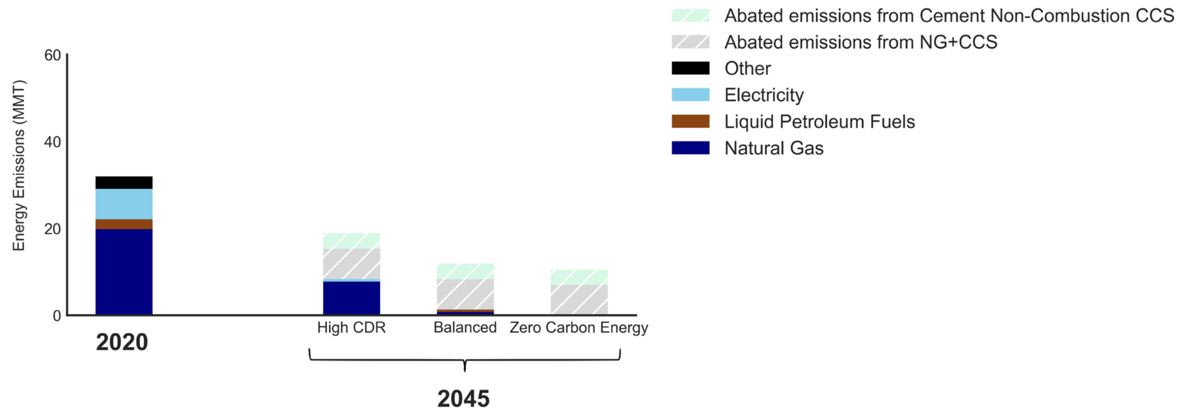


Figure 17: Energy emissions from Agriculture in 2020, and in 2045 across the three scenarios

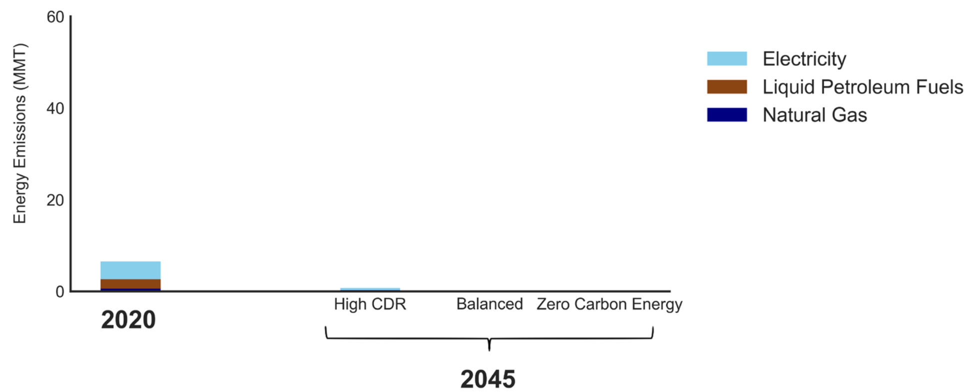
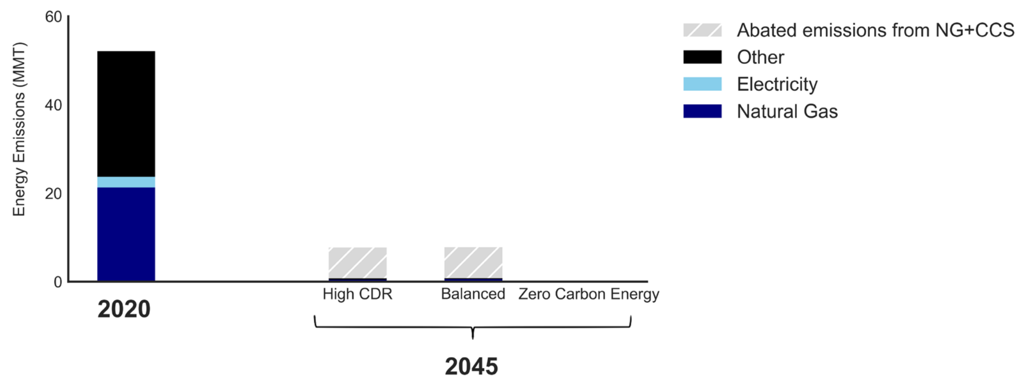


Figure 18: Energy emissions from Petroleum Refining and Oil & Gas Extraction in 2020, and in 2045 across the three scenarios



2.4.5 ELECTRICITY

Pairing electrification of vehicles and buildings with high amounts of renewable energy generation are often considered the “low hanging fruit” of decarbonization due to their near- and long-term economic benefits. Electrification provides significant gains in energy efficiency across those sectors and shifts the decarbonization of these sectors to that of the electricity sector. Furthermore, recent and continuing declines in the cost of solar, wind and battery storage resources mean that these resources can be lower cost than fossil-based thermal resources, up to a point.

Decarbonization of the electricity sector has been well underway over the past decade with significant adoption of renewables in California, the US, and across the globe (IRENA, 2019). In 2018, over 60% of global new energy capacity was from renewables, mainly solar and wind. Total energy share from renewables remains small at 15% (EIA, 2019) (of which about half is from hydro power), but this is projected to grow while generation from thermal resources, particularly coal, is projected to decline over the next decades.

Pathways developed to meet deep decarbonization targets by mid-century typically include a significant reliance on renewables, such as, solar, onshore and offshore wind, complemented by some form of firm capacity (Ming, Olson, De Moor, Jiang, & Schlag, 2019), (Sepulveda, 2018). The exact resource mix that will provide cost-effective decarbonized electricity generation will vary based on geography, resource availability and technological advancements.

The European Commission consolidated 14 energy scenarios that achieve net-zero or near zero emissions by mid-century and 9 of 14 relied on over 50% of generation from wind and solar resources and up to 85% of generation in some scenarios. Hydrogen and bioenergy also play a significant role in providing zero emissions electricity generation for scenarios with very high levels of electrification.

Regional limitations and political appetite are likely to influence differences in decarbonization pathways that may include future developments of long-duration energy storage, hydrogen, advanced nuclear and CCS technologies. There is a general agreement that some form of firm, zero-carbon capacity is needed to complement large increases in renewable generation, as well as regional transmission where feasible.

Large-scale renewable resource deployment also requires significant land use. One MW of utility-scale solar photovoltaics requires approximately 7 acres of land, while 1 MW of onshore wind requires up 2 acres of land cover for the turbine, but will impact up to 140 acres of land, which can be used for agriculture purposes, but not for buildings or other densely populated activities (NREL, 2017).

2.4.5.1 The California Context

California's electricity sector is on a path to adopting significant amounts of renewable generation including solar, wind, geothermal, biomass and small hydro. These already make up about 31% of the state's total power generation in 2018 (CEC, 2019). Senate Bill 100 (SB 100), passed in 2019, targets at least 60% renewable energy generation by 2030 and 100% of electric retail sales to be met by renewable resources and other zero carbon resources by 2045.

California's abundant and high-quality solar energy resource, access to geothermal energy and potential for offshore wind or importing wind from other states to the east[6] makes renewable resource adoption a particularly attractive decarbonization strategy for electricity. Studies focusing on California's electricity sector decarbonization have shown that in order to meet its climate goals, the state will be increasingly reliant on variable renewables, in particular solar and wind with a limited amount of geothermal energy (about 80% of total generation) and significant amounts of energy storage to balance these resources (Ming, Olson, De Moor, Jiang, & Schlag, 2019). Electricity sector studies have also shown the notable value

[6] This refers to Wyoming, Montana and New Mexico wind, for example.

of offshore wind to provide least cost electricity generation in California in the next 10 to 20 years while meeting these goals (E3, 2019).

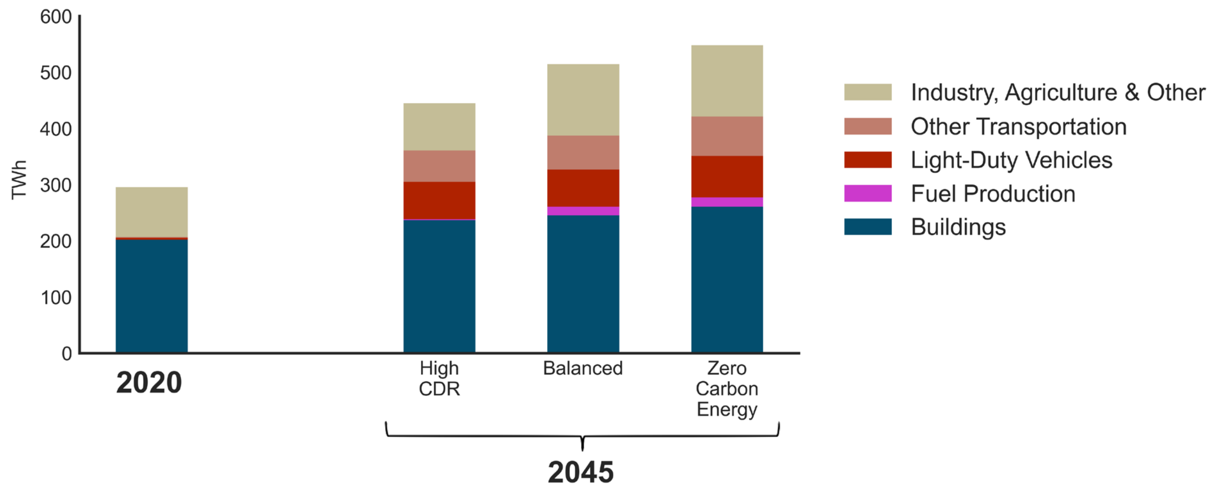
While renewable energy generation can displace the majority of emissions in the electric sector, these studies have shown that, due to reliability concerns, some form of dispatchable generation also referred to as "firm capacity" is needed to maintain system reliability. Some of this firm capacity can be provided by geothermal energy but economic access to large amounts of geothermal energy is expected to be quite limited. Biofuels such as biomethane can displace remaining emissions from gas generation as a low or zero carbon dispatchable fuel, at an incremental cost, while fulfilling the firm capacity need. However, biomass for biofuels is needed across all sectors to meet decarbonization goals, and its availability in 2045 may be limited.

