PATHWAYS TO CARBON NEUTRALITY IN CALIFORNIA

What will it take to get to Net-zero Emissions in California?

November 2023

Stanford | Doerr School of Sustainability | Stanford Center for Carbon Storage

About

About the Stanford Center for Carbon Storage

Carbon Capture, Utilization, and Storage is a key technology for achieving net-zero greenhouse gas emissions. The Stanford Center for Carbon Storage (SCCS) uses a multidisciplinary approach to address critical questions related to flow physics, monitoring, geochemistry, geomechanics and simulation of the transport and fate of CO_2 stored in partially- to fully depleted oil & gas fields and saline reservoirs. SCCS is an affiliates program associated with the Stanford University Doerr School of Sustainability

About the Stanford Carbon Removal Initiative

The Stanford Carbon Removal Initiative (SCRI) seeks to create science-based opportunities and solutions for gigaton-scale negative emissions and atmospheric carbon removal. The initiative helps to enable removal of atmospheric greenhouse gases at scale by generating and integrating knowledge, creating scalable solutions, informing policies for technology deployment and governance, and demonstrating approaches and solutions with industry collaborators. All of this is done with a focus on social acceptance and equity, as well as environmental, economic, and social costs. SCRI is an affiliates program associated with the Precourt Institute for Energy and the Woods Institute for the Environment.

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Acknowledgements

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California Manufacturers & Technology Association

California State Building and Construction Trades Council

International Brotherhood of Boilermakers

Western States Petroleum Association

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List of Acronyms

AB	Assembly Bill
AC	Air conditioner
AD	Anaerobic digestion
AIM act	American Innovation and Manufacturing act
ATR	Auto thermal reformer
BAU	Business as usual
BEV	Battery electric vehicle
BiCRS	Biomass with Carbon Removal and Storage
CARB	California Air Resources Board
CCS	Carbon capture and storage/sequestration
CDR	Carbon dioxide removal
CEC	California Energy Commission
CGC	Clean generation constraint
CHP	Combined heat and power
CI	Carbon intensity
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
Comm	Commercial
CPUC	California Public Utilities Commission
DAC	Direct air capture
DECAL	The model used in this study – DEcarbonize CALifornia
D&S	Distribution and storage (hydrogen)
e-	Electricity
E-gen	Electricity generation
EO	Executive Order
EOL	End of life
EPA	U.S. Environmental Protection Agency
ER	Electric Resistance (space or water heater)
EV	Electric vehicle
FCEV	Fuel cell electric vehicle
F-gas	Fluorinated gas (e.g., refrigerant)
GHG	Greenhouse gas
GW	Gigawatts
GWh	Gigawatt-hours
GWP	Global warming potential
H2	Hydrogen
HDV	Heavy-duty vehicle
HFC	Hydrofluorocarbon
HP	Heat pump
ICE	Internal combustion engine
ITC	Investment Tax Credit
kWh	Kilowatt-hours
LCFS	Low Carbon Fuel Standard
LDV	Light-duty vehicle
Li Ion	Lithium-ion batteries

LEAP	Low Emissions Analysis Platform
LPG	Liquid propane gas
MACC	Marginal Abatement Cost Curve
MMBTU	Million British thermal units
$MtCO_2e$	Million (or Mega) metric tonnes of CO_2 equivalent
MWh	Megawatt-hours
MW	Megawatt
NG	Natural gas
NGCCS	Natural Gas combined cycle power plant with CCS
NWL	Natural and working lands
O&G	Oil and gas
PEV	Plug-in EV
PHEV	Plug-in hybrid EV
PTC	Production Tax Credit
PV	Photovoltaic
RD	Renewable diesel
Res	Residential
RFS	Renewable Fuel Standard
RNG	Renewable natural gas
RPS	Renewable Portfolio Standard
S&D	Supply and demand
SB	Senate Bill
SG	Steam generator
SH	Space heater / space heating
SMR	Steam methane reformer
T&D	Transmission and distribution (electricity)
VMT	Vehicle miles travelled
WH	Water heater / water heating
ZEV	Zero emissions vehicle

Key Findings

- Greenhouse gas emissions estimated with our system-wide model for California agree well with the estimates of the California Air Resources Board (CARB) Reference Case and Proposed Scenario with similar assumptions.
- There is no single technology or resource that would allow California to reach net-zero emissions by 2045. A combination of efficiency improvements, renewable electricity generation, carbon capture & storage (CCS), electrification, biofuels, hydrogen, low global warming potential (GWP) refrigerants and carbon dioxide removal (CDR) are needed.
- This study finds that about ~80% of emissions reductions in the CARB Proposed Scenario can be realized via eight proposed measures: CDR, clean electricity generation, heavy-duty vehicles zero emission vehicle (ZEV) sales and renewable diesel usage, F-gas mitigation, light-duty vehicle (LDV) ZEV sales, industrial CCS, industrial electrification, and residential electrification.
- Reaching net-zero will require some relatively expensive actions, including industrial electrification, CDR, and LDV and HDV fuel switching. Less costly actions include clean electricity generation, industrial CCS, and residential electrification.
- This study suggests that approximately 250 – 450 GW of capacity additions will be required to power California's decarbonized future. The scale of this buildout equals roughly 3 – 6 times California's current grid capacity and 8 – 15 times the amount of capacity California has added since 2000.
- Without an expandable, 100% carbon free, dispatchable power source, reaching 100% emission-free electricity generation will be quite difficult, requiring large amounts of solar and battery storage to maintain reliability during periods of limited renewables. Use of a small amount of natural gas power with carbon capture and storage (NGCCS) would produce emission reductions comparable to a 100% carbon-free grid at lower cost.
- Demand response can reduce battery storage buildout, but even in the most aggressive load shifting scenarios, battery storage is still needed in a significant way.
- Battery electric vehicles (BEVs) are a relatively affordable and effective mitigation option for the transportation sector. Deploying ZEVs as rapidly as possible will be required if 2045 goals are to be met. Gradual deployment towards those goals can reduce transportation emissions substantially even if the timing goals are not met. The speed with which ZEVs are deployed is one of the single largest drivers in cumulative emissions impacts and has a direct influence on the amount of CDR that will be needed in 2045 to meet California's goal of net-zero emissions.
- CCS is an effective and relatively affordable option for the industrial sector. Incentives like 45Q and the Low Carbon Fuel Standard (LCFS) have a large impact on CCS technoeconomic competitiveness, and a case can be made to extend the expiry date of 45Q, especially for the manufacturing subsector.

- Refrigerant leaks are one of California's largest emissions sources and are projected to grow due to heat pump installations. Responsible end-of-life management can help, but innovative low GWP refrigerants will be needed for deep reductions.
- The buildings sector is and will remain the largest user of electricity. Setting aggressive electric appliance (electric resistance, heat pumps) targets is an important element to reducing building emissions.
- Hydrogen is currently a relatively expensive fuel switching option but is presently most cost-effective for HDVs. Hydrogen generation costs are relatively small compared to the cost of end-use technologies (hydrogen vehicles, industrial process hydrogen heating, etc.) and distribution and storage (D&S). Research and development (R&D) will be needed to reduce these costs.
- Renewable natural gas (RNG) and renewable diesel (RD) are like-for-like replacements with their fossil counterparts (natural gas and diesel), making them attractive decarbonization options. However, supply of these fuels is limited, demand for them is global, and thus their uses should be prioritized carefully, perhaps in difficult to decarbonize applications.
- Reaching net-zero will be difficult to impossible without significant CDR or the development of new technologies that can replace the need for CDR. R&D is needed to reduce the cost of Direct air Capture (DAC).
- Meeting California's emission goals will require a massive amount of infrastructure buildout (electricity generators, transmission & distribution [T&D], BEV charging, CDR, CCS, building upgrades, and more) in a short amount of time. It is critical that the state find ways to eliminate red tape, streamline permitting activities and foster cooperation between public and private entities.

Chapter 1: Introduction

California is the largest state in the United States by population, and is poised to become the fourth largest economy in the world, after only the United States, China, and Japan [1]. California has long been a leader in climate policy, which has inspired climate policies globally and across the U.S. The California Global Warming Solutions Act of 2006, also known as Assembly Bill (AB) 32, was the first program in the country to require a reduction of greenhouse gas (GHG) emissions and take a comprehensive, long-term approach to doing so [2]. Since the passing of AB 32, several other policies have been put in place to support California's ambition for climate action, most notably, Executive Order (EO) B-55-18, which calls for the state to achieve carbon neutrality economy-wide by 2045 [3]. More recent legislative activity is highlighted below. California's historical emissions (by sector) as well as near and long term GHG reduction goals are shown in Figure 1.

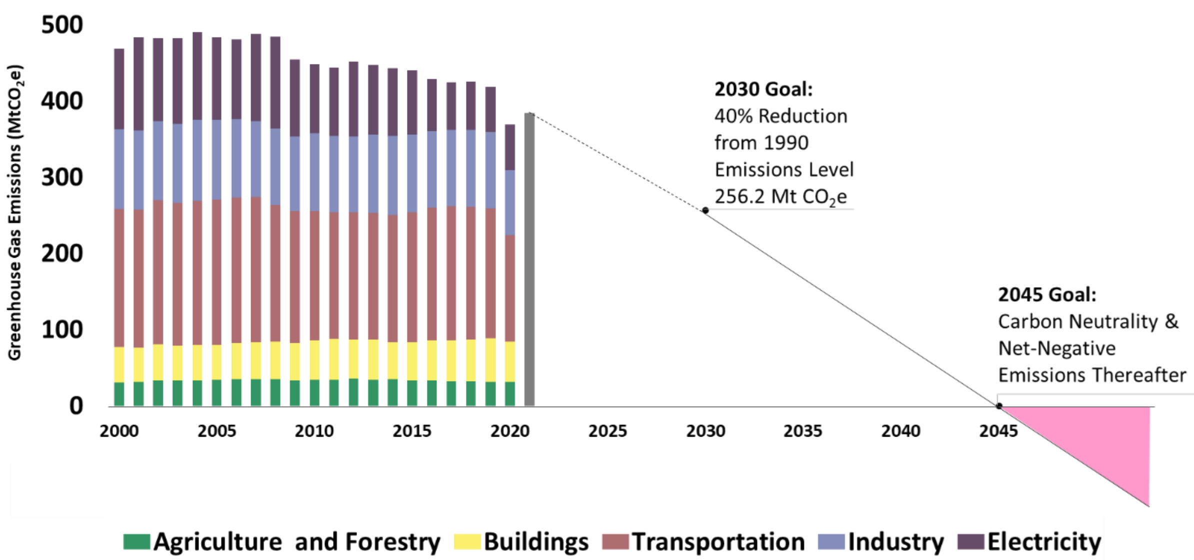


Figure 1: California's historical emissions and GHG Reduction Goals (Adapted from CARB, 2021) [4].