Other potentially promising options exist that can meet the need for firm capacity (or dispatchable generation). These include, but are not limited to, long-duration energy storage (Spector, 2020) and advanced zero carbon fuels to burn in existing or new turbines. In addition to biomethane, these could also include hydrogen and synthetic natural gas. Other dispatchable generation options include gas with CCS, and advanced nuclear power technologies such as small modular reactors and molten salt reactors. However, the development of such dispatchable generation options and fuel production processes remains uncertain and has yet to be demonstrated at commercial scale. Furthermore, California has prohibited the development of new nuclear facilities absent the existence of a federal nuclear waste repository. Thus, advanced nuclear technologies, while potentially promising as a zero-carbon resource, are not assumed in this study.

2.4.5.2 Scenario comparison

In the context of achieving net zero gross emissions, the scenarios developed in this study reflect similar electricity sector results to those developed in other California studies. Figure 19 highlights the total amount of electric load in 2045 and its allocation by sector, the bulk of which is attributed to building energy consumption. Electricity use for fuel production highlighted in Figure 19 refers to liquid hydrogen fuel production used in transportation[7].

Figure 19: Electricity loads by category in 2020 and in all three scenarios in 2045



Levels of electrification by scenario increase in the following order: High CDR, Balanced and Zero Carbon Energy. Figure 20: Electric highlights that, across all scenarios, there is a heavy reliance on variable renewables, amounting to at least 80% of total generation. The remaining generation across all scenarios, 15-20%, are from a combination of large hydro resources (including imports), some geothermal capacity and some form of dispatchable gas. Depending on the scenario, the dispatchable gas used is either fossil based, i.e. natural gas (High CDR scenario) or biomass based i.e. biomethane (Balanced and Zero Carbon Energy scenarios). In the absence of other technologies highlighted in the previous section, the firm capacity need is met by a combination of geothermal and dispatchable gas generation. Here, dispatchable biomethane enables the Balanced and Zero Carbon Energy scenarios to achieve zero emissions electricity generation, while the High CDR scenario still has 10 million metric tons of CO_2 emitted from natural gas

[7] Hydrogen used in other parts of the economy is assumed to have a dedicated off-grid production process that feeds into the natural gas pipeline.

generation in 2045. All scenarios comply with SB 100 providing at least 100% of electricity retail sales with zero carbon resources, which reflects at least 95% of generation from zero emissions resources.

Figure 20: Electric shows the resources used to generate electricity in 2020, as well as in all scenarios in 2045. the generation figures shown below do not include curtailed renewables[8], but do include exports. In these scenarios, on-grid hydrogen production is an electric load which increases the total demand for renewable electricity and may also be used to reduce renewable curtailment.

Figure 20: Electricity Generation by Resource in 2020 and in all three scenarios in 2045

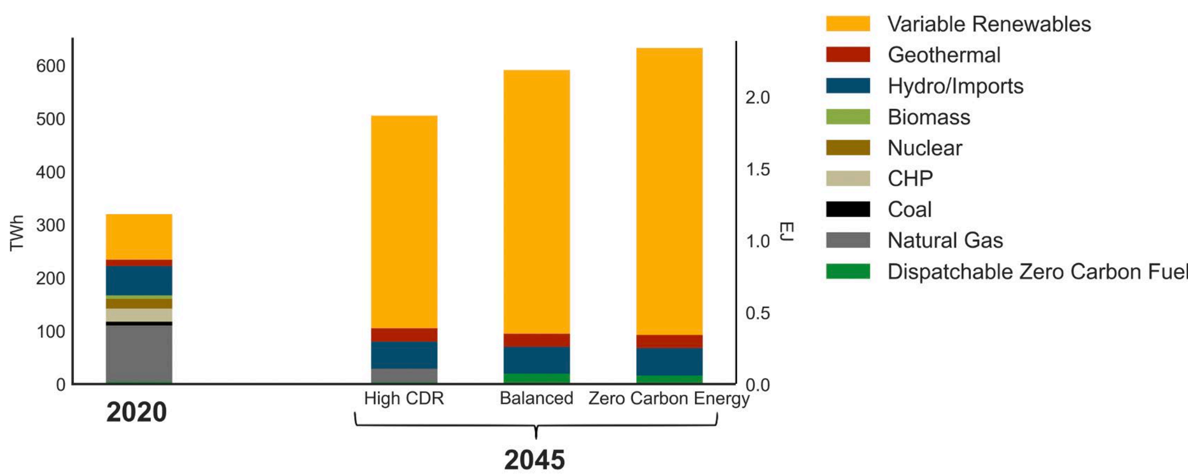


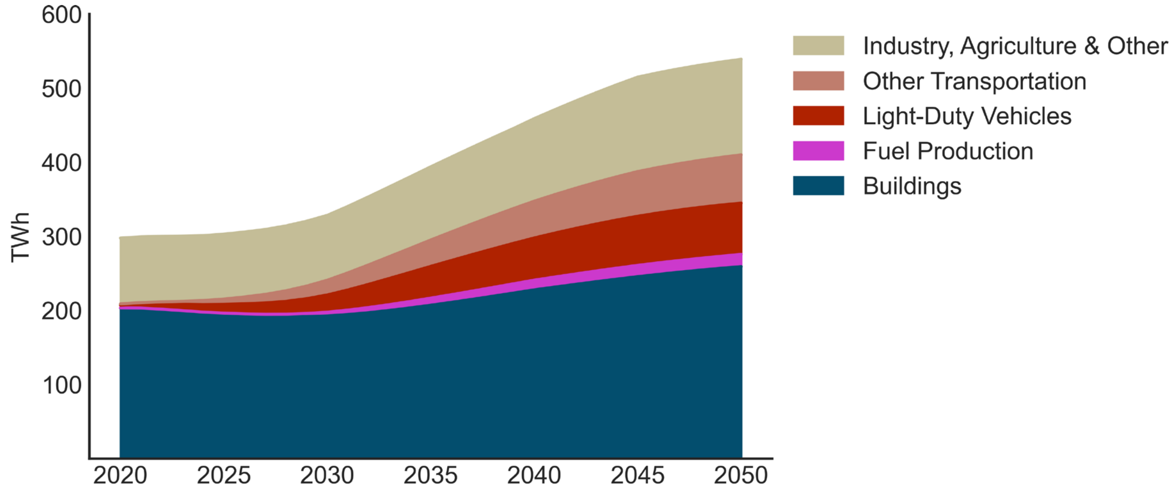
Figure 19 similarly shows the electric loads by category in 2020 and in 2045 across scenarios, while Figure 21 shows electric loads over time for the Balanced scenario. The "fuel production" loads, shown in Figure 19, are associated with on-grid hydrogen production using electrolysis, for use in hydrogen fuel cell vehicles. Note that hydrogen for industry and hydrogen blended into the gas pipeline is assumed to be produced with off-grid, dedicated renewable resources (or out of state renewables), and so does not

[8] The PATHWAYS model does not generate a precise estimate of renewable curtailment due to the limitations in the modeling framework. A more detailed electricity sector model, such as RESOLVE, would be needed to more accurately estimate renewable curtailment in a high renewables future.

appear in the in-state electricity demand numbers. This additional off-grid electric load for hydrogen production is equal to about 90 TWh in 2045 in the Balanced and Zero Carbon Energy scenarios.

Likewise, the electric loads associated with any direct air capture (DAC) are assumed to occur either off-grid, or out-of-state. It is important to note that the loads for DAC in particular could be significant, as DAC requires about ~500 MW of nameplate solar capacity for every MMT of CO2 captured annually (thus, even the Zero Carbon Energy scenario would require about 15 GW of additional solar buildout, if all CDR in this scenario was achieved through DAC powered by solar).

Figure 21: Electricity loads by category in the Balanced scenario



2.4.6 HIGH GLOBAL WARMING POTENTIAL GASES AND NON-COMBUSTION GREENHOUSE GAS EMISSIONS

Non-combustion emissions were responsible for about 15% of total emissions in California in 2017. Non-combustion emissions in California include F-gases (mainly refrigerants), methane emissions from agriculture and waste, methane leakage from oil & gas production and distribution, as well as other smaller categories. These emissions are particularly difficult to abate, given that F-gas emissions are projected to increase in the absence of new regulations, and given that some emissions sources (i.e.

enteric fermentation) are difficult to impossible to eliminate completely. The challenges and opportunities for abatement of each type of non-combustion emissions are detailed further in the sections below.

2.4.6.1 F-gases

F-gases consist primarily of hydrofluorocarbons (HFCs), and are used in refrigerants, aerosols, and foams. HFCs were introduced as replacements to ozone-depleting chlorofluorocarbons (CFCs), which are being phased out under the Montreal Protocol. Both HFCs and CFCs have a very high global warming potential (GWP), often in the range of 2,000 on a 100-yr basis[9], which means that reducing these gases is an important part of any GHG reduction strategy.

Emissions from HFCs are particularly difficult to mitigate, since many low-GWP refrigerant options are not yet commercialized or have yet-to-be-addressed implementation issues such as flammability. Of note, emissions from CFCs are not included in GHG inventories by international convention, as CFCs are already being addressed by the Montreal Protocol. This second point means that, as older CFC-containing appliances are replaced with newer HFC-containing appliances, the emissions from F-gases included in California's GHG inventory are going *up* over time. Thus, F-gases have an increasing baseline against which any reductions must be estimated.

In 2016, the U.S. committed to reducing F-gas emissions under the Kigali Amendment to the Montreal Protocol. However, whether the U.S. will follow through with these commitments remains to be seen. Analysis by CARB indicated that, while following through with the Kigali Amendment would help California meet its HFC reduction goals, the reductions required by this agreement alone would not be sufficient to allow California to meet its 2030 goal of a 40% reduction, relative to 2013 levels, as required by SB 1383

[9] GWP refers to the potency of a greenhouse gas relative to CO2. If a substance has a 100-year GWP of 2,000, this means that the substance produces 2,000 times the warming effect of CO2 on a mass basis, over a period of 100 years.

(Research Division of the California Air Resources Board, 2017). Additional f-gas reduction measures would be required.

2.4.6.2 Methane from Livestock and Waste

Biogenic methane emissions from the decomposition of animal waste, food waste, and wastewater represent another difficult-to-mitigate source of GHG emissions, but if these sources are diverted for anaerobic digestion, or if their emitted methane is captured, they represent a potential source of biomethane. Enteric fermentation (emissions from the digestion of ruminant animals such as cattle) is another significant source of methane that is difficult to fully mitigate as long as there is animal husbandry in the state.

2.4.6.3 Fugitive Methane Emissions

Methane, the primary component of natural gas, is an important high GWP gas, with a 100-year GWP of 25. Leaking natural gas causes significantly more global warming compared to burning it, although this difference, using the 100-year GWP, is a factor of 9 rather than 25 as the GWP would intuitively imply[10]. Methane is emitted across all parts of the natural gas supply chain, and in particular during exploration, production, and processing. Most of the methane emissions associated with California's natural gas consumption occur out-of-state, since California imports about 95% of its natural gas, and are thus not included in the state's GHG inventory. However, there is still a significant amount of methane emitted in-state, from oil & gas extraction and natural gas transmission and distribution, which is included in the

[10] Leaking methane as opposed to burning it has a 9x greater impact on global warming, rather than 25x, because each ton of methane that is burned emits 2.7 tons of CO2. Therefore, leaking methane instead of burning it increases the total GHGs emitted by a factor of 25/2.7 = 9. The more technical description of this effect is that methane has a mass-based GWP of 25, but a molar GWP of 9 (i.e. one ton of methane has the same global warming impact as 25 tons of CO2, but one molecule of methane has the same global warming impact as 9 molecules of CO2).

state's inventory. Reducing methane leaks, as well as methane consumption overall, are both important strategies to reduce GHG emissions.

2.4.6.4 Other Industrial and Agricultural Sources

Other non-combustion GHG emissions included this report are: CO2 released during the production of cement (included in the Industry sector, for the purposes of this report), nitrous oxide resulting from the application of fertilizer, and methane produced in flooded fields associated with rice agriculture. Some options exist for mitigating these emissions and are included in all scenarios, such as substituting fly ash for Portland cement used in making concrete, and increased efficiency in fertilizer application. However, the mitigation potential in these categories is expected to be relatively limited compared to other GHG emissions.

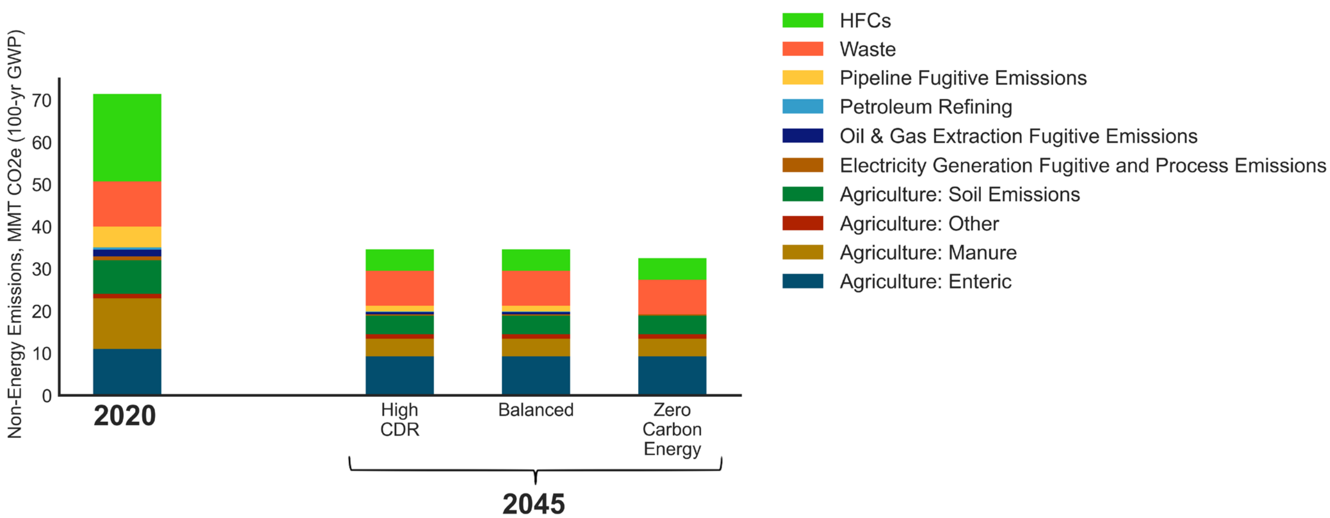
2.4.6.5 The California Context

Non-combustion emissions represent a significant fraction of California's total GHG emissions (about 15% in 2017), due in no small part to the state's large agricultural sector. California has taken significant steps to date to reduce non-combustion emissions. The state has a goal of reducing methane and HFC emissions by 40% below 2013 levels by 2030, as mandated by SB 1383. The California Air Resources Board has outlined a strategy, the "Short Lived Climate Pollutant (SLCP) Reduction Strategy," for meeting these goals.

2.4.6.6 Scenario comparison

All scenarios in this study assume a ~40% reduction in methane emissions and a ~75% reduction in HFC emissions by 2045, in line with previous E3 decarbonization scenarios (Mahone, 2018); (Aas, 2020). These reductions match CARB's SLCP Reduction Strategy for 2030 and go beyond the Strategy past 2030, in the case of HFCs. All scenarios include a near phase-out of HFCs by 2050[11]. Even with these aggressive measures, there are still 30-34 MMT CO_2e of non-combustion emissions remaining in our scenarios in 2045. The Zero Carbon Energy scenario assumes a complete phase-out of petroleum refining, oil & gas extraction, and the low-pressure natural gas distribution grid, meaning that non-energy emissions are slightly lower in this scenario, since fugitive methane emissions from these sources are reduced.

Figure 22: Non-energy emissions by category in 2020, and in 2045 across the three scenarios



2.4.7 CARBON DIOXIDE REMOVAL

The need for carbon dioxide removal was introduced in the IPCC's Fourth Assessment report, highlighting that, in order to reach stable levels of temperature rise, the amount of anthropogenic carbon dioxide

[11] HFC emissions in PATHWAYS are not explicitly tied to an increasing penetration of heat pumps, because a near phase-out of HFCs is assumed in all mitigation scenarios. Furthermore, electrification on its own is not expected to significantly increase the amount of HFC emissions in the state, since most heat pumps will replace air conditioners that use the same refrigerants. Thus, any increase in refrigerant emissions is expected to be due to heat pump water heaters (which use much less refrigerant than air source heat pumps), heat pump clothes dryers (which also use very little refrigerant), and to the installation of heat pumps in homes that did not previously have air conditioning.

emissions need to be lower than or equal to natural anthropogenic carbon sinks by 2100 or "net zero". The IPCC 2018 report on 1.5°C then highlighted the need to achieve net zero emissions earlier, by 2050, due to the risk and impacts of reaching 2°C of warming. However, solutions to mitigate all economy-wide emissions by mid-century, including hard to abate sectors such as agriculture and aviation, are not expected to be economic or technologically realized by 2050. Hence, the scenarios presented by the IPCC highlight that limiting global warming to 1.5°C is likely to require CDR to remove 10-100 billion metric tons of CO_2 globally and over the course of the 21st century.

Similarly, regional decarbonization studies have also highlighted the need for CDR to achieve net zero emissions. The National Academy of Sciences produced a report in 2018 summarizing the state of CDR options (National Academies of Sciences, Engineering, and Medicine, 2019)[12]. These are, broadly, two categories of CDR:

- Land-based solutions
- Negative emissions technologies or NETs

Land-based solutions typically include land use and management practices such as afforestation and reforestation, changes in forest management and changes in agricultural practices to increase carbon dioxide intake also known as soil carbon sequestration. Other land-based solutions, categorized as "coastal blue carbon" focus on increasing the carbon dioxide intake of living plants, tidal marshlands, and other tidal wetlands. The resource potential for these solutions is challenging to quantify but ultimately is limited by land availability and the ability to implement improved land management practices. The National Academy of Sciences study estimates that land-based solutions at below $100/t$CO_2$ removed could achieve up to about 500 million metric tons CO_2e removal per year, while globally the potential could reach close to 6 billion metric tons CO_2e removed per year. A UK Royal Society study published in

[12] Negative Emissions Technologies and Reliable Sequestration, National Academy of Science, 2018

2018 focusing on Greenhouse Gas Removal concluded that the potential for such land-based solutions could remove 60 billion metric tons of CO_2 per year (Royal Society, 2018). As previously discussed, E3's California-focused study does not include land-based carbon sinks or sources within the scenarios modeled.