As seen in Figure 1, in order to achieve carbon neutrality by 2045, the five large emitting sectors will need to drastically reduce their emissions. A more detailed view of sectoral emissions is shown in Figure 2. Some of the recent legislative and regulatory actions that will help to reduce sectoral emissions include:

- Transportation:
    - The Advanced Clean Cars II Regulation requires 100% of new passenger car and light-duty truck sales to be zero-emission by 2035 [4].
    - The Advanced Clean Truck Program requires all new medium- and heavy-duty vehicles sold in California to be zero-emission by 2045 [5].
    - The Advanced Clean Fleets rule requires fleet owners operating vehicles for private services including last-mile delivery, Postal Service, and state and local

government fleets, to begin their transition toward zero-emission vehicles starting in 2024 [6].
    - As part of AB 32, Executive Order (EO) B-48-18 creates a goal of 5 million zero emission vehicles (ZEVs) on California roads by 2030 [7].
    - More recently, the Biden administration granted California the legal authority to require that half of all garbage trucks, tractor-trailers, cement mixers and other heavy vehicles sold in the state to be all-electric by 2035 [8].
- Buildings
    - In the residential and commercial building sectors, several cities are banning natural gas connections for new housing builds, fundamentally requiring electrification for those buildings [9] [10] [11].
    - California's 2022 Building Code encourages electric heat pump technology as well as establishes electric-ready requirements for new buildings when natural gas is installed [12].
    - The California Air Resources Board (CARB) is in the process of defining zero-emissions standards for new sales of gas heaters, furnaces, and water heaters, with a likely implementation date of 2030 [13].
- Industry
    - Mandatory reporting of GHG emissions by major reporting sources is required by AB 32 [14].
    - SB 905 establishes a carbon capture, removal, utilization, and storage program for the state [15].
- Agriculture and Forestry
    - EO N-82-20 enlists California's vast network of natural and working lands to store and remove carbon from the atmosphere [16].
- Electricity
    - SB 100 establishes a 60% Renewable Portfolio Standard (RPS) goal for 2030 and a 100% clean electricity grid goal by 2045 [17].
- Hydrofluorocarbons
    - SB 1013 establishes the Fluorinated Gases Emission Reduction Incentive Program which promotes voluntary adoption of low-GWP refrigerant technologies [18].
    - The AIM Act directs the EPA to phase down the production and consumption of HFCs in the US by 85 percent over the next 15 years [19].

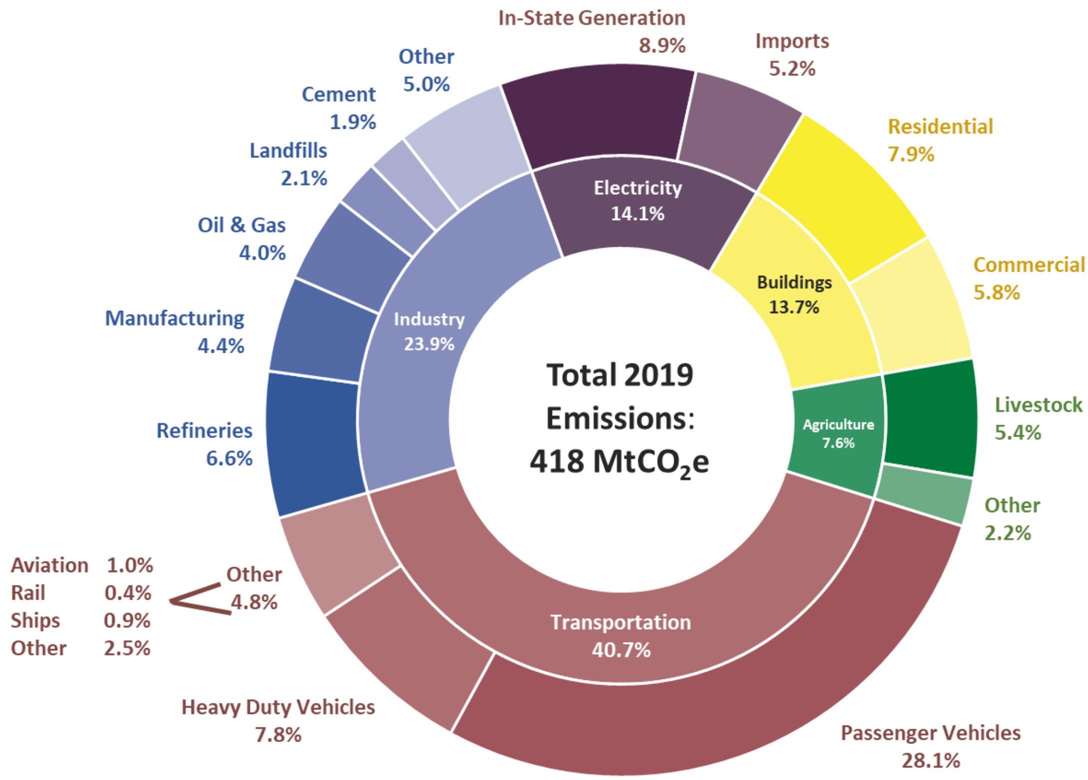


Figure 2: California GHG Emissions by Sector and Subsector, 2019 (Adapted from CARB, 2021) [4]. Note: Sum of percentages may not add to 100 due to rounding.

A detailed review of the emissions from each of these sectors, as well as options and costs to abate was conducted in year 1 of this study ("deep dives"). The results of these sectoral analyses as well as fuel switching options can be found in the following reports:

- *Anna Tarplin, Sarah D. Saltzer, Jacques de Chalendar, and Sally M. Benson, "Pathways to Carbon Neutrality in California: **Decarbonizing the Commercial Buildings Sector**", Stanford Center for Carbon Storage and Stanford Carbon Removal Initiative, May 2022* [20].
- *Joshua Neutel, Adam Brandt, Sally M. Benson and Sarah D. Saltzer, "Pathways to Carbon Neutrality in California: **Decarbonizing the Residential Sector**", Stanford Center for Carbon Storage and Stanford Carbon Removal Initiative, May 2022* [21].
- *In Jae Cho, Michael L. Machala, Alexander Evers, Sarah D. Saltzer and Adam Brandt, "Pathways to Carbon Neutrality in California: **Decarbonizing the Industrial Sector**", Stanford Center for Carbon Storage and Stanford Carbon Removal Initiative, May 2022* [22].
- *Eleanor M. Hennessy, Madalsa Singh, Andrew Robert Berson, Inês L. Azevedo, and Sarah D. Saltzer, "Pathways to Carbon Neutrality in California: **Decarbonizing the Transportation Sector**", Stanford Center for Carbon Storage and Stanford Carbon Removal Initiative, January 2023* [23].

- *Ejeong Baik and Sally M. Benson, "Pathways to Carbon Neutrality in California:* ***Decarbonizing the Electricity Sector****", Stanford Center for Carbon Storage and Stanford Carbon Removal Initiative, March 2022* [24].
- *Anela Arifi and Christopher B. Field, "Pathways to Carbon Neutrality in California:* ***The Bioenergy Opportunity****", Stanford Center for Carbon Storage and Stanford Carbon Removal Initiative, April 2022* [25].
- *John Foye and Christopher B. Field, "Pathways to Carbon Neutrality in California: The* ***Forest Management Opportunity****", Stanford Center for Carbon Storage and Stanford Carbon Removal Initiative, April 2022* [26].
- *Justin Bracci, Adam Brandt, Sally M. Benson, Gireesh Shrimali and Sarah D. Saltzer, "Pathways to Carbon Neutrality in California:* ***The Hydrogen Opportunity****", Stanford Center for Carbon Storage and Stanford Carbon Removal Initiative, February 2022* [27].

Additional insights obtained via interviews and a 2-day workshop can be found in the following report:

- *Terry Surles, Thomas Grossman, and Sarah D. Saltzer, "Pathways to Carbon Neutrality in California:* ***Clean Energy Solutions that Work for Everyone - Summary of Interview and Workshop Findings****", Stanford Center for Carbon Storage and Stanford Carbon Removal Initiative, September 2021* [28] .

All of these reports can be downloaded from the following website:
https://sccs.stanford.edu/california-projects/pathways-carbon-neutrality-california

Given California's ambitious climate goals, many energy systems models have been used to assess the impact of California's decarbonization policies. Scenario-based models assessing pathways for reaching California's AB32 goals indicate that widespread electrification would be crucial, and decarbonized electricity would become the primary form of energy supply [29], [30], [31]. Wei et al. (2013) emphasized energy efficiency, electrification, and a shift from fossil fuel resources in meeting future greenhouse gas emissions targets [32]. Yang et al. (2015) found that while all low-carbon resources are important, carbon capture and storage (CCS) would be a key technology for achieving the lowest mitigation costs [33]. Jacobson et al. (2014) considered an energy system for California utilizing only renewable resources [34]. Overall, economy-wide studies of California's decarbonization options have shown the importance of decarbonizing the grid, as well as the importance of a wide range of technologies, including but not limited to renewable resources, energy efficiency, and CCS. Similarly, more recent U.S.-wide studies that assess pathways for reaching economy-wide net-zero emissions by 2050 also commonly emphasize the need for 1) end-use energy efficiency, 2) electrification, 3) clean electricity, and 4) CCS [35], [36].

Additionally, AB 32 requires CARB to develop a Scoping Plan that describes a pathway to reduce GHGs. The first Scoping Plan was approved by CARB in 2008 and the plan is now updated every five years. The latest update was completed in 2022 [37]. The plan lays out a sector-by-sector roadmap for the state based on a technologically feasible, cost-effective, and equity-focused path.

This study integrates the findings of the year 1 sectoral and decarbonized fuel "deep dives' as well as the year 1 interview and workshop findings into a comprehensive assessment of the energy system. Specifically, data from year 1 'deep dives' was used in tandem with an energy planning and climate change mitigation assessment [38] tool called the Low Emissions Analysis Platform (LEAP) to build an economy-wide energy model for California, which we refer to as DECAL (**DE**carbonize **CAL**ifornia). The goal was to provide an independent assessment of decarbonization options and alternatives, including electrification, CCS, biofuels, hydrogen, CDR, and other technologies.

DECAL is a "what-if" pathways model, which allows for economy-wide decarbonization experiments. After inputting proposed policy or technology changes, the model outputs a number of results including emission savings, cost, and various metrics related to resource constraints/availability (example: grid peak, biofuel imports, etc.). This simple framework can provide answers to a variety of questions such as:

- What are the cost and emissions implications of 100% electric light-duty vehicle (LDV) sales by 2035? What if 100% of natural gas (NG) furnace sales are instead heat pumps by 2035? For these two scenarios, what is the impact on the grid?
- What are the cost implications of extending federal incentive programs from 2032 to 2045?
- Which makes more sense from a cost and emissions point of view, fuel cell electric vehicles (FCEVs) or BEVs? Is the answer different for LDVs vs. HDVs?

The next chapter of this report is an overview of the DECAL model - what it does and how it works. This is followed in Chapter 3 with a comparison of DECAL and the CARB Scoping Plan modeling results using similar assumptions. This step was done as a 'check' to ensure broad compatibility of results. Chapters 4-12 contain a series of analyses each aimed at answering the question "What will it take to get to net-zero by 2045?" Finally, Chapter 13 contains a sensitivity analysis. The goal is ultimately to outline the technologies and policies that will be needed for a feasible and cost-effective transition, as well as to illustrate the speed & scale with which California needs to move.

Chapter 2: LEAP and DECAL

Overview

LEAP is a software tool for energy policy analysis and assessment of climate change mitigation options. According to the developers, it has been used by governments, NGOs, consulting companies and energy utilities in more than 190 countries. It can be used at many different scales, from cities or states to regional and global applications. Many countries use LEAP as part of their commitment to report to the U.N. Framework Convention on Climate Change [38].

LEAP can be used to model energy consumption, production, and resource extraction, as well as account for energy and non-energy sector GHG emission sources and sinks. The structure of LEAP's calculations is shown in Figure 3. In the figure, arrows are shown to represent the *automatic* flow of information within LEAP, however most variables (inputs and output) are available for reference within LEAP when manually writing equations, including in the **Non-Energy** area. Note that the flow of information in LEAP is in the opposite direction from the flow of fuels through the energy system.

Energy demand is first calculated in the **Demand** area. This area includes end-users of energy, such as homes, cement plants, vehicles, and more. Information from the Demand area flows down into the **Transformation** area, where LEAP either generates the requisite fuel or imports it. In addition, any additional fuel demanded by Transformation modules higher in the tree must be generated by Transformation modules lower in the tree. For example, electricity used in refining processes adds further requirements to electricity processes lower in the tree. In this way, information can be thought to flow downward within LEAP (as represented in Figure 3), first from Demand to Transformation, and then from the top Transformation process to the bottom Transformation process. For this reason, the order of Transformation processes is material[2]. Finally, import/export information is summarized in the **Resources** area. Further detail on modeling methodologies and raw data entries used in the Demand and Transformation areas can be found in Appendices C&D.

Emissions associated with fuel combustion are calculated in the Demand and Transformation areas, as well as any costs. The **Non-Energy** area can be used to model emissions that do not result directly from fuel combustion (e.g., fugitive emissions, enteric fermentation) as well as other relevant costs (e.g., incentives).

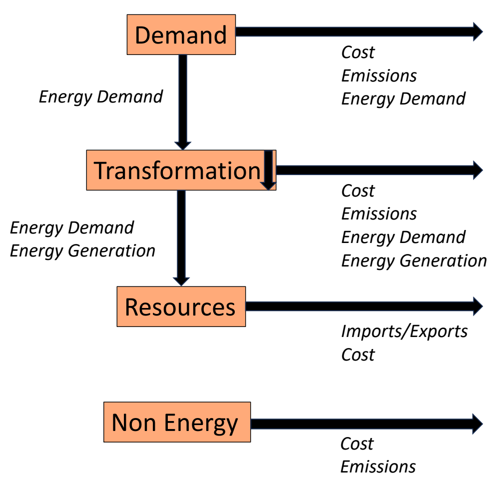


Figure 3: Structure of LEAP's calculations.

LEAP is not an equilibrium model – i.e., it will not endogenously calculate sales based on market conditions. Rather, it is a what-if model, that simply calculates the consequences of

[2] Note that it is possible to create an ordering in which LEAP cannot generate the requisite fuel, for example, if the electricity sector was placed above the refining sector. In this case, DECAL would simply import the remaining fuel. DECAL's tree was designed to minimize the occurrence of these issues.

projections forced upon it by the user. To this end, LEAP is designed around the concept of scenario analysis or storylines of how an energy system might evolve over time. Using LEAP, policy analysts can create and then evaluate alternative scenarios by comparing their energy requirements, their social costs and benefits and their environmental impacts (GHG emissions) [38].

LEAP is not a plug-and-play model (e.g., En-ROADs [39]). Rather, LEAP provides a flexible framework to build customizable models to the desired level of detail. LEAP's flexibility is in part afforded by its tree structure. For example, DECAL's tree to two levels is shown in Figure 4, along with additional levels in the residential sector. Level one is provided by default in LEAP, and includes the aforementioned Demand, Transformation, and Non-Energy branches. Afterward, users are free to tailor their tree structure; for example, DECAL's residential sector is organized by old and new dwellings, climate zone, and finally end-use. The last branch in the tree is an end technology or process, where raw data are ultimately input. LEAP offers excellent accounting functionality, keeping track of energy, emissions, and cash flows by branch. Refer to Appendix E to see DECAL's full tree.

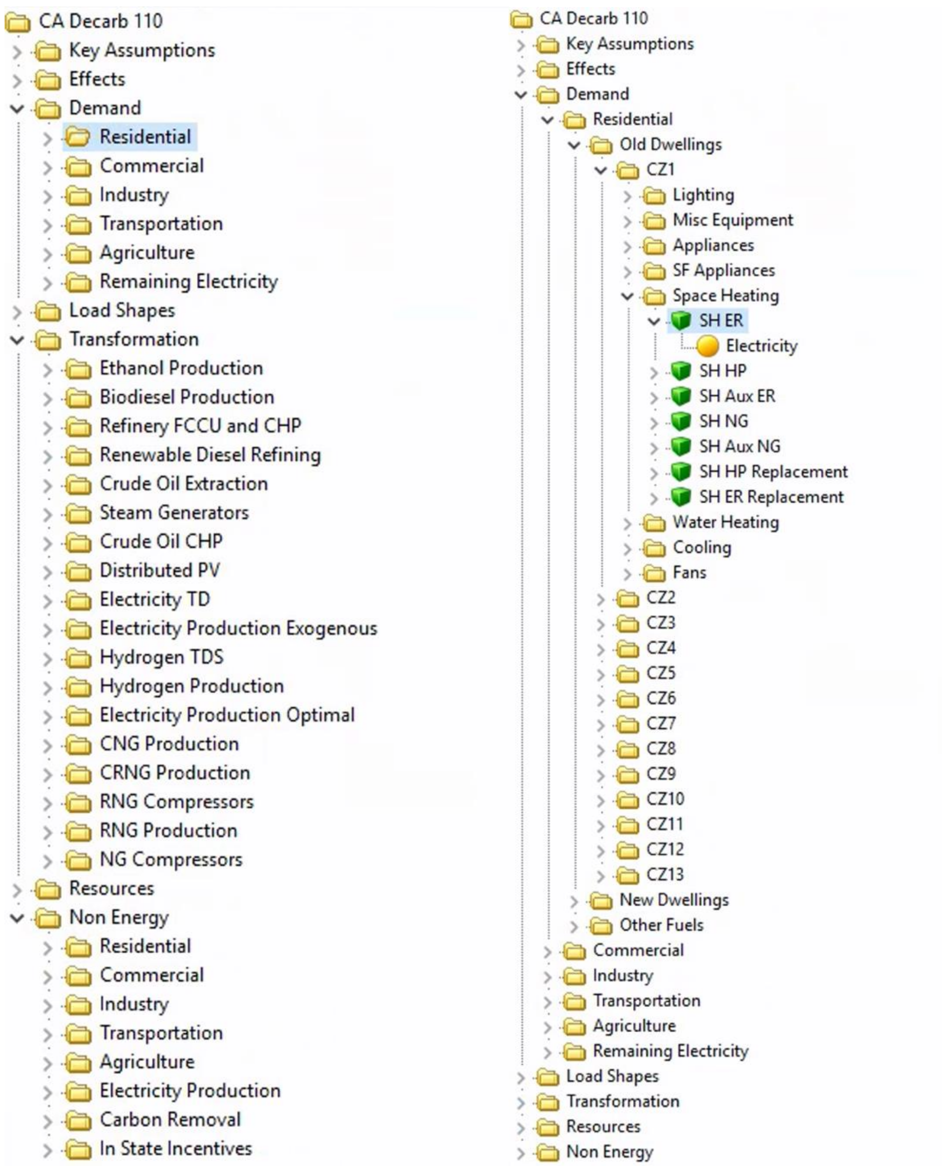


Figure 4: DECAL's tree to two levels (left); zooming in on the residential sector (right).

Modeling Methodologies Used in DECAL

To build DECAL, detailed sectoral data from Year 1 reports was entered into LEAP. In some cases, especially in data-rich/high-energy use sectors, highly detailed data is entered into LEAP. In data-poor or low-energy use sectors or subsectors, data is less detailed. A high-level summary of the methodology for each sector is discussed below. Refer to Appendix C for more details about the modeling frameworks (e.g. Stock and Flow, Technology with Energy Intensity, Capacity With Costs, Top-down, etc.) that are mentioned below. Appendix D contains a guide to excel sheets that were used to populate DECAL, and also lists major raw data sources. Appendix E contains a comprehensive version of DECAL's tree. Finally, Appendix E lists even more detailed resources that can be used to learn about DECAL, as well as instructions for using the model.

Demand

- **Transportation**: A stock and flow[3] model is used to track the inventory of four sub-types of light-duty and 10 sub-types of heavy-duty vehicles over time. Planes, trains and ships, as well as dispersed transportation emission such as those from airport support vehicles and industrial equipment, are modeled in a top-down[4] manner.
- **Residential**: Homes are organized by new dwellings versus old dwellings, by climate zone (13 in total), and by load type. Major loads, especially those expected to be electrified, are modeled using stock and flow. For appliances that will be replaced with like-for-like systems (example: pool pumps), Technology With Energy Intensity[5] (see Appendix C for more information) is used and cost is ignored (marginal cost is zero). Top-down modeling is used for fuels other than NG and electricity, including diesel, RD, biodiesel, kerosene, liquid propane gas (LPG), and wood.
- **Commercial:** Commercial buildings are organized by building type – e.g., schools, offices, etc. (12 in total) – by climate zone (five in total), and by load type. Similar to the Residential sector, major loads are modeled using stock and flow, and some other loads are modeled using Technology With Energy Intensity. Top-down methods are used to model a material amount of electricity and NG usage, due to bottom-up[6] data sources being limited in scope (specifically, bottom-up sources did not cover all building types and regions). Similar to the residential sector, top-down modeling is applied for fuels other than NG and electricity, including diesel, RD, biodiesel, ethanol, gasoline, kerosene, LPG, and wood.
- **Industry:** Given the number of energy intensive subsectors, several approaches were taken. Industrial activities were organized into the following groups: cement plants, food production, petrochemical plants, timber drying plants, and direct air capture (DAC) plants. Cement plants were modeled at the individual plant level (8 in total). Conversely, food and petrochemical plants were grouped by plant size (<25k t CO_2e/yr, 25k-100k t CO_2e/yr, and >100k t CO_2e/yr). DAC is used in decarbonization scenarios; two processes are currently available, one that utilizes aqueous solutions and high temperature processing, and one that uses solid sorbents and low temperature processing [40]. DAC electricity usage is captured as an industrial load, just like any other industrial load. Industrial plants in the Demand area are modeled using the Technology With Energy Intensity framework. Finally, other dispersed industrial sources were grouped and modeled together in a top-down manner. Upstream oil and gas (O&G) production and refineries, although part of the industrial sector, were modeled in the Transformation section discussed below. Landfills were modeled in both the Transformation (to create RNG) and Non-Energy areas.
- **Agriculture**: Emission sources from this sector were modeled in a top-down manner. This is for several reasons: 1) data paucity, 2) the large majority of emissions in this sector come from Non-Energy emissions (mainly enteric fermentation and manure),

[3] Stock and Flow modeling explicitly captures inventory, sales, retirements, and market flow.
[4] Top-down means that energy and emissions are input exogenously.
[5] Technology with Energy Intensity means that energy is broken down into the number of processes and the energy used per process.
[6] Bottom-up means that energy and emissions are not exogenously input. They are computed in the model based on stock and flow, Technology with Energy Intensity, etc.

and 3) decarbonization options in this sector are sparse and therefore are modeled using top-down mitigation costs.

Transformation

Sectoral energy demands (discussed in the previous section) are summed by LEAP and then the Transformation area is run to satisfy demand. Several transformation processes are used to generate the requisite fuels.