Negative emissions technologies include:

- Bioenergy with CCS (BECCS) whereby biomass is combusted or gasified to produce a fuel or electricity and the CO2 that emitted is captured and sequestered in deep geological reservoirs.
- Direct air capture (DAC) with CCS, whereby chemical processes are used to capture CO_2 from ambient air and coupled with carbon sequestration in geological reservoirs. This last step is critical for both DAC with CCS and BECCS to produce negative emissions.
- Carbon mineralization, also referred to as "enhanced weathering," whereby CO_2 forms a very strong chemical bond with reactive minerals. The cost and potential for this technology remains speculative and it is unclear that this option would be available at large scale by mid-century.

The focus and research around CDR options has grown significantly over the past 10 years with large bodies of research and funding focusing on these options (Minx, Fuss, & Nemet, 2018). Today it is still unknown which strain of these solutions will be most cost-effective by mid-century. However, there is a consensus on the need to maximize the use of existing land use and management solutions to remove as much carbon dioxide as possible, which will vary in potential by region. Negative emissions technologies such as BECCS and DAC with CCS are also expected to become viable options in the 2040-2050-time frame. In this study, the focus is not on any specific CDR option, but instead on highlighting the scale of the need for CDR to meet net zero emissions by 2045.

2.4.7.1 The California Context

NETs, such as BECCS and DACCS in California could potentially play a key role in removing unabated carbon emissions, though these also face constraints. The potential for BECCS is limited by the availability of biomass in California, while DAC with CCS is limited only by available, non-productive, or protected land. Both are limited by the potential for geological carbon sequestration in the state, of which there is an estimated 5 $GtCO_2e$ in the largest oil & gas basins in California and an estimated 30-420 $GtCO_2e$ of storage potential estimated in saline aquifers, though the saline aquifers in the state have limited characterization and actual storage capacity could be substantially lower (WESTCARB 2010) [13] . Table 6 highlights the amount of CDR that each scenario relies on to mitigate remaining gross emissions.

Table 6: Carbon Dioxide Removal Estimated by Scenario

Scenario	Carbon Dioxide Removal Need ($MtCO_2e$/year)
High CDR	80
Balanced	56
Zero-Carbon Energy	33

[13] The majority of these reservoirs, saline aquifers and depleted oil and gas reservoirs, are located in the Central Valley (Sacramento Basin and San Joaquin Valley) with some offshore sequestration potential in depleted oil fields in the Los Angeles basin.

3 Discussion of Key Findings

3.1 Scenario Comparison Across Key Metrics

As presented in the previous section, all three scenarios presented in this study achieve net zero emissions across all sectors of the economy, excluding sources from natural and working lands. This is achieved through a combination of measures including large amounts of energy efficiency, fuel switching, including substantial amounts of electrification, and decreasing fuel emissions intensity. A combination of these measures allows for all three scenarios presented to achieve at least 80% GHG reduction by 2045 from 1990 levels. Advanced mitigation measures and carbon dioxide removal (outlined in Table 7) are assumed to displace all remaining emissions to achieve net zero emissions, as defined here, by 2045. In this analysis the relative impact of each scenario is evaluated against the following risk factors and highlighted in Figure 23:

+ Implied health impacts from criteria pollutants - estimated based on the total amount of fuel combustion,
+ Climate change mitigation risk – as measured by gross emissions levels, and
+ Technological adoption and implementation risk.

Figure 23. Relative comparison across key risk factors

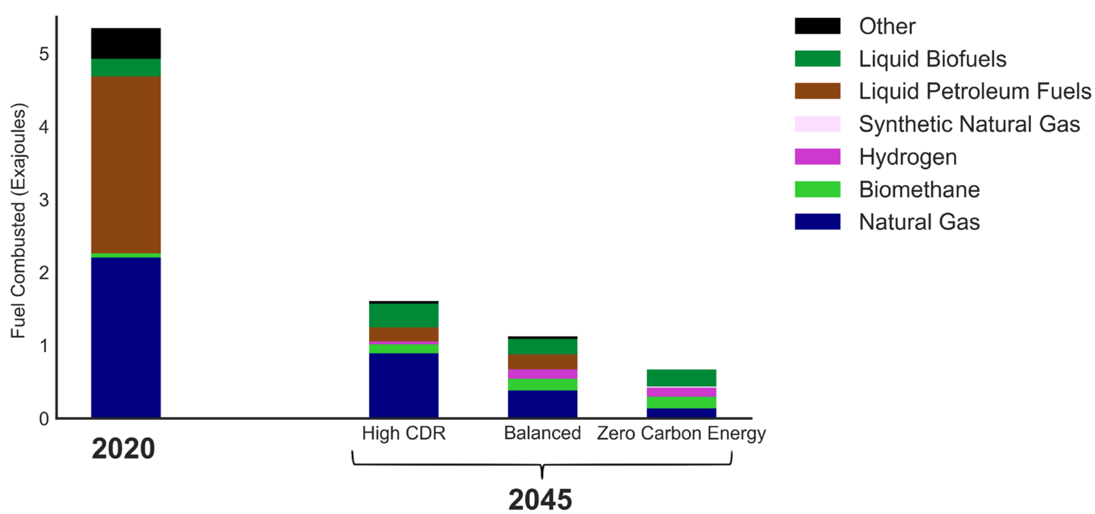
Evaluating each scenario across these key risk factors, as highlighted in Figure 23, shows the relative benefit of the Balanced scenario with a *mid*-level impact on each of these criteria. These key risk factors and their scoring by scenario is discussed in further detail in subsequent sections.

The relative energy system costs, based on the suite of measures adopted, including the amount of CDR required to achieve net zero emissions in each scenario, is too uncertain to deem one scenario more or less expensive than another. However, the cost of carbon abatement ($/metric ton) estimated ranges for each of these advanced mitigation measures and CDR options considered are presented in Figure 25.

3.2 Fuel Combustion: Implications for Air Quality and Health Considerations

Recent research has highlighted the impact of fuel combustion on air quality, both indoor and outdoor, and the resulting negative health impacts (Seals & Krasner, 2020) (Aas, 2020), (EPRI, 2019). Climate change, local air quality, and the associated health impacts, have a disproportionate impact in low-income and disadvantaged communities, meaning that air quality is an important part of environmental justice and equity (Perera, 2017), (Gridworks, 2019). While the analysis presented in this study does not include a detailed air quality assessment, Figure 24 highlights the substantial decrease in fuel combustion from 2020 to 2045 across all three scenarios: 71% decrease in the High CDR scenario, 79% decrease in the Balanced scenario and 87% decrease in the Zero Carbon Energy scenario from 2020. Hence, the 2045 scenarios will see significant improvements in air quality, including improvements in indoor air quality with the electrification of most building end-uses. In all three scenarios, over 60% of the fuel combustion still taking place in 2045 is of methane (fossil natural gas, synthetic natural gas, or biomethane) which has a lower impact on air pollution than liquid fuels (Union of Concerned Scientists, 2014).These impacts are viewed here on a statewide level, while local health benefits within specific communities will depend on local fuel combustion.

Figure 24: Total fuel combustion by scenario



3.3 Climate Change Mitigation Risk

Reducing emissions as early as possible can have a significant impact on minimizing climate risk and can help avoid a temperature “overshoot” (IPCC 2018). Furthermore, achieving carbon neutrality will require a comprehensive evaluation of all anthropogenic and natural carbon dioxide sources, which implies that minimizing gross emissions can help improve the chances of achieving carbon neutrality. Minimizing energy-sector GHG emissions and moving away from the use of high GWP gases will also limit the reliance on CDR options that may be needed to further mitigate natural carbon sources.

The Zero Carbon Energy scenario is estimated here as having the lowest climate change mitigation risk because it has the lowest cumulative GHG emissions among the three scenarios. The Zero Carbon Energy scenario achieves a 45% reduction in gross emissions in 2030, as opposed to a 40% reduction in the other two scenarios, as well as the lowest gross emissions by 2045. The Balanced and High CDR scenarios follow in their levels of climate change mitigation risk, “Mid” and “Highest” respectively. The High CDR scenario has the highest climate change mitigation risk due to its large reliance on CDR and 80 MMT of gross emissions remaining in 2045. Table 6 provides the estimated gross emissions remaining in each scenario.

3.4 Technology Adoption & Implementation Risk

All three scenarios presented in this report require aggressive measures to achieve carbon neutrality, and there are technology adoption and implementation risks inherent to each of the decarbonization pathways examined. All scenarios require a rapid buildout of a statewide EV charging network, and all scenarios see a significant reduction in use of the low-pressure, retail natural gas distribution system (with a complete phase-out of gas use in buildings in the Zero Carbon Energy scenario). The infrastructure planning and implications of both of these transitions are monumental. Further, these scenarios assume, to varying degrees, the creation of a dedicated production and distribution network for green hydrogen prior to 2045.

The High CDR scenario is consistent with previous 80x50 scenarios for many sectors but relies heavily on the development of CDR, which carries the risk of being unable to deploy NETs, such as direct air capture at scale, and land management strategies, whose potential is still being determined. According to the IEA, there are currently 15 DAC plants worldwide that capture 0.9 million metric tons of carbon dioxide annually, while the High CDR scenario requires the sequestration of 80 million metric tons (MMT) of carbon dioxide annually by 2045 for California alone. Furthermore, the energy required by this process must be supplied either by on-grid or off-grid renewables, which would be equivalent to over 100 TWh of electricity demand, with large associated land use requirements.

Although the Zero Carbon Energy scenario relies less heavily on NETs, it requires the deployment of electrified and hydrogen-powered technologies on an even more aggressive timeline than in previous 80x50 scenarios. To reach aggressive targets like 100% ZEV sales for passenger vehicles by 2030, new legislation and/or policy incentives will be needed, and these carry political risk. Even with supporting policies in place, there is an implementation risk to actually transitioning all forms of fossil fuel consumption to zero carbon energy in under three decades. The ZCE Scenario requires replacing almost every fossil fuel vehicle, building appliance, and piece of industrial equipment in California with a device that is powered by electricity or hydrogen by 2045. Finally, the ZCE scenario relies on further decarbonizing the energy supply for sectors like interstate trucking, rail, and aviation that are not entirely under the direct regulatory authority of California state agencies.

The Balanced scenario was designed to incorporate both aggressive supply-side decarbonization and widespread deployment of NETs while mitigating the risk of relying too heavily on either. Many of the fuel-switching measures present in the ZCE scenario are also achieved in the Balanced scenario, but at a slower pace, while the most speculative or expensive measures are omitted (e.g. aviation electrification, synthetic natural gas blend in the pipeline). In addition, the Balanced scenario only requires 56 MMT of atmospheric CO_2e to be sequestered to reach carbon neutrality, 24 MMT less than the High CDR scenario.

Table 7 summarizes some of the key implementation and adoption challenges involved with each of the advanced mitigation measures and NETs that are considered for the scenarios to go beyond 80x50 and achieve net zero emissions in the energy sector.

Table 7: Implementation and adoption challenges of key advanced mitigation and CDR measures considered in this study

Mitigation Measure	Implementation & Adoption Challenges
MDV & HDV Electrification	Requires establishment of a state-wide charging network that will likely necessitate transmission and distribution system upgrades.
Hydrogen Fuel Cells for HDV	Requires substantial state-wide infrastructure for hydrogen refueling and maintenance.
Industry CCS	Relies on the adjustment of the industrial process to accommodate a CO_2 capture plant and development of a CO_2 transport system and storage site either within the state or out of state.
Industry Electrification	Technically unsuitable for some applications (e.g. cement kilns) and costly for others (e.g. resistance boilers). Limited to its application to industries that have relatively low heating demands and can see significant efficiency benefits through electrification.
Building Electrification	Requires changes to the building code, appliance codes and standards, electrical distribution upgrades, electrical panel upgrades, as well as consumer adoption decisions and contractor education and awareness of electric heat pump technologies.

Green Hydrogen Fuel	Relies on the large-scale development of electrolysis and a significant renewable energy source to power the process. Hydrogen storage is also likely to be required to close the gap between supply and demand.
Zero Carbon Electricity Generation	Relies on dispatchable zero-carbon resources that either have limited potential (geothermal, biomethane) or have not yet been deployed at scale (e.g. natural gas with CCS, hydrogen combustion turbines).
Direct air capture with CCS	Requires a substantial amount of energy use to power the direct air capture process; If powered by off-grid solar this requires about 700 MW of solar PV per MMT removed and a significant amount of land for both the DAC process and energy needs (about 1,700 acres for DAC and 4,900 acres for solar PV to remove 1 MMT) (National Academies of Sciences, Engineering, and Medicine, 2019) (NREL, 2017). If powered by the grid, this will add significant amounts of load.[14] Also relies on the development of a CO2 transport and storage system large enough to accommodate gross emissions reduction in 2045.
Bioenergy with CCS	Potential is limited by biomass availability and competing uses for biofuels and also relies on the CO_2 transport and storage infrastructure. It is also important to note that all scenarios in this study utilize all of the waste biomass considered to be available to California, for liquid and gaseous fuel production. If some of this biomass were diverted to other uses, such as biomass gasification to hydrogen with CCS which represents negative emissions when considered on its own, then there would be higher remaining fossil fuel emissions, unless these remaining emissions are mitigated some other way. Thus, diverting biomass from liquid fuel production to hydrogen production with CCS does not necessarily lead to lower emissions.

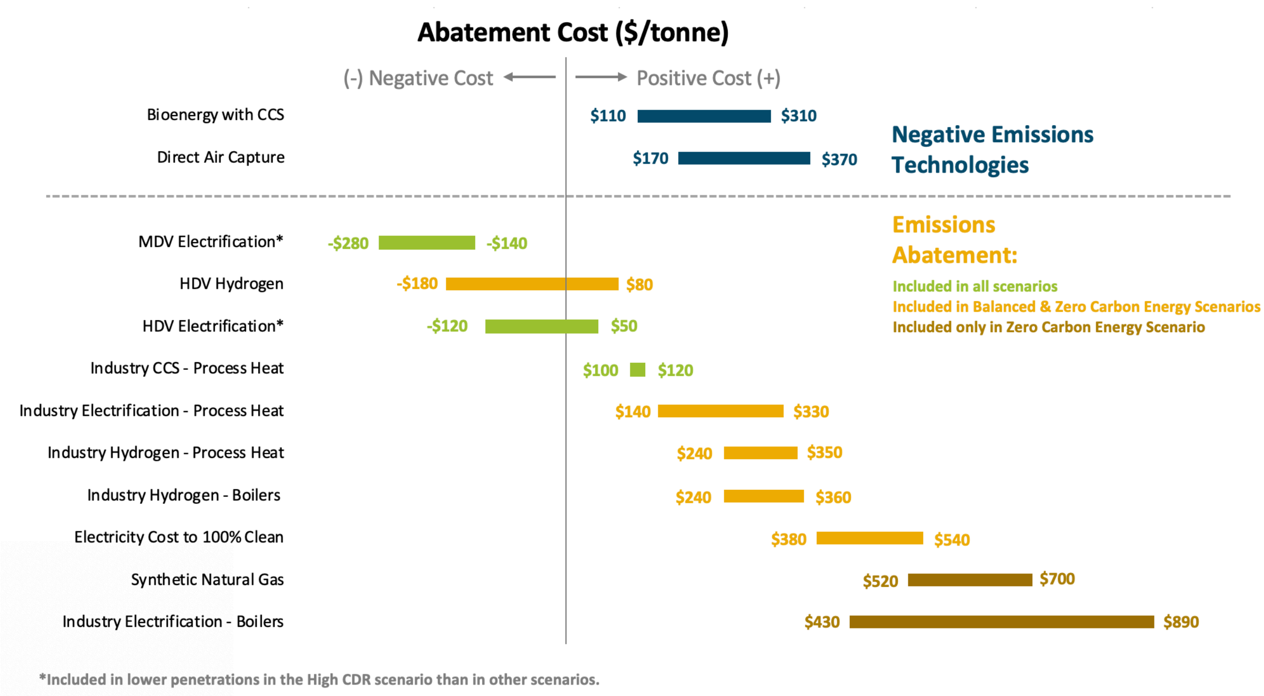
[14] The National Academy of Sciences report that the land area required to remove 1 million metric ton of CO2 from the air would require about 1,700 acres (equivalent of 7 km^2) (National Academies of Sciences, Engineering, and Medicine, 2019)[14]. Meanwhile, the amount of land required to power DAC with renewables only is even greater; for example, 1 MMTCO2 captured/year with DAC would require on average 700 MW of solar photovoltaic (PV) capacity[14]. NREL estimates that each MW of solar PV requires 7 acres of land (NREL, 2017)resulting in an average 6,600 acres of total land required to remove 1 MMTCO2/year via DAC. In comparison, the equivalent forest land required to capture 1 MMTCO2/year is about 15 times greater.

As noted earlier in the report, the geological sequestration potential for carbon dioxide in California is large and is not likely to be a limiting factor for CCS development, with an estimated 5.2 GtCO2e in oil & gas reservoirs and at least 30 GtCO2e in saline aquifers (WESTCARB 2010).

3.5 Estimated 2045 Cost Per Ton of Advanced Mitigation Measures

The cost of measures to achieve at least 80x50 in California has been documented extensively. In this analysis, all three scenarios adopt a very similar combination of measures to decrease emissions by at least 80% by 2045 from 1990 levels and thereby embody similar costs for these measures. To achieve net zero emissions by 2045 (excluding NWL), each scenario adopts a different combination of advanced mitigation and carbon dioxide removal measures (or NETs) that will incur additional cost. These are referred to as mitigating the "last 20%" of gross emissions in the State, because they reflect the additional measures that reduce the last 20% of emissions from 80% to 100%. The future cost of these advanced mitigation measures and CDR options are uncertain, particularly as we look farther into the future. However, based on information available today, the cost ranges of each mitigation measure are evaluated and presented in Figure 25.