- **Electricity**: In-state electricity production is modeled via optimization. Specifically, several generator types are made available to DECAL – including NG with and without CCS, solar and wind (both onshore and offshore) in several different geographic regions, hydro, geothermal, nuclear, hydrogen fuel cell, and battery storage – and then LEAP finds the lowest cost solution subject to a number of constraints, including the clean generation constraint (see Appendix C for more details). Out-of-state generation and distributed generation (residential and commercial photovoltaics (PVs)) are modeled using LEAP's Capacity With Costs[7] framework (see Appendix C for more information), and are thus out of scope of the optimization decision making framework. The optimization module is responsible for generating all electricity that's not imported or created behind the meter.
- **Refineries**: Refineries take in crude oil (in-state production and imports) and hydrogen and create a slate of products (gasoline, diesel, jet fuel, etc.). 15 refinery plants are individually modeled – specifically, the fluidized catalytic cracker and CHP processes, which account for the majority of energy demand and emissions. These processes create demand for hydrogen, which is satisfied via refinery steam methane reformer (SMR) plants, which are also individually modeled (18 SMRs in total). If demand for refinery products decreases, then refining outputs/inputs also decrease along with associated emissions. DECAL also allows for refinery changes/upgrades to produce renewable diesel. Refineries are modeled with LEAP's Capacity With Costs module.
- **Upstream oil and gas:** Crude oil demand is created by refineries, and then that crude must either be produced or imported. First, DECAL dispatches available crude oil production wells, which creates demand for heat. The heat demand is satisfied by in-state CHPs and steam generators (SGs), which collectively capture the majority of energy use and emissions associated with steam flooding operations. SG units were modeled as a group whereas CHPs were modeled as individual plants (23 in total). Crude production wells, CHPs, and SGs are modeled with LEAP's Capacity With Costs module.
- **Hydrogen**: Hydrogen is initially generated at existing refinery SMR plants. As mentioned above, existing SMRs are modeled at the individual plant level (18 in total). DECAL allows excess hydrogen generated at refinery SMRs to be distributed and used in other places in the economy, such as HDVs or industrial heating. This is especially relevant in decarbonization scenarios where refinery hydrogen demand decreases and non-refinery hydrogen demand increases. Importantly, it is assumed

[7] Capacity with Costs means that capacity additions and dispatch are handled exogenously and costs are broken down into capital and operating costs.

that existing SMR plants cannot be retired, but CCS can be added, and the feedstock RNG blend percentage can be altered. In scenarios where existing refinery SMR capacity is not sufficient, DECAL can also build new hydrogen plants, including SMR (optionally with CCS and/or RNG feedstock), ATR (auto thermal reforming) (optionally with CCS and/or RNG feedstock), gasification (optionally with CCS), and electrolysis. Hydrogen plants are modeled using LEAP's Capacity With Costs module.

- **Bioenergy**: RNG, ethanol, and biodiesel demand are separately satisfied with RNG production, ethanol production, and biodiesel production modules respectively. RNG is either created from landfill gas capture or anaerobic digestion (AD). Three types of AD plants are available – wastewater, green/food waste, and manure – the lattermost being the largest potential source of RNG. Ethanol and biodiesel are made from corn and oils/fats respectively, though demand for these fuels is predominantly satisfied via imports. Ethanol and biodiesel are each modeled using one lumped generator. Bioenergy facilities are also modeled LEAP's Capacity With Costs module.
- **Transmission/Distribution/Storage:** the distribution of three fuels (NG, hydrogen, and electricity) is modeled in DECAL. It is assumed that all NG is imported, but DECAL does consider the energy needed to compress the NG to flow through pipelines, as well as fugitive emissions from NG pipelines and compressor stations. The cost of hydrogen distribution and storage (D&S) is approximated using a flat $/MWh charge. Electricity transmission and distribution is considered to be 95% efficient, and cost is also approximated using a flat $/MWh charge. Explicitly modeling of pipelines (NG and hydrogen) and poles/wires (electricity) was out of scope for this study but should be considered for future research.

Non-Energy

Most emission sources in this area are input in a top-down manner. Two exceptions are NG pipeline leaks and refrigerant leaks, which are tied respectively to the amount of NG (in energy) and refrigerants (number of devices) used in other places within the model. Negative emission sources – CCS and CDR – are also tabulated here, with equations tied to the Demand and Transformation areas. The Non-Energy area is also organized by sector – residential, commercial, transportation, industry/transformations, and electricity production – as well as by emission source (e.g., NG leaks, enteric fermentation, solvents, etc.). Some costs/benefits that have no energy demand associated with them are also applied in this area, mainly in-state incentives and transportation infrastructure (BEV chargers and hydrogen refueling stations).

Levers

Scenario analysis in DECAL is driven by a series of exogenously defined levers. Levers can be adjusted by the user and typically define the following:

- Rates at which technologies and fuel transformations are deployed (e.g., sales rates of ZEVs)
- Types of technologies that are deployed (e.g., CCS vs fuel switching)
- Biofuel blend percentages
- The Clean Generation Constraint (CGC), a lever that essentially applies an emissions constraint on the modeled electricity system

- Incentive prices
- Costs and learning rates (for sensitivity analysis)

Some of the most important levers in DECAL are shown in Table 1. See Appendix F for a more detailed list of levers.

Sector	Lever
Residential & Commercial Buildings	• Sales rate of space and water heaters • Space and water heater technology choice (e.g., electric resistance vs heat pump)
Industry	• Adoption rate of fuel switching • Fuel switching technology choice (e.g., electric resistance vs heat pump vs hydrogen) • Adoption rate of CCS
Transportation	• Sales rate of ZEVs • ZEV technology choice (e.g., BEV vs FCEV) • Renewable diesel blend %
Electricity Production	• Clean generation constraint
Hydrogen Production	• CCS adoption rate for existing SMRs • Technology choice for new H2 facilities (e.g., SMR CCS vs Electrolysis)
Bioenergy Production	• Adoption rate of anaerobic digesters
Applicable to Multiple Sectors	• Refrigerant GWP • Refrigerant EOL leak rate • RNG blend % • Renewable diesel blend %
Financial Levers	• Technology learning rates – cost of technologies over time • Cost of fuels • Incentive prices and program end-dates

Table 1: Major levers used in DECAL.

Of the 2019 emissions of 412 Mt CO_2e, 346 Mt CO_2e can be “levered” in a “bottom-up” manner, 48 Mt CO_2e can be levered into in a “top-down” manner, and 18 Mt CO_2e cannot be levered at all (see Figure 5). “Bottom-up” levers are those levers that are active in subsectors that have been modeled in a “Bottom-up” manner, whereas “Top-down” levers are active in subsectors that have been modeled in a “top-down” manner (see Appendix F for more details). Bottom-up modeling typically implies a detailed understanding of cost (e.g., automobiles, residential space heating, electricity generation, etc.), whereas Top-down modeling implies a more superficial understanding of cost (e.g., residential sector “other emissions”, trains/planes/boats, etc.). More concretely, Bottom-up modeling commonly includes prices at the device level (e.g., $/vehicle, $/heat pump, $/plant), whereas Top-down costing is typically done via a Top-down abatement price ($/t) set to match the bottom-up counterpart (e.g., residential other costing is set to be similar to the $/t price of bottom-up portions of the residential sector). Given the net-zero goal, Top-down levers are still used in many scenarios.

Levers have not been defined in portions of the model where solutions are currently non-existent or commercially infeasible. Some emission sources that cannot be levered include leftover landfill gas[8] (8.5 Mt), fertilizers (3.6 Mt), and emissions from wastewater and composting (2.4 Mt), as well as highly dispersed sources (each less than 1 Mt) such as aerosols, foams, fire protection, solvents, residue burning, crop residue, liming, histosol cultivation (e.g., peats and bogs), and rice cultivation. Any emission source without a lever cannot be decarbonized in DECAL. In other words, DECAL requires at least 18 Mt CO_2e of CDR to reach net-zero – an inevitable reality in the absence of innovation in the aforementioned areas.

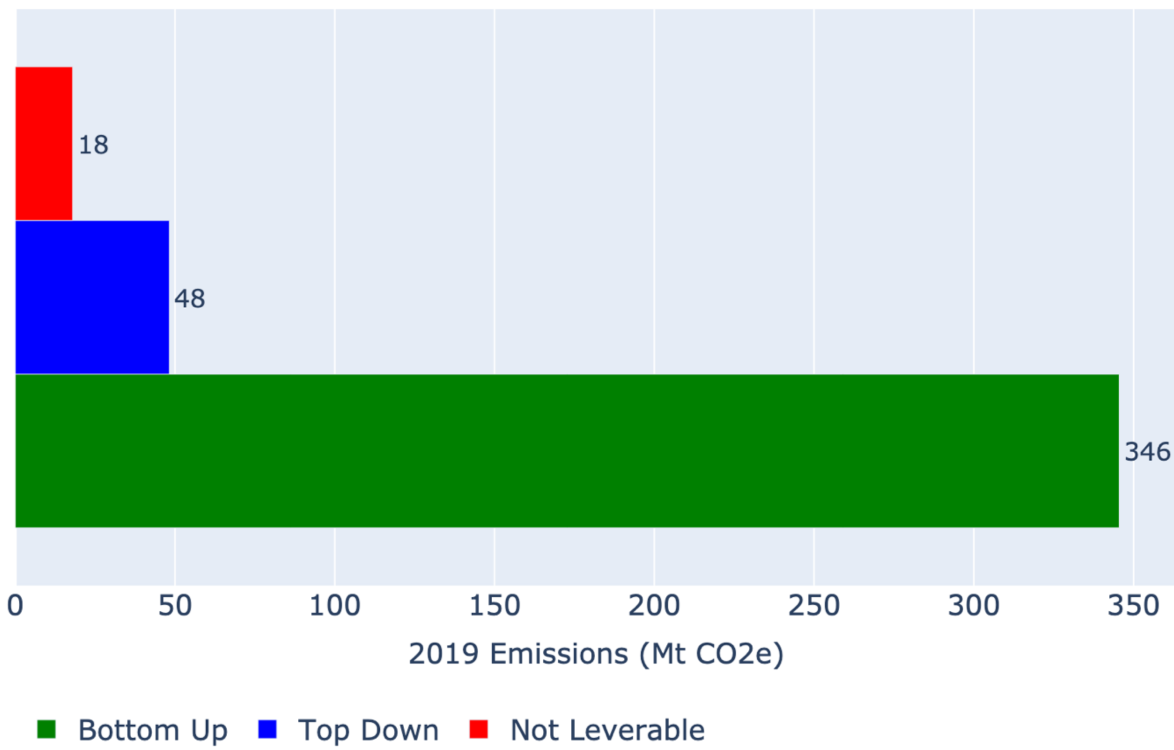


Figure 5: Bottom-up, top-down, and unleverable emissions in DECAL.

Economics

Total Resource Cost Test

DECAL performs a total resource cost test. In other words, DECAL accounts for all additional spending or savings from the perspective of society. DECAL **does not** perform an economic cost test from the perspective of the user, e.g., a ZEV buyer, a homeowner, a cement plant operator, etc. This distinction is particularly important for fuel prices. In the case of electricity, from a societal perspective, there is a cost for marginal generators, as well as the transmission and distribution (T&D) required to distribute additional electricity. End-users may pay additional costs, such as from legacy contracts and more. This difference is

[8] Landfill gas capture is already used broadly throughout the state. The remaining emissions are assumed to be at small/dispersed facilities, or from inefficiencies in existing methane capture plants. These remaining emissions cannot be levered.

relevant for fuels that are generated in DECAL rather than imported, most notably electricity, gasoline, and diesel.

Note that the total resource cost test operates on a marginal basis, meaning, it reports the delta in cost between one scenario and another. Choosing scenarios to compare, and thus the cost to report, depends on the question being asked. That said, costs are commonly compared to the Reference Case, or some strategic variation of the Reference Case. Appendix G contains a link to the excel data used to generate all graphs in this report, which clarifies precisely how scenarios are compared to generate cost metrics.

Reporting costs on a marginal basis means that cost projections are unnecessary for some technologies. For example, if a technology exists identically in both a scenario and the Reference Case, then the cost of that technology (replacing it upon retirement, operating it, etc.) on a marginal basis is zero. Thus, cost evaluations are not needed for all technologies in DECAL, only those that are subject to change on the margin. A good example is pool pumps – no scenarios reported in this study make changes to pool pumps, or in other words, it is assumed that pool pumps are replaced with like-for-like systems upon retirement. In this case, the cost of pool pumps is irrelevant. For this reason, as will be found in supporting spreadsheets and the DECAL model itself (see Appendices D and E), cost projections are absent for many technologies. That said, the energy usage and emissions of unchanging technologies are still relevant, as energy and emissions are often reported here on an outright (non-marginal) basis. These energy loads and emission sources have been captured in DECAL appropriately.

Learning

Costs are amongst the most uncertain data entries in DECAL, especially projected costs into the future. Learning rates are commonly used to estimate cost reductions over time. However, most literature sources define learning rates as a function of global production, and as DECAL is limited in scope to only California, it is challenging to apply these learning rates. In addition, there is no one literature source that contains projections for all technologies used in DECAL, and using several different sources – each of which may differ in methodology, aggressiveness in their projections, etc.– is problematic. For this reason, in this study, a two-step approach was used to defining learning rates and then cost projections for relevant technologies used in DECAL: 1) technologies were grouped into buckets of high maturity, medium maturity, low maturity, DAC (its own category), and then 2) high, medium, and low cost-reduction rates were defined for each bucket. In the scenario analyses, medium cost reduction rates were used by default. However, Chapter 13 and Appendix B explore the sensitivity of the system to learning by iterating between low and high reduction rates. Technologies were grouped by maturity as shown in Table 2.

Maturity Group	Sector	Technologies
High Maturity	Residential & Commercial Buildings	• Air conditioners • Natural gas furnaces and boilers • Space heat pumps • Electric resistance furnaces • Natural gas water heaters • Heat pump water heaters

		• Electric resistance water heaters • Solar water heaters • Electric panels
	Industry	• NG compressors • Electric resistance heating
	Transportation	• LDV internal combustion vehicles • LDV battery electric vehicles • LDV plug-in hybrids • HDV internal combustion vehicles • LDV BEV chargers
	Electricity Production	• Natural gas • Coal • Solar • Onshore wind • Geothermal • Biomass & municipal solid waste • Pumped hydro storage
	Hydrogen Production	• Steam methane reforming • Autothermal reforming
	Bioenergy Production	• Landfill capture • Anaerobic digestion (manure, wastewater, food & green waste) • Ethanol production • Biodiesel production
Medium Maturity	Industry	• Carbon capture & storage • Heat pump heating
	Transportation	• LDV fuel cell vehicles • HDV battery electric vehicles • HDV BEV chargers • FCEV refueling stations
	Electricity Production	• Offshore wind • Hydrogen fuel cell • Natural gas CCS • Li ion storage
	Hydrogen Production	• Steam methane reforming with CCS • Autothermal reforming with CCS • Gasification • Gasification with CCS • Electrolysis
Low Maturity	Industry	• Hydrogen heating
	Transportation	• HDV fuel cell electric vehicles

Table 2: Maturity groupings.

Table 3 shows the fractional cost reductions by 2045 as a function of maturity under low, medium, and high learning assumptions. Cost reductions start at 0% and then are linearly interpolated to the fraction shown in the table by 2045, such that in 2045, $Cost = (Cost\ in\ 2018) * (1 - Cost\ Reduction\ Fraction)$. As mentioned above, medium learning (the middle column) is used by default in most scenarios, with this assumption being tested in a sensitivity analysis (see Chapter 13 and Appendix B).

	Low Learning	Medium Learning	High Learning
High Maturity	0.00	0.10	0.20
Medium Maturity	0.05	0.15	0.30
Low Maturity	0.10	0.20	0.40
DAC	0.15	0.30	0.60

Table 3: Cost reduction rates as a function of maturity.

Electric generators were treated slightly differently as shown in Table 4.

	Low Learning	Medium Learning	High Learning
High Maturity	No learning	Learning rate defined using deep dive	20% additional learning
Medium Maturity	No learning	Learning rate defined using deep dive	30% additional learning

Table 4: Learning as a function maturity for electric generators.

Incentives

Incentives can play a critical role in decarbonization affordability. There are many federal incentives that have been introduced to help encourage carbon mitigation activities, and many of these have been incorporated into DECAL, including the following federal programs:

- **Renewable Fuel Standard (RFS)** which requires refiners and importers of gasoline/diesel to blend in certain volumes of renewable fuels. Those that outperform annual goals can receive credits (RINs) which can be traded (sold) to those entities that are unable to comply.
- **Carbon Capture Tax Credit 45Q** which provides (for 12 years) $85/t CO_2 for CCS projects and $180/t CO_2 for DAC projects.
- **Clean Electricity Production Tax Credit (PTC)** will commence in 2024 and provide for 0.3-1.5 cents/kWh of emission-free electricity produced.
- **Clean Energy Investment Tax Credit (ITC)** will commence in 2024 and provides for 30% credit on investment costs with a 10% bonus in certain situations. Note that the ITC and PTC cannot be stacked, and that DECAL by default utilizes the PTC.
- **Zero-Emission Nuclear Power Production Tax Credit** of 0.3 cents per kWh of electricity produced by a nuclear power plant.
- **Clean Hydrogen Production Tax Credit** is a 10-year credit of up to $0.60 per kg of clean hydrogen produced; the exact dollar per kg rate depends on the life cycle emissions of the hydrogen produced.
- **Alternative Fuel Refueling Property Credit** provides a credit of 30% of the cost (not to exceed $1,000 for residential EV chargers or $100,000 for commercial EV chargers) for fueling equipment for NG, propane, hydrogen, electricity, E85 and diesel fuel blends.
- **Clean Vehicle Credit** is worth up to $7,500 for buyers of EVs and plug-in hybrid electric vehicles (PHEVs).
- **Commercial Clean Vehicle Credit** is worth up to $40,000 and applies to those purchasing vehicles with gross vehicle weight greater than 14,000 pounds.
- **Credit for Residential Clean Energy** allows homeowners to deduct up to 30% of the cost of clean energy systems installed in home from federal taxes. Applicable technologies in LEAP include solar water heaters.

- **Energy Efficiency Home Improvement Credit** is equal to 30% of the sum of amounts paid by the taxpayer for certain qualified expenditures, including (1) qualified energy efficiency improvements installed during the year, (2) residential energy property expenditures during the year, and (3) home energy audits during the year. Applicable technologies in LEAP include space and water heat pumps.

Amongst in-state programs, only cap-based incentives are included. The economic rationale is that cap-based programs attach innate economic value to the regulated externality. While substantially abstracted from how these complex policies work in reality, in DECAL, benefits are obtained anytime the environmental benefit is achieved – for example, increasing the share of renewable electricity (RPS), producing low carbon fuels (LCFS), and reducing emissions (Cap and Trade). The per unit benefit is set equal to the price of each trading commodity (REC credit, LCFS credit, emissions allowance).

- **Renewable Portfolio Standard (RPS)** requires utilities to provide a certain amount of renewable electricity or buy credits if unable to do so.
- **Low Carbon Fuel Standard (LCFS)** is a cap-and trade-program designed to encourage the development of lower carbon intensity transportation fuels that are ultimately sold in California. Credits trade on the open market with market pricing that can range from a floor of $0 to up to $200/t CO_2e. DECAL assumes the price remains at $75/t CO_2e. There are currently three LCFS credit pathways – fuel pathways that incentivize the use of low carbon transportation fuels, project-based crediting which incentivize DAC and CCS projects in the petroleum supply chain, and capacity-based crediting which incentives ZEV charging infrastructure; only the prior two pathways are included in DECAL.
- **Cap and Trade** is a program that limits emissions from facilities in California. Those that limit emissions below the current year threshold can receive credits which can be traded (sold) to those entities that are unable to comply or for whom the cost of purchasing credits is lower than the cost of reducing emissions directly.

Further details as to how these incentives were included in DECAL can be found in Table 5 below.

The following incentives were not included in DECAL:

- New Advanced Manufacturing Production Tax Credit
- Clean Fuel Production Tax Credit
- Geothermal Heating Tax Credit
- Revival of Qualifying Advanced Energy Project Credit
- Extension of Second-Generation Biofuel Incentive
- Extension of Biodiesel and Renewable Diesel Credit
- High-Efficiency Electric Home Rebate Program
- Previously Owned Clean Vehicle Credit

Prices

Table 5 lists some of the most significant base case assumptions that were used for this analysis. Note that many of these assumptions are levers that can be easily changed. In

Chapter 13 and Appendix B, a sensitivity analysis is performed to measure the sensitivity of system-wide costs to fuel prices and incentives.

Parameter	Value	Unit	Notes
Discount rate	5	%	
Inflation	2	%	
Natural Gas Price	5.11	$/MMBTU	
Crude Oil Price	83.09	$/BBL	
Gasoline Price	3.46	$/Gal	
Diesel Price	3.56	$/GGE	
LPG Price	4.49	$/GGE	
Coal Price	223.57	$/Mt	
RNG Price	18.00	$/MMBTU	
Renewable Diesel Price	4.83	$/GGE	
Biodiesel Price	4.17	$/GGE	
Ethanol Price	3.80	$/GGE	
RFS Credit Price	37.31 for D3 fuels 18.76 for D4 fuels 15.78 for D6 fuels	$/MMBTU	D3 – RCNG D4 – Renewable Diesel, Biodiesel D6 – Ethanol
Carbon Capture Credit Price	85 for CCS 180 for DAC	$/t	Small plants that are below the regulated threshold are ineligible. Both fossil and biogenic CO_2 apply.
PTC Credit Price	15	$/MWh	Applicable to biomass/biogas, geothermal, solar, wind, and H2FC
ITC Credit Price	30	%	Additionally applicable to Li Ion A generator can only apply for one of PTC or ITC. By default in DECAL, they apply for the PTC.
Nuclear PTC Credit Price	15	$/MWh	
Clean Hydrogen Tax Credit Price	H2 CI (kg CO_2e / kg H2) — Credit Price $/kg 0.00 – 0.45 — 3.00 0.45 – 1.50 — 1.00 1.50 – 2.50 — 0.75 2.50 – 4.00 — 0.60	$/kg	As this a new program, federal guidance is still being published, and so carbon intensities were estimated using published LCFS pathways.
Alternative Refueling Property Credit Price	30	%	Minimum of 30% and $1,000
Clean Vehicle Credit Price	3,750	$/Vehicle	Applicable to passenger cars only
Commercial Clean Vehicle Credit Price	Up to 7,500 for T1–T3 Up to 40,000 for T4 and larger	$/Vehicle	15%/30%/30% of the cost of PHEVs/BEVs/FCEVs is covered for commercial vehicles, but up to a maximum of 7,500 for grades T1, T2, or T3 vehicles, and up to a maximum of 40k for vehicles sized T4 or larger
Residential Clean Energy Credit Price Energy Efficiency Home Improvement Credit Price	30	%	Applicable to space heat pumps, water heat pumps, and solar water heaters

RPS Credit Price	5.00	$/MWh	Applicable to biomass/biogas, geothermal, solar, and wind. For computational reasons, RPS is applied after the optimization model makes its decisions, in other words, the model does not make decisions with RPS in mind.
LCFS Credit Price	75.00	$/t	Clean hydrogen and electricity used for transportation applies for the fuel production pathway. Carbon intensities are estimated using published LCFS pathways (see excel spreadsheet for further details). Sustainable liquid fuels additionally apply – ethanol, biodiesel, renewable diesel, compressed RNG, and CNG. The following generators apply for the carbon removal pathway when adding CCS retrofits: NG generators to make electricity, existing SMR plants steam generators, crude oil CHPs, and refineries. In addition, DAC is applicable.
Cap & Trade Credit Price	28.45	$/t	Cap and trade is implemented in DECAL via a carbon tax, in that each ton produced creates a cost to society. Only 80% of emissions apply (about 80% of emission sources are under the cap), and emissions reductions from carbon removal (CCS, DAC) is not included as a benefit (consistent with the regulation).

Table 5: Key economic assumptions used in DECAL.

Modeling limitations

Every model has its strengths and weaknesses. DECAL is best suited to reveal high-level, cross-sectoral insights about California's pathways to net-zero. That said, some of DECAL's limitations are described below. It is important to consider these limitations when considering results shown in later chapters.