Figure 25. 2045 greenhouse gas abatement cost ranges for technologies that could be used to mitigate the "last 20%" of energy sector emissions to achieve carbon neutrality in California



The CDR options highlighted in the figure focus only on two NET options: Bioenergy with CCS and Direct Air Capture (with CCS). Additional carbon sequestration options might be available in the future such as carbon mineralization, but limited information is available on these today to provide a reasonable cost range. Natural and working lands may also provide an additional carbon sink for the State but the availability and amount of these is unclear and is contingent on the impact of natural sources of emissions[15].

[15] This will be the topic of future CARB analysis.

Negative emissions technology cost ranges reflect low and high technology costs sourced from academic literature. Emissions abatement cost ranges are based on E3 analysis and academic literature. Cost ranges provided in Figure 25 reflect low and high costs for the following input variables:

- Electricity Price – MDV & HDV Electrification, Industry Electrification
- Hydrogen Price – HDV Hydrogen, Industry Hydrogen
- Synthetic Natural Gas Price – Synthetic Natural Gas
- Zero emissions dispatchable generation cost - Electricity Cost to 100% Clean

The qualitative attribution of each of these "last 20%" measures by scenario is as follows, while the specific breakdown of measures by scenario is provided in Table 1:

- All scenarios adopt MDV and HDV electrification and HDV hydrogen fuel cell adoption (for long-distance use) in order go beyond 80x50 to an 80% reduction by 2045 emissions abatement level. These mitigation measures can provide savings of as much as \$280/tCO_2 - thanks to the fuel savings that come with avoiding fossil fuel use in transportation - and costs as much as \$80/tCO_2 for the adoption of hydrogen fuel cell HDV. *The Balanced and Zero Carbon Energy scenarios achieve greater emissions abatement from these measures than the High CDR scenario does.*
- Industry CCS is also adopted across all scenarios at a cost range of \$100 - \$120/tCO_2. This range reflects a weighted average of the cost ranges for industry applications in the state including glass, non-mineral materials and cement manufacturing, The *Balanced and Zero Carbon Energy scenarios achieve greater emissions abatement from this measure than the High CDR scenario does.*
- The electrification of industrial process heat as well as using hydrogen to displace some natural gas for high temperature industrial process heat requirements and in boilers are adopted in both the Balanced and Zero Carbon Energy scenarios at a cost range of \$140-\$360/tCO_2.
- 100% zero carbon electricity generation is also adopted in both the Balanced and Zero Carbon Energy scenarios reflecting a range of costs for zero carbon dispatchable generation options to

decarbonize the last 5% of emissions from electricity generation in the state. This is estimated at an average cost of \$380-\$540/tCO_2 based on prior analysis using E3's RESOLVE model, whereby either electricity generation with CCS or with a zero carbon fuel (e.g. biomethane, hydrogen) are available as firm capacity resources, to balance high levels of renewable generation.

+ The Zero Carbon Energy Scenario is the only one to adopt synthetic natural gas use and the electrification of industrial boilers each reflecting a cost range of \$520-\$700/tCO_2 mitigated and \$430-\$890/tCO_2.
+ All scenarios assume some amount of negative emissions from NETs to mitigate remaining gross emissions in 2045 (see Table 6). Based on the literature reviewed, these costs are estimated to range between \$110/tCO_2 and \$370/tCO_2. The range of costs quoted for BECCS reflect the cost of biomass combustion combined with CO_2 capture technology (Consoli, 2019) while the cost of direct air capture reflects the range of cost for solvent-based DAC (National Academies of Sciences, Engineering, and Medicine, 2019). Both assume a \$20/tCO_2 cost adder for transportation and storage of CO_2 (Edward S. Rubin, 2015)

Given the range of costs for advanced mitigation measures and NETs as well as the varying amounts of reliance on each in the three scenarios, the relative cost impact these have on each scenario is uncertain and likely to fall within the same large range of total adoption cost. Further detail on the cost ranges estimated for each of the advanced mitigation measures and NETs highlighted here is provided in Appendix 6.1.

4 Conclusions and Next Steps

4.1 Summary of Key Conclusions

This study aims to help inform the discussion on carbon neutrality in California by focusing on achieving net zero emissions across California's energy economy[16]. Three scenarios are developed in this work to highlight a variety of plausible pathways towards carbon neutrality in the energy sector.

Each of the three scenarios developed (High CDR, Balanced, and Zero Carbon Energy) includes a combination of known mitigation strategies that achieve an 80x50 target, including significant amounts of energy efficiency, electrification, and low carbon fuel adoption. To go beyond 80x50 and reach 80% emissions reduction by 2045 a suite of advanced mitigation options and negative emissions technologies are needed and discussed in this study. The advanced mitigation measures highlighted in this study are (listed in Table 7) the adoption of industry CCS, electrification of medium and heavy duty vehicles and hydrogen fuel cells for long-distances, electrification of industrial boilers, hydrogen use in industry, zero emissions electricity generation, synthetic fuel adoption and the electrification of industrial process heat. Finally, carbon dioxide removal strategies are needed as well, and would include negative emissions technologies such as direct air capture with CCS, to mitigate remaining emissions and reach net zero emissions by 2045.

[16] The CARB Scoping Plan process will provide a broader forum for statewide decision-making on carbon neutrality pathways.

While all scenarios assume some level of these advanced mitigation measures and NETs, the scenarios are ranked based on their relative amounts of each and degree of fuel combustion (implying impacts on local air pollution and health), climate change mitigation risk, and technology implementation and adoption risk. Two bookend scenarios are developed, which either rely on a significant amount of CDR options ("High CDR") or limit the amount of gross emissions as much as possible by adopting a broad suite of advanced mitigation measures and early emissions reduction strategies to minimize the need for CDR ("Zero Carbon Energy"). The High CDR scenario has the highest potential risks for local air quality, and implied health impacts, as well as climate change mitigation risk, while the Zero Carbon Energy scenario has the lowest risk for these two factors. Meanwhile, both scenarios are deemed to have a high technological implementation and adoption risk as these both rely significantly on technologies that are not commercialized to date and rely on the very early adoption of decarbonization measures.

The Balanced scenario, which includes a combination of the measures adopted in each of the bookend scenarios, may provide a balance of trade-offs in terms of impacts on health and air pollution, climate change mitigation risk, and technological implementation and adoption risk. The cost of these scenarios relative to one another is uncertain as the strategies that each of these rely on are for the most part not commercialized to date and are each subject to their own range in costs. The NETs considered might vary between \$110/tCO_2 and \$370/tCO_2 while the advanced mitigation measures vary from negative cost (MDV and HDV electrification displacing expensive fuel options) and up to \$890/tCO_2 for the electrification of industry process heat.

The measures adopted to achieve 80x50 in all three scenarios (energy efficiency, electrification in transportation and buildings, and the decarbonization of electricity generation), are considered "least regrets" mitigation strategies. Cross-sector decarbonization is also particularly reliant on the availability of low carbon fuels. Whether these fuels are biomethane, hydrogen or synthetic fuels will depend on their relative economics by 2045 and their availability. Continued development of these zero-carbon fuel sources is likely to be a key for achieving economy-wide carbon neutrality. In addition, a significant reliance on negative emissions across all scenarios is far from being trivial, with the lowest at 33 MMT/year in 2045 and at the highest 80 MMT/year in 2045. Given the limited commercial availability of NETs today, it is critical that continued research and investment be dedicated to these if they are to become a key pillar to help achieve statewide carbon neutrality.

4.2 Areas for Further Study and Next Steps

This analysis focuses on the emissions from sources under AB 32 and technology-based strategies to mitigate them and uses these strategies to define a qualitative impact that carbon neutral strategies (as defined in this study) might have on health, climate risk and technology adoption and implementation. Further investigation is needed in several areas pertaining to the risk and feasibility of such carbon neutral scenarios, a few of which are listed here:

+ Maximizing co-benefits for heavily burdened communities with respect to environmental justice issues and equity;;
+ The impact of large infrastructure development associated with renewable energy development, hydrogen production, and/or DAC with CCS on land use compared to the use of natural and working lands as a carbon sink;
+ A better understanding of the adoption challenges that vehicle and building electrification strategies might face as well as the practical infrastructure rollout needed, e.g. distribution and transmission upgrades to match growth in electric loads;
+ Strategies to incentivize the development of advanced mitigation strategies, in particular low carbon fuel production, CCS, and NETs and to bring down their costs;
+ The infrastructure development needs to deploy a hydrogen and/or carbon dioxide transport and storage system in-state, and potentially out of state.

The above list is an initial attempt at highlighting areas of continued research which might help inform new and more specific policies to incentivize the suite of advanced mitigation measures and CDR needs that this study highlights. Finally, this draft report may be revised in parts based on comments received from stakeholders. Subsequent to this report, CARB will be developing their 2022 Scoping Plan which will provide more focus on the implications of the state's 2045 goal on policy and implementation needs for 2030.

5 References

Aas, D. (2020). *The Challenge of Retail Gas in California's Low-Carbon Future.* California Energy Commission.

Bui, M., Fajardy, M., Zhang, D., & Mac Dowell, N. (2020). *Delivering Negative Emissions from Biomass-Derived Hydrogen.* H2FC SUPERGEN.

Buildings Performance Institute Europe. (2017). *97% of Buildings in the EU need to be Upgraded.* Brussels: BPIE.

CARB. (2017). *California's 2017 Climate Change Scoping Plan.* California Air Resources Board.