- **Exogenous Modeling:** as has been mentioned, DECAL is mostly an exogenous model, in that the user instructs the model which technologies to deploy and at what pace. Technology costs and incentives still affect the overall cost-benefit-analysis, but reducing costs or implementing incentives cannot automatically push the model in a particular direction. This is in contrast to an equilibrium model or an optimization model, which evaluates market conditions (cost, incentives, mandates, global market conditions, and more) and then installs infrastructure in response. Exogenous modeling can be helpful to explore the effect of specific what-if scenarios – for example, “what if FCEVs were used instead of BEVs?” These cases may not be explored in an equilibrium or optimization model because they are not cost optimal. On the other hand, equilibrium and optimization modeling can be helpful to evaluate incentive or cost thresholds in which the model makes particular decisions – for example, “at what cost-point, or with what incentive, do FCEVs become optimal?” Overall, exogenous modeling can be both a limitation and a strength depending on the context.

- **Outside Agents:** As DECAL is an exogenous model, it does not consider changes that occur outside of California, for example, the effect of changing global market conditions, fuel prices, policies of neighboring states, etc.
- **Projections vs Forecasts:** DECAL is not a forecasting tool – it does not make predictions about the future. It simply projects the results of a future that the user chooses.
- **Technology Scope:** There are numerous technologies that may be introduced over the next two decades ranging from industrial heating, long duration grid-scale energy storage, modular nuclear reactors, alternative liquid fuels, innovative materials, CDR with lower input energy requirements, and much more. The modeling team did not have the bandwidth the evaluate technoeconomics of all technologies, but tried to include most technologies that are proven at scale.
- **Economic Scope:** DECAL only evaluates cost from the perspective of society. Solutions that look low cost from the perspective of society may be financially un-suitable to particular agents within society. DECAL should be thought of as an initial cost-benefit screening, but policymakers should consider additional perspectives.
- **Emissions Scope:** DECAL’s emission scope aligns with CARB’s annual GHG inventory (Figure 2) [41]. As a result, greenhouse gas emissions created outside California are out of scope (with exception to emissions that are created when producing imported electricity). Likely the most notable emission source not included in DECAL are those caused by land-use changes in other states and countries due to biofuels used in California. In addition, emissions generated to manufacture technologies (for example, batteries) used in California are not considered. Emissions sources and sinks from natural and working lands (NWL) are not yet considered in the GHG inventory, and so they are not included in DECAL. Furthermore, CARB’s 2022 Scoping Plan suggests that NWL are a small source of emissions (7 – 9 Mt CO_2e) [37], and so NWL mitigation options were not considered in this study. DECAL can help policymakers identify high-level tradeoffs of various technologies and pathways, but in practice, policymakers should further evaluate life cycle emissions before implementing programs.
- **Other Impacts:** In any lifecycle cost-benefit analysis, it is important to carefully define the impact-metrics of interest. In this study, those are greenhouse gas emissions, societal costs, and resource constraints. There are many other impacts one may consider. A notable example is criteria air pollutants (NOx, SOx, and particulate matter) – these pollutants have a major impact on <u>local</u> health outcomes and are critical to consider when evaluating environmental justice. Other environmental impacts of interests may be water-usage, soil quality, and much more. One economic impact noted in an earlier report associated with this project [28] is leakage – the degree to which strict decarbonization policies drive people and/or business to

neighboring states or countries. These impacts and are out of scope for this project but remain a possibility for future work.

- **Capacity Expansion Model:** DECAL's dispatch model has two major limitations: 1) it uses 288-hour time slices, and 2) it uses a single node. For (1), DECAL assumes the that every day in a particular month is the same. This removes temporal variance of loads such as heating, cooling, and BEV charging, and also abstracts out temporal variance of solar and wind availability. Extreme weather events can impact both the demand and supply side of electricity. For example, heat waves can cause spikes in cooling, and the grid must be built to accommodate. In addition, storms can reduce solar capacity for several days in a row, necessitating solar overbuilding and/or long-duration energy storage. Overall, due to using 288-hour time slices, DECAL's capacity expansion model should be considered optimistic - it may in fact *undershoot* actual required capacity additions. For (2), DECAL does not consider *where* load comes from, or *where* generation is available; in other words, all loads and generators are assumed to be located at the same node. The practical implication of this is that transmission and distribution (T&D) constraints are not considered in DECAL, which could have an impact on capacity expansion and dispatch. In addition, T&D build-out is not explicitly modeled, though the marginal cost of T&D is approximated in a top-down manner using a flat $/MWh charge,
- **Refinery Model:** In DECAL, refineries are unable to change the proportions of gasoline, diesel, and other refined fuels that they produce. If LDVs electrify far quicker than HDVs, it may be in refineries best interest to increase the proportion of diesel-to-gasoline that they produce, however this is not possible in DECAL. In practice this means that refining emissions reported by DECAL may be overestimated in scenarios where LDVs are decarbonized more quickly than HDVs.

Chapter 3: Comparison Between DECAL and the CARB Scoping Plan

Questions that this section will address:

- *Do DECAL model results match the yearly emissions forecast by the CARB Reference Case and Proposed Scenario when run under the same set of assumptions?*
- *Do DECAL decarbonization costs align with CARB cost estimates?*

The CARB 2022 Scoping Plan published Nov 16, 2022, provides a Reference Case and a Proposed Scenario. The Reference Case reflects current trends and expected performance of policies identified in the 2017 Scoping Plan — some of which are performing better (such as the RPS and LCFS) and others that may not meet expectations (such as vehicle miles traveled (VMT) reductions and methane capture) [37]. The Proposed Scenario achieves carbon neutrality by 2045, deploys a broad portfolio of existing and emerging fossil fuel alternatives and clean technologies, and aligns with statutes, Executive Orders, Board direction, and direction from the Governor [37]. To build our confidence in the output from the DECAL, the results were compared to the CARB Reference Case and Proposed Scenario under similar assumptions. The results are shown in Figure 6.

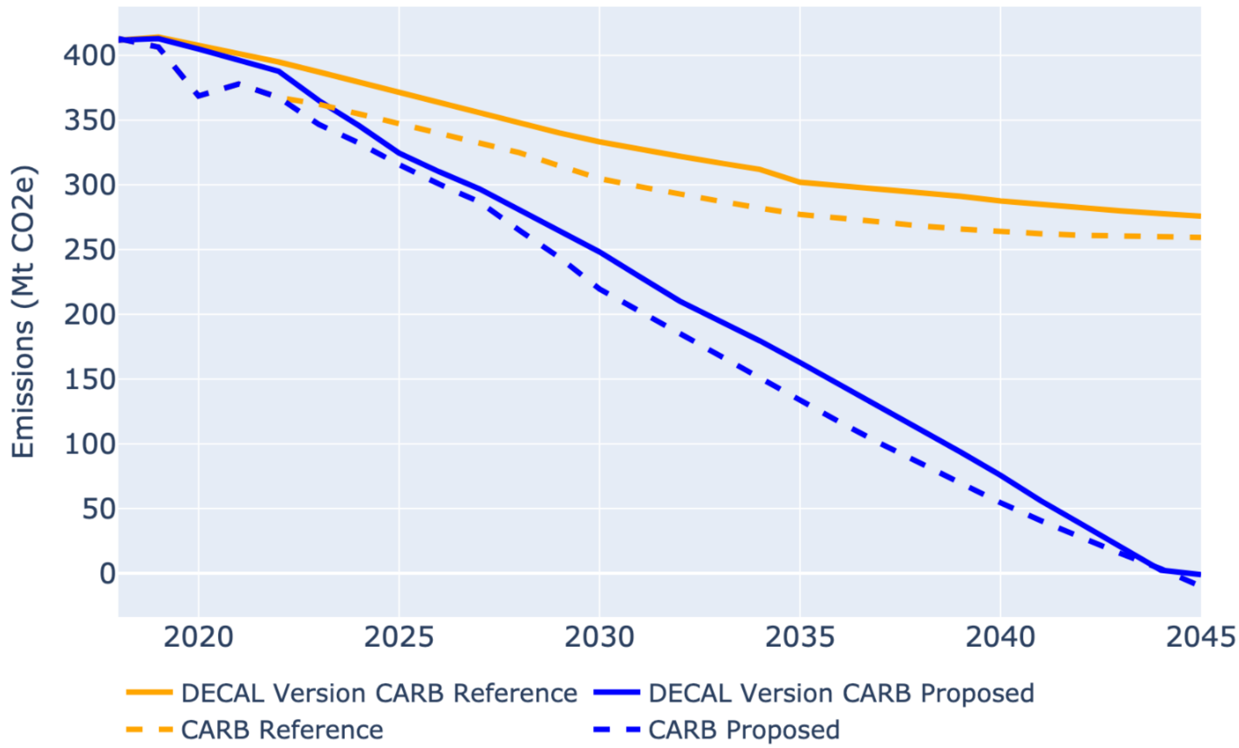


Figure 6: Emissions over time, CARB Reference Case and Proposed Scenario vs DECAL under a similar set of assumptions.

Reference Case

The CARB Reference Case and DECAL were run under similar assumptions (shared by CARB in Appendix H) in the 2022 Scoping Plan [37] and provide broadly similar results as shown in Figure 6. Emissions in 2045 differ by only 16.3 Mt. Explanations for the differences are described in Table 6. Given the number of assumptions, data inputs, and variables at play, we consider the agreement to be reasonable. Going forward, the CARB Reference Case will be adopted as the Business as usual (BAU) for this study, and as such, many alternative scenarios will be compared against the DECAL version of the CARB Reference Case.

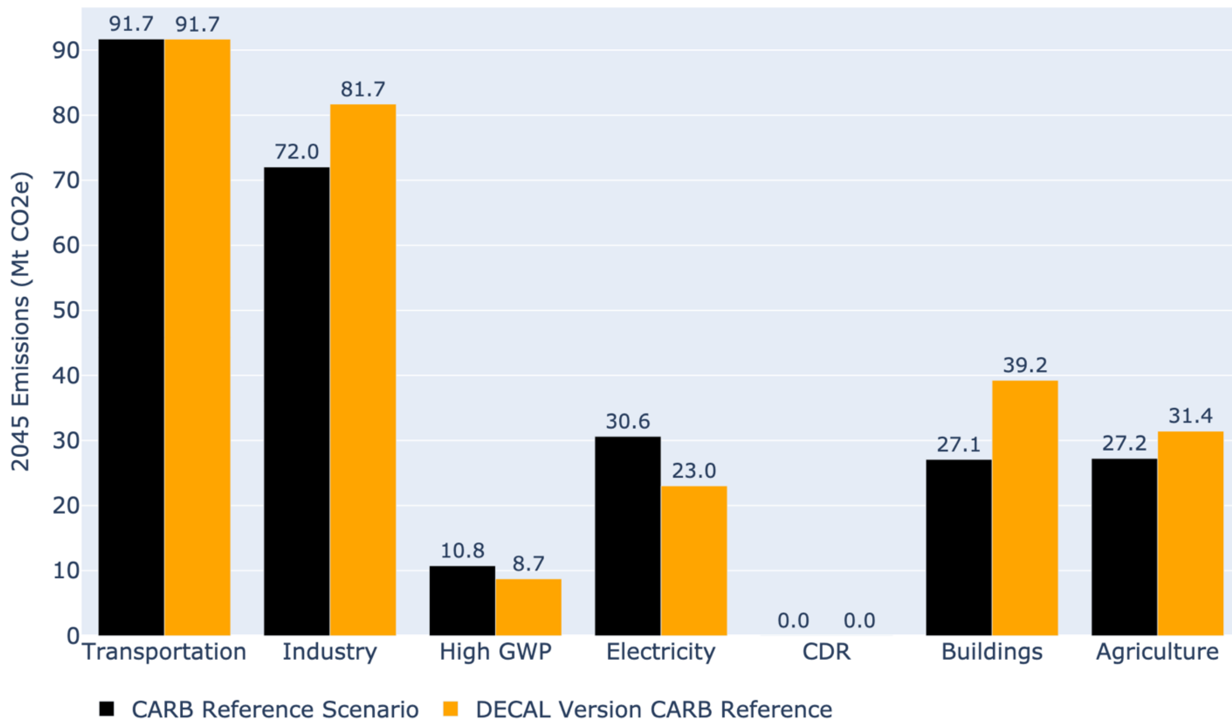


Figure 7: 2045 Emissions, CARB Reference case compared to DECAL run with a similar set of assumptions.

2045 Annual Emissions (Mt CO_2e)	CARB	DECAL	Δ	Explanation of significant differences
Transportation	91.7	91.7	0.0	
Industry	72.0	81.7	9.7	DECAL starts 6 Mt higher than the Scoping Plan to align with the GHG inventory
High GWP	10.8	8.7	-2.1	
Electricity Production	30.6	23.0	-7.6	Iteration on DECAL's CGC was done in an attempt to match CARB's results as closely as possible
CDR	0.0	0.0	0.0	
Buildings	27.1	39.2	12.1	DECAL starts 7 Mt higher than the Scoping Plan to align with the GHG inventory
Agriculture	27.2	31.4	4.2	DECAL does not assume any changes to livestock populations or manure management practices
Total	**259.4**	**275.7**	**16.3**	

Table 6: Explanation of differences between CARB Reference Case and DECAL run with a similar set of assumptions.

Proposed Scenario

The CARB Proposed Scenario and DECAL were run under similar assumptions (provided by CARB in Table 2-1 in the 2022 Scoping Plan [37]) and provide broadly similar results as shown in Figure 8. Emissions in 2045 differ by only 9.1 Mt. Explanations for the differences are described in Table 7. Again, given the number of assumptions, data inputs, and variables at play, we consider the agreement to be reasonable. Many analyses in this study involve making slight perturbations to the DECAL version of the CARB Proposed Scenario, which proved to be a tractable and valuable learning approach.

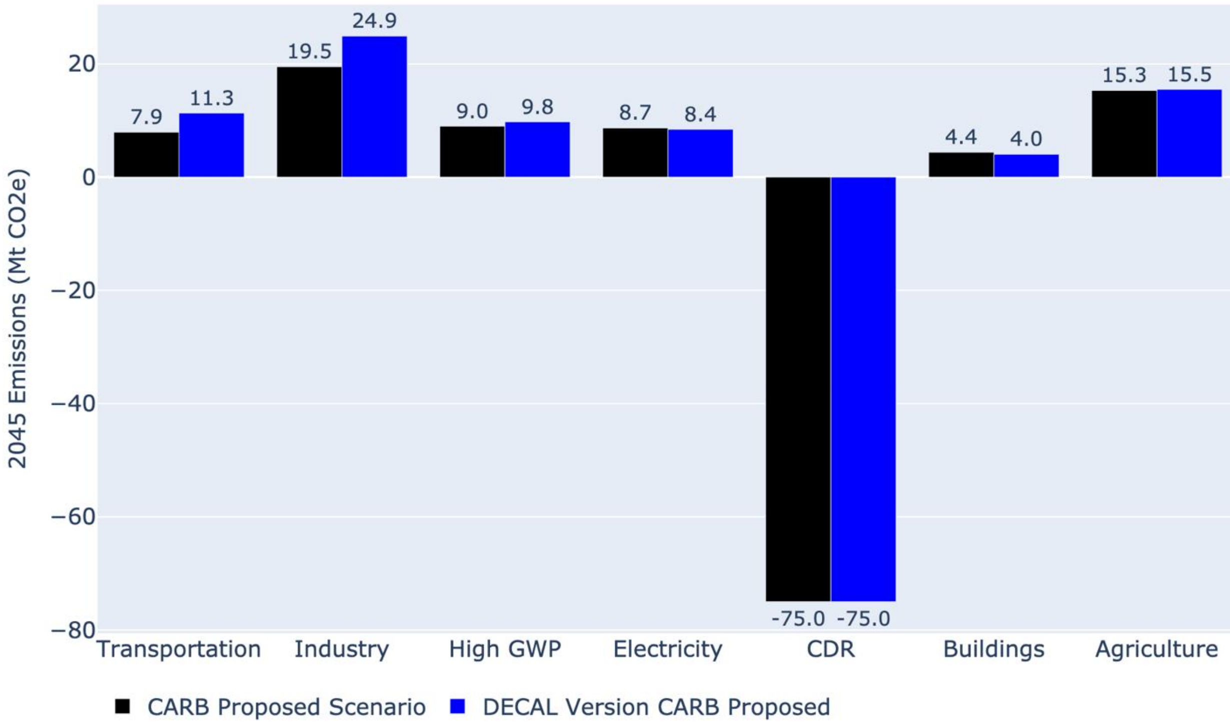


Figure 8: 2045 Emissions, CARB Proposed Scenario and DECAL run with a similar set of assumptions.

2045 Annual Emissions (Mt CO_2e)	CARB	DECAL	Δ	Explanation of significant differences
Transportation	7.9	11.3	3.4	DECAL likely assumes slower transportation stock and flow transition dynamics than the Scoping Plan
Industry	19.5	24.9	5.4	DECAL starts 5 Mt higher than the Scoping Plan to align with the GHG inventory
High GWP	9.0	9.8	0.8	
Electricity Production	8.7	8.4	-0.3	
CDR	-75.0	-75.0	0.0	
Buildings	4.4	4.0	-0.4	
Agriculture	15.3	15.5	0.2	
Total	**-10.2**	**-1.1**	**9.1**	

Table 7: Explanation of differences between CARB Proposed Scenario and DECAL run with a similar set of assumptions.

CARB also provides a breakdown of 2045 annual carbon mitigation contribution by intervention in Table 3-5 of the 2022 Scoping Plan [37]. DECAL results are broadly similar as shown in Figure 9.

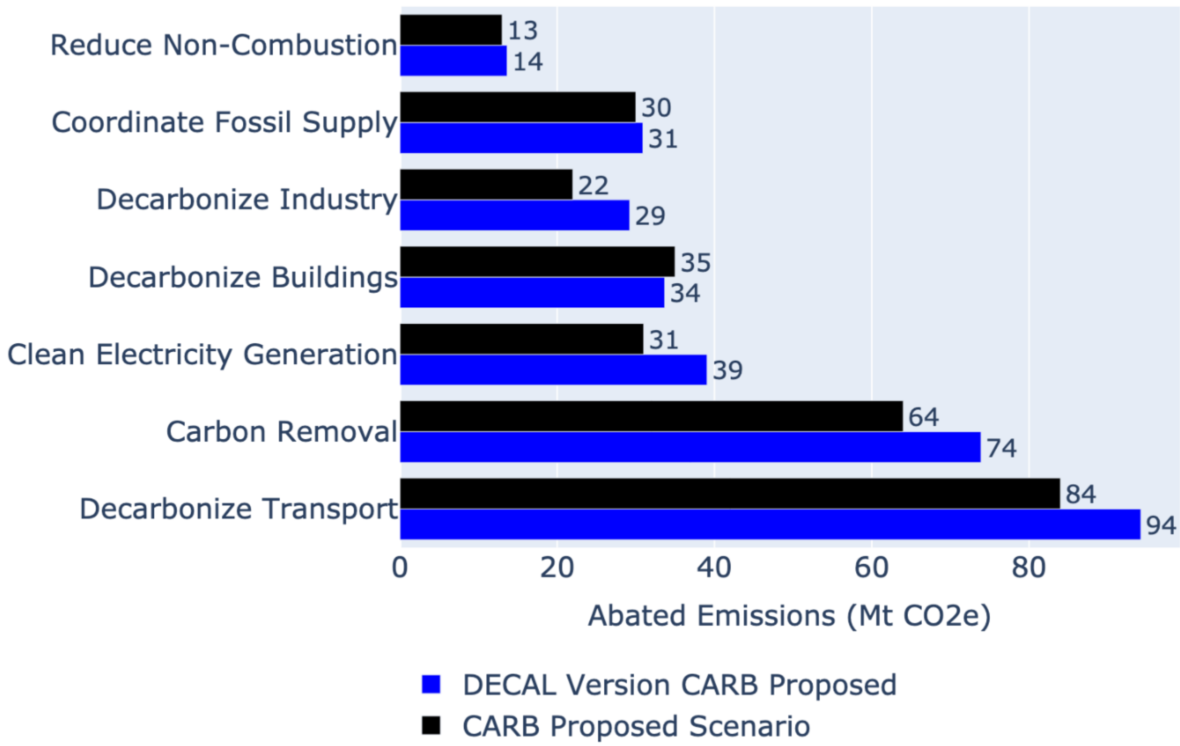


Figure 9: 2045 annual carbon mitigation contribution by intervention, CARB Proposed Scenario versus DECAL run with a similar set of assumptions. Categories compared in this plot are consistent with those in Table 3-5 from the 2022 Scoping Plan [37].

Additional emissions comparisons are made in Appendix A, including to the CARB Scoping Plan in the model *start* year, and to CARB's GHG inventory.

Cost Comparison

Abatement costs are highly uncertain. A comparison of abatement costs for the Proposed Scenario from CARB and DECAL is shown in Figure 10. Note that the categories (along the vertical axes) are consistent with those used by CARB in Table 3-11 of the 2022 Scoping Plan [37]. For 4 out of the 7 categories, costs are somewhat similar. Note the large differences in cost estimates for clean electricity generation and decarbonizing transportation. It is difficult to compare costs between models because 1) cost projections are highly uncertain, 2) it is unclear in some cases what is and isn't included in a reported cost metric (e.g., federal incentives, in-state incentives, resource savings, learning, etc.), and 3) there is uncertainty in defining the baseline scenario and associated costs. We speculate that the difference in electricity costs per ton is partially because CARB does not include GHG reductions occurring outside of California in their abatement cost calculation (impacting the denominator), whereas DECAL does. As for transportation, in CARB's analysis the incremental costs of new vehicles are generally offset by gains in efficiency and fuel consumption, however this is not the case in DECAL.

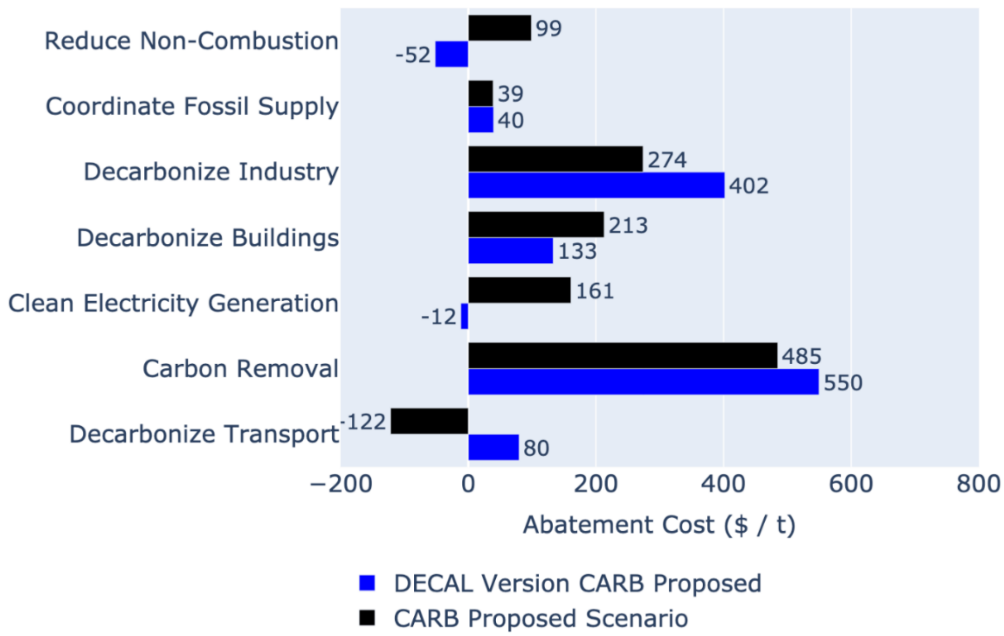


Figure 10: Abatement costs by intervention, CARB Proposed Scenario versus DECAL run with a similar set of assumptions. Categories compared in this plot are consistent with those in Table 3-11 from the 2022 Scoping Plan [37].

Chapter 4: Economy-wide Insights

Questions that this section will address:

- *Can one resource or technology get us to net-zero by 2045?*

To assess the high-level decarbonization potential of a single technology or resource, four scenarios were run in DECAL– high electrification, high hydrogen, high bioenergy, and high CCS, where each of these resources were respectively and separately deployed throughout the economy (where applicable) and pushed to an aggressive upper bound. Table 8 details how levers were set in these four scenarios. As an example, the high electrification scenario involves aggressive deployment of all electrification technologies in DECAL – including electric home appliances, battery electric vehicles, electric industrial heating, and electrolysis – but importantly does not include additional deployment (i.e., more deployment than the Reference Case) of non-electric technologies such as hydrogen, bioenergy, CCS, or CDR. This exercise was undertaken to assess if there were any single technology options that could be relied upon to achieve carbon neutrality, and the results are shown in Figure 11. Note all scenarios listed in Table 8 were run with a clean generation constraint reaching 97% by 2045 (same as DECAL version of CARB Proposed scenario).

Scenario	Main Levers
High Electrification	• 100% electric sales in buildings by 2045 • 100% electric sales in cars by 2045 • 100% industry electrification where possible (food and petrochemical plants, Industry Other) by 2045 • Partial electrification of trains and planes • Electrolysis for additional hydrogen capacity requirements (likely N/A because hydrogen demand is small)
High Hydrogen	• 60% LDV FCEV sales by 2045 (balance 20% BEV, 20% hybrid) • 70% HDV FCEV sales by 2045 (balance 30% BEV) • 60% H2 fuel switch in industry by 2045 where possible (food and petrochemical plants, Industry Other) • Partial H_2 fuel-switch of train, planes, and boats • Gasification used for additional hydrogen capacity requirements
High Bioenergy	• Increase economy wide RNG blend to 30%, including in the hydrogen and electricity production subsectors • Increase ethanol blend to 15% by 2045 • Increase economy-wide RD blend to 100% by 2045, including in automobiles, trains, boats, etc. • Use 100% renewable jet fuel in planes by 2045 • Maximize in-state RNG production by 2045 • Build out in state renewable diesel capacity • SMRs with RNG used for additional hydrogen capacity requirements (likely N/A because hydrogen demand is small)
High CCS	• 100% CCS adoption by 2045 on cement plants, large food plants, large petrochemical and mineral plants, refinery CHPs, and SRMs • 80% CCS adoption by 2045 on medium-sized food plants, medium-sized petrochemicals and mineral plants, timber drying plants, and crude oil CHPs • 60% CCS adoption rate by 2045 on small food plants and small petrochemical and mineral plants • SMRs with CCS used for additional hydrogen capacity requirements (mostly N/A)

Table 8: Main levers used for each single technology scenario.

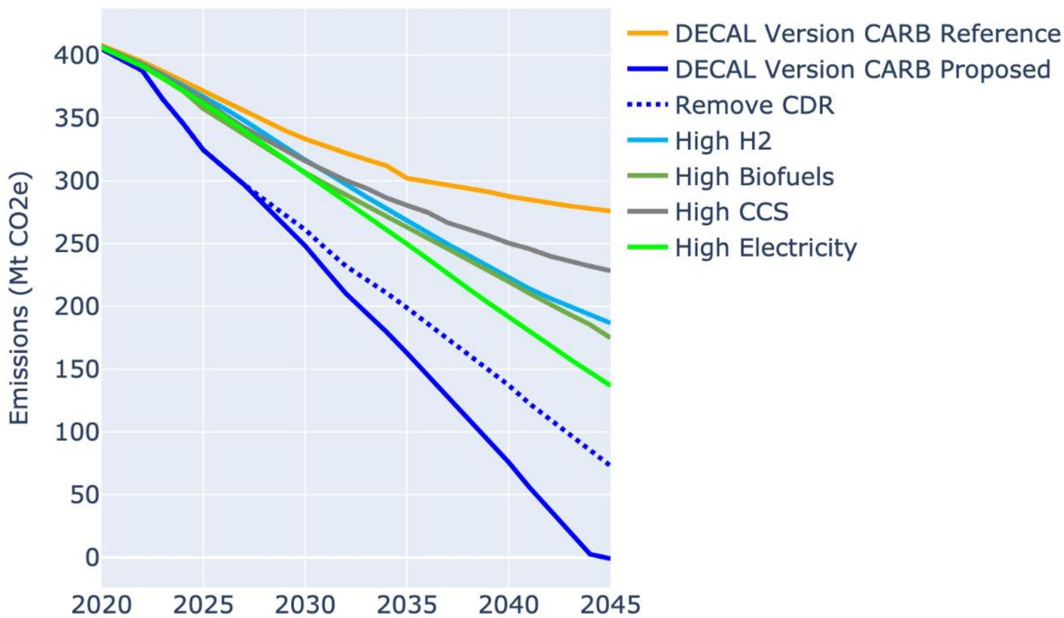


Figure 11: Emissions over time, CARB Reference Case (orange) and Proposed Scenario (solid blue) as estimated by DECAL (same as in Figure 6). Blue dashed line shows impact of removing CDR from the Proposed Scenario. Additional solid lines illustrate the impact from 4 'single technology' or 'single resource' scenarios (high biofuels, high electrification, high CCS and high hydrogen).

Figure 11 shows clearly that a strategy of focusing on a single decarbonization technology will not bring emissions nearly as low as a strategy that blends different decarbonization technologies, such as the CARB Proposed Scenario. Electricity and CCS are notably complementary, in that many emission sources that cannot utilize CCS can often be electrified (for example, buildings and transportation), while many emission sources that cannot be electrified can often utilize CCS (for example, industrial plants like cement, refining, and upstream O&G). Ultimately reaching net-zero emissions will rely on employing a diversified set of technologies and resources.

Conclusion: What is it going to take to reach net-zero by 2045?

All decarbonization technologies are needed

Chapter 5: Policies and Programs that are Key to Achieving CARB's Proposed Scenario

Questions that this section will address:

- *What policies and technologies have the most impact on emissions reductions?*
- *Is there any "low hanging fruit"? How far can those approaches take us?*

The Scoping Plan is a thoughtful, well-researched proposal resulting from the best efforts of

CARB, a global leader in decarbonization policy – as such, it should be seen as an instructive example for decarbonization strategies. Given the close alignment of the CARB Reference Case and Proposed Scenario with those derived with the DECAL model, the DECAL results can be used to garner further insights about policies and programs that will be key to achieving CARB's Proposed Scenario. To do this, DECAL was run with groups of levers 'turned off' one at a time, reverting from the settings in the Proposed Scenario to the settings in the Reference Case. The results of this analysis are shown in Figure 12.

Note that in some cases (e.g. LDV ZEV sales), aggressive mitigation in the Reference Case will reduce the marginal emissions impact of the Proposed Scenario shown in Figure 12. Note also that the cost of the following measures are largely unknown: F-Gases and Trains/Planes/Boats. For these measures, a top-down cost of $250/t is used, though the final abatement costs as they appear in Figure 13 may differ due to resource savings and discounting.

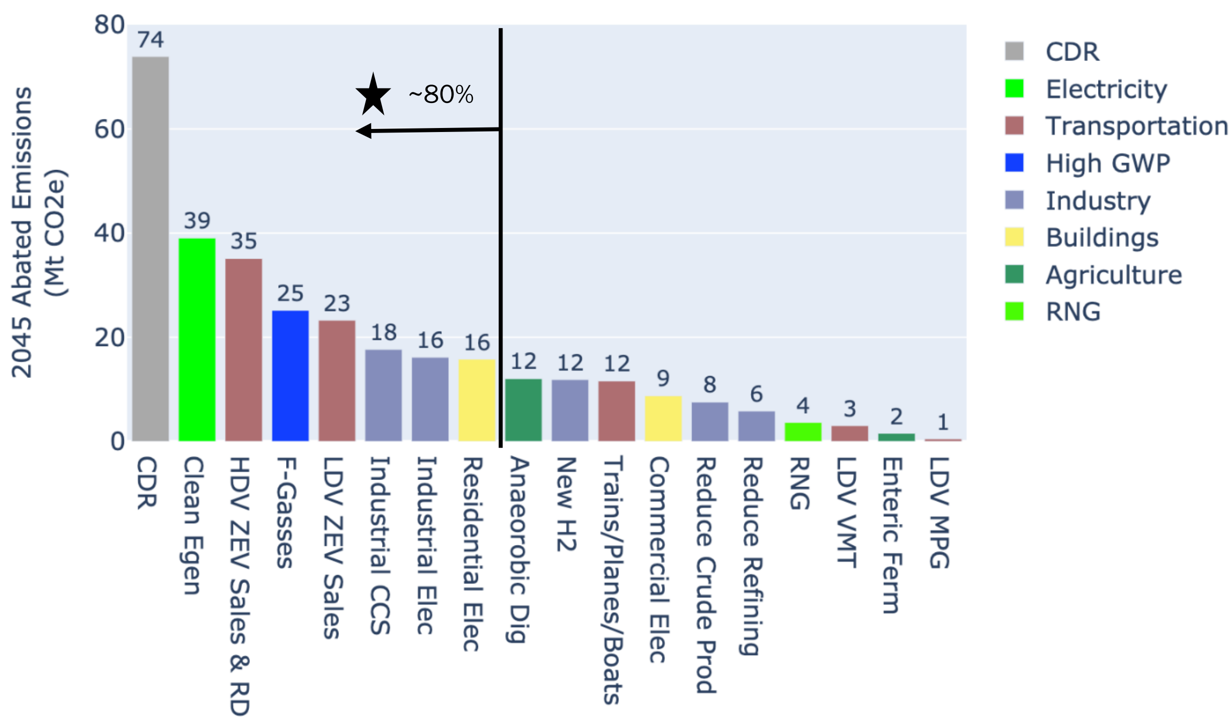


Figure 12: 2045 abated emissions, each bar represents mitigation contribution from a particular measure.

Notably, approximately 80% of 2045 annual emissions can be mitigated with policies and technologies in eight key areas. These eight areas should be seen as high leverage opportunities for the state where policy action and R&D funding would have the largest effect on emissions.

- **Carbon Dioxide Removal:** The Proposed Scenario in the 2022 CARB Scoping Plan relies on 75 Mt of CDR in 2045. CDR is discussed in detail in Chapter 12. Additional innovation and research funding will be needed to find ways to reduce the cost and energy requirements of CDR.

- **Clean Electricity Generation**: As the State decarbonizes, electric load will inevitably grow. The speed and scale of capacity additions required will be unprecedented. Most of the technologies we need are available today, in large part thanks to precipitous cost declines of renewables. However, further cost reductions for Li Ion batteries and/or innovation in clean dispatchable power (example – NGCCS) would make the transition more feasible and affordable. Electrification and impacts on the grid are discussed in detail in Chapter 6.
- **HDV ZEV Sales & Renewable Diesel:** HDVs make up 7% of the on-road vehicle fleet in California and are responsible for 20% of transportation sector emissions and 7.8% of total emissions. The rate at which buyers convert to ZEVs (BEVs or FCEVs) has a major impact on emissions, making it critical to set ambitious HDV BEV sales targets (see Chapter 7). Further innovation is needed to make HDV BEVs