Carbon Neutral Cities Alliance. (2018). *Framework for Long-Term Deep Carbon Reduction Planning.*

CCC. (2019). *Net Zero - The UK's Contribution to Stopping Global Warming.*

CEC. (2019, June 24). *2018 Total System Electric Generation*. Retrieved from https://www.energy.ca.gov/data-reports/energy-almanac/california-electricity-data/2018-total-system-electric-generation

Cefic. (2013). *European Chemistry for Growth: Unlocking a competitive, low carbon and energy efficient future.*

Cembureau. (2020). *Cementing the European Green Deal.*

Consoli, C. (2019). *Bioenergy and Carbon Capture and Storage.* Global CCS Institute.

E3. (2019). *The Economic Value of Offshore Wind Power in California.* Energy and Environmental Economics, Inc.

Edward S. Rubin, J. E. (2015). The cost of CO2 capture and storage. *International Journal of Greenhouse Gas Control*.

EIA. (2019, September 24). *EIA projects nearly 50% increase in world energy usage by 2050, led by growth in Asia*. Retrieved from Today in Energy: https://www.eia.gov/todayinenergy/detail.php?id=41433

Environment and Climate Change Canada. (2020). *Canadian Environmental Sustainability Indicators: Progress towards Canada's greenhouse gas emissions reduction target.* Retrieved from https://www.canada.ca/content/dam/eccc/documents/pdf/cesindicators/progress-towards-canada-greenhouse-gas-reduction-target/2020/progress-ghg-emissions-reduction-target.pdf

EPRI. (2019). *Air Quality Implications of an Energy Scenario for California Using High Levels of Electrification.* California Energy Commission.

Eurofer. (2050). *A Steel Roadmap for a Low Carbon Europe.*

European Climate Foundation. (2018). *Net Zero by 2050: From whether to how.* Climact.

European Commission. (2018). *2030 climate & energy framework*. Retrieved from Climate strategies & targets: https://ec.europa.eu/clima/policies/strategies/2030_en

European Commission. (2019). *A European Green Deal: Striving to be the first climate-neutral continent*. Retrieved from https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

European Commission. (2020). *A hydrogen strategy for a climate-neutral Europe.*

Federal Government of Germany. (2020). *The National Hydrogen Strategy.* Federal Ministry for Economic Affairs and Energy.

Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. (n.d.). *Climate Action Plan 2050 - Germany's long-term emission development strategy.* Retrieved from National Climate Policy: https://www.bmu.de/en/topics/climate-energy/climate/national-climate-policy/greenhouse-gas-neutral-germany-2050/

Gasunie. (2020). *Moving Towards 2030 and 2050 with Hydrogen.*

GlobalABC & International Energy Agency. (2019). *2019 global status report for buildings and construction: Towards a zero-emission, efficient and resilient buildings and construction sector.* United Nations Environment Programme.

Government of the Netherlands. (2019). *National Climate Agreement.* The Hague.

Government Offices of Sweden. (2018). *The Swedish Climate Policy Framework.*

Gridworks. (2019). *California's Gas System in Transition: Equitable, Affordable, Decarbonized, and Smaller.*

Hydrogen Council. (2017). *Hydrogen Scaling Up: A Sustainable Pathway for the Global Energy Transition.*

IEA. (2019). *The Future of Hydrogen.*

International Energy Agency. (2019). *World Energy Outlook 2019.* Paris: IEA.

IPCC. (2018). *Global Warming of 1.5°C.An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, .*

IRENA. (2019). *Renewable Capacity Statistics.*

Kalansky, J. D. (2018). *California's Fourth Climate Change Assessment.*

Lempert, R., Preston, B., Edmonds, J., Clarke, L., Wild, T., Binsted, M., . . . Townsend, B. (2019). *Pathways to 2050: Alternative Scenarios for Decarbonizing the U.S. Economy.* Center for Climate and Energy Solutions.

Leung, J. (2018). *Decarbonizing U.S. Buildings.* Center for Climate and Energy Solutions.

Lucon, O., Urge-Vorsatz, A., Zain Ahmed, H., Akbari, P., Bertoldi, L., Cabeza, N., . . . Vilarino, M. (2014). *Buildings. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge: Cambridge University Press.

Mahone. (2018). *Deep Decarbonization in a High Renewables Future.* California Energy Commission.

Mahone, A., Mettetal, L., & Stevens, J. (2020). *Hydrogen Opportunities in a Low-Carbon Future: An Assessment Of Long-Term Market Potential in the Western United States.* San Francisco, CA: Energy and Environmental Economics, Inc.

Ming, Z., Olson, A., De Moor, G., Jiang, H., & Schlag, N. (2019). *Long-Run Resource Adequacy under Deep Decarbonization Pathways for California.* Energy and Environmental Economics, Inc.

Minx, J., Fuss, S., & Nemet, G. (2018, January 6). *Guest post: Seven key things to know about 'negative emissions'*. Retrieved from CarbonBrief: https://www.carbonbrief.org/guest-post-seven-key-things-to-know-about-negative-emissions

N.Y. (2019). Climate Leadership and Community Protection Act. *S.B. 6599*. 2019-2020 Legislative Session.

National Academies of Sciences, Engineering, and Medicine. (2019). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda.* The National Academies Press.

New Zealand Ministry for the Environment. (2019). *About New Zealand's emissions reduction targets*. Retrieved from https://www.mfe.govt.nz/climate-change/climate-change-and-government/emissions-reduction-targets/about-our-emissions

NREL. (2017). *Land-Based Wind Power Plants*. Retrieved from Annual Technology Baseline: https://atb.nrel.gov/electricity/2017/index.html?t=lw

NYSERDA. (2020). *Pathways to Deep Decarbonization in New York State Presentation*. Retrieved from Meetings and Materials: https://climate.ny.gov/Meetings-and-Materials

Parliament, S. (2018, May 23). *Climate Change Emissions Reduction Scotland Bill.* Retrieved from Beta Parliament : https://beta.parliament.scot/-/media/files/legislation/bills/previous-bills/climate-change-emissions-reduction-targets-bill/introduced/explanatory-notes-climate-change-emissions-reduction-targets-scotland-bill.pdf

Perera, F. (2017). Pollution from Fossil-Fuel Combustion is the Leading Environmental Threat to Global Pediatric Health and Equity: Solutions Exist. *International Journal of Environmental Research and Public Health*.

Philibert, C. (2018, May 25). *Offshore wind and hydrogen for industry in Europe*. Retrieved from IEA: https://www.iea.org/commentaries/offshore-wind-and-hydrogen-for-industry-in-europe

Republique Francaise. (2018). *Plan de deploiément de l'hydrogène pour la transition energétique.* Paris: Ministère de la Transition Ecologique et solidaire.

Research Division of the California Air Resources Board. (2017). *Potential Impact of the Kigali Amendment on California HFC Emissions .* California Air Resources Board.

Rogelj, J., Shindell, K., Jiang, S., Fifita, P., Forester, V., Ginzburg, C., . . . Vilarino, M. (2018). *Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. .* In Press.

Royal Society. (2018). *Greenhouse Gas Removal.*

Schmidt, O., Gambhira, A., Staffell, I., Hawkes, A., Nelsona, J., & Few, S. (2017). Future cost and performance of water electrolysis: An expert elicitation study. *International Journal of Hydrogen Energy*, 30470-92.

Seals, B., & Krasner, A. (2020). *Gas Stoves: Health and Air Quality Impacts and Solutions.* Rocky Mountain Institute.

Sepulveda, N. (2018). The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation. *Joule*, 2403-2420.

Spector, J. (2020, March 31). *The 5 Most Promising Long-Duration Storage Technologies Left Standing*. Retrieved from Greentech Media: https://www.greentechmedia.com/articles/read/most-promising-long-duration-storage-technologies-left-standing

The Oxford Institute for Energy Studies. (2019). *The Great Dutch Transition.* Oxford: University of Oxford.

Tsiropoulos, I., Nijs, W., Tarvydas, D., & Ruiz, P. (2020). *Towards net-zero emissions in the EU energy system by 2050 - Insights from scenarios in line with the 2030 and 2050 ambitions of the European Green Deal.* European Commission Joint Research Center.

U.S. Department of Energy. (2016). *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving.* Oak Ridge, TN: Oak Ridge National Laboratory. doi:10.2172/1271651

UK. (2019). *UK becomes first major economy to pass net zero emissions law*. Retrieved from https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law

UNFCCC. (2019). *Climate Ambition Alliance: Nations Renew their Push to Upscale Action by 2020 and Achieve Net Zero CO2 Emissions by 2050.*

Union of Concerned Scientists. (2014, June 19). *Environmental Impacts of Natural Gas.* Retrieved from https://www.ucsusa.org/resources/environmental-impacts-natural-gas

Wang, A., van der Leun, K., Peters, D., & Buseman, M. (2020). *European Hydrogen Backbone.* Utrecht, the Netherlands: Guidehouse.

White House. (2016). *United States mid-century strategy for deep decarbonization.*

Williams, J. H., DeBenedictis, A., Ghanadan, R., Mahone, A., Moore, J., Morrow III, W. R., . . . Torn, M. S. (2012). The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity. *Science*, 53-59.

6 Appendix

6.1 Description of Cost Ranges of Advanced Mitigation Measures and NETs

This section provides more detail on the cost ranges provided in Figure 25. 2045 greenhouse gas abatement cost ranges for technologies that could be used to mitigate the “last 20%” of energy sector emissions to achieve carbon neutrality in California .

Electrification of medium duty trucks generates net cost savings, due to avoided fossil fuel use in trucks. The California Air Resources Board recently adopted the Advanced Clean Truck standard, which requires between 40% and 75% zero-emission truck sales by 2035 depending on vehicle class. The CARB Board called on the agency to determine how to transition the state’s truck fleet to zero-carbon by 2045. This analysis suggests that getting the state’s trucking fleet to zero-carbon by 2045 is among the lower-cost options available to reduce the last 20% of emissions from the state.

Bioenergy with carbon capture and sequestration (CCS), or BECCS, and direct air capture with CCS are the main negative emissions technologies considered today. BECCS is limited by the amount of biomass available in California. The amount of direct air capture with CCS available to California (with assumed energy provided by solar PV), is limited by the amount of land required to capture each metric ton of carbon dioxide. Bioenergy with CCS costs reflect the cost of capturing CO2 from a high purity stream though a post-combustion amine-based process and transporting and storing it in a deep geological reservoir. The range of DAC costs reflect low and high estimates for solvent-based DAC (National Academies of Sciences, Engineering, and Medicine, 2019) and powered by off grid solar PV at $25/MWh also combined with transport and storage costs. The cost of transporting and storage CO2 is estimated at $20/tCO2.

Decarbonization in the industrial sector, through a combination of carbon capture and sequestration (CCS), hydrogen and electrification (both industrial heat pumps and resistance heating), has a range of costs. The emission abatement potential for CCS in California industry is relatively limited and is estimated at 15-19 MMTCO2 avoided per year. Meanwhile, hydrogen is also considered a viable carbon-free alternative to burning natural gas for process heat and energy input. The cost range associated with Industry hydrogen in Figure 25reflects cost ranges for alkaline electrolyzers by 2045 powered by off-grid solar PV in California or the Southwest and delivered to an industrial plant. The effective cost of delivered hydrogen by 2045 is estimated at $21/MMBTU on the conservative end and $15/MMBTU on the optimistic side.

The range of options for decarbonizing the electricity sector depends on what technologies are available to reduce the last 5% of emissions from that sector. The higher end of the cost range presented in Figure 25 reflects a future that relies mostly on renewable energy and battery storage technologies with high cost renewable fuel in existing gas capacity providing a limited amount of back-up power at about 1-2% of generation. Meanwhile, the lower end of the range represents a future with a greater variety of zero-carbon firm capacity available such as a greater share of zero carbon fuels, hydrogen or biomethane, or even advanced nuclear generation and advanced CCS.

Electrification in the transportation and buildings sector are important decarbonization strategies in any low-carbon future. Electrification in these sectors means that an increasingly large share of energy services across the economy rely on electricity. Thus, decarbonizing the electricity sector enables higher GHG reductions across the economy.

Table 8: Estimated land requirement by scenario if all negative emissions were from DAC

Scenario	Land Use Requirement for DAC
High CDR	541,000 acres or 4.2% of California state owned forest land[17]
Balanced	376,000 acres or 2.4% of California state owned forest land
Zero-Carbon Energy	238,000 acres or 0.9% of California state owned forest land

6.2 Carbon Neutrality Goals in Other Jurisdictions

Before the current U.S. administration decided to withdraw from the Paris Agreement, the previous U.S. Obama administration was developing plans for the U.S. to achieve an 80% reduction in greenhouse gas emissions by 2050. The United States Mid-Century Strategy report released in November 2016 illustrates pathways for the US to achieve an 80 by 50 goal cost-effectively (White House, 2016). This study laid out recommendations for transforming the energy system in the U.S. with significant amounts of energy efficiency, electrification, decarbonization of electric power, emissions reduction through land sinks and carbon removal technologies, and measures to reduce non-energy emissions.

Following the release of the IPCC's 1.5C Special Report published in November 2018 (IPCC, 2018), jurisdictions around the country and world have since adopted more ambitious climate targets that are in

[17] California's forest land accounts for 33 million acres of land in 2016 of which 19 million is own and managed by the federal government (Ecosystems of California 2016)

line with the aim of limiting global temperature increases to 1.5C. In addition to California, other jurisdictions that are aiming for economy-wide carbon neutrality by mid-century or earlier include, but are not limited to, New York, Hawaii, Canada, South Korea, New Zealand, the United Kingdom (UK), the European Union (EU) as well as specific EU country goals. In December 2019, the United Nations announced that 73 countries, as well as 14 regions and 398 cities are working towards achieving net-zero CO2 emissions by 2050 (UNFCCC, 2019). A summary of some of these state and national goals and efforts in other jurisdictions are provided below:

+ New York's Climate Leadership and Community Protection Act (CLCPA), passed in June 2019, updated the state's climate targets to aim for net zero carbon emissions by 2050 with a clean electric grid by 2040 (N.Y., 2019). Of these emission reductions, 85% must come from New York's own energy emissions, the remaining 15% can come from carbon reductions. New York is currently hosting a series of Climate Action Council (CAC) Meetings in support of achieving this carbon neutral law. In June 2020, NYSERDA released a public report on, "Pathways to Deep Decarbonization in New York State," describing scenarios that could achieve the state's carbon neutrality goal by mid-century (NYSERDA, 2020).
+ A UK law, passed in June 2019, says that the country will need to bring emissions to net zero by 2050 (UK, 2019). The law reflects recommendations from the UK's independent advisory group, the Committee on Climate Change (CCC) as laid out in their "Net Zero" Report released in May 2019 (CCC, 2019).
+ New Zealand set the Climate Change Response (Zero Carbon) Amendment Act into law in 2019, which aims at net zero emissions of all greenhouse gases other than biogenic methane by 2050 (New Zealand Ministry for the Environment, 2019). With the agricultural sector responsible for a large part of New Zealand's GHG emissions, the country has an additional target of 24% to 47% reductions of biogenic methane emissions by 2050 compared to 2017 levels.
+ In Canada, the Government recently announced that it will develop a plan to set Canada on a path to achieve net-zero emissions by 2050 (Environment and Climate Change Canada, 2020).

- In anticipation of strengthened 2030 targets in the European Green Deal, many European countries, such as Germany, Switzerland, the Netherlands and Norway, have already adopted national targets that exceed the currently binding EU target of 40% by 2030 (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety). In addition, Austria, Sweden, France, Denmark and Germany have climate policies in place that aim at zero net greenhouse gas emissions by 2040 (Austria), 2045 (Sweden) and 2050 (rest) respectively.
- One of the countries within the European Union with progressive, country-specific climate goals is Sweden. In 2017, Sweden enacted a climate policy framework that sets a target of zero net emissions by 2045 and negative emissions thereafter (Government Offices of Sweden, 2018). Within this framework, emissions from activities in Sweden must be at least 85% below 1990 levels by 2045, the remaining emissions may be covered by carbon sinks or offset by emission reductions abroad.
- Scotland, likewise, has set a legally binding target requiring the country to achieve net zero emissions by 2045. Currently, 20% of these emissions reductions may come from purchased carbon credits, while the remaining 80% must come from within Scotland. By 2050, the amount of carbon credits must be reduced to 10%, with the goal of eliminating the use of carbon credits thereafter (Parliament, 2018).

The European Union and its Member States formally ratified the Paris Agreement in 2016 and are committed to a binding target of at least a 40% reduction in greenhouse gas emissions (from 1990 levels), 32% share of renewable energy and 32.5% improvement in energy efficiency by 2030 (European Commission, 2018). To operationalize these targets, Member States have been mandated to comply with the integrated monitoring and reporting rules towards 2030 set forward by the European Commission. Under this governance system, all Member States submitted National Energy and Climate Plans for the period 2021-2030 in December 2019 (European Commission, 2018).

The European Union is now on route to agreeing on more ambitious emission reduction targets with the launch of the “European Green Deal”. This Green Deal represents a roadmap towards a climate neutral Europe in 2050 and outlines a financial investment plan to support the proposed measures (European

Commission, 2019). As part of this proposal, the Commission aims to raise the EU target to at least 50% reductions and is moving towards 55% greenhouse gas emissions reductions by 2030. A European Climate Law that would make the net-zero goal by 2050 legally binding for all Member States is currently under consideration.

On July 8, 2020, the European Commission published "A Hydrogen Strategy for a Climate-neutral Europe", announcing hydrogen as a key priority to achieve the European Green Deal and Europe's clean energy transition (European Commission, 2020).[18] By 2030, renewable hydrogen technologies are expected to reach maturity and be deployed at large scale, anticipating that about a quarter of renewable electricity might be used for hydrogen production by 2050 (European Commission, 2020). Some European Member States, such as Germany, France and the Netherlands, already have individual hydrogen targets in place: Germany plans to establish up to 5 GW of generation capacity by 2030 and an additional 5 GW no later than 2040; the Netherlands aims to realize 3-4 GW of installed electrolysis capacity by 2030, expecting a reduction in capital expenditures of up to 65% (Federal Government of Germany, 2020), (Government of the Netherlands, 2019). In 2018, France published a hydrogen deployment plan aiming to increase the industrial consumption of hydrogen to 20-40% by 2028 (Republique Francaise, 2018). These hydrogen strategies are designed to complement the country's existing carbon reduction strategies, including efforts to improve energy efficiency and to electrify large swaths of the transportation and building sectors.

[18] The plan consists of an objective to install at least 6 GW of electrolysis to produce up to 1 million tons of renewable hydrogen by 2024, growing to 40 GW and 10 million tons respectively in 2030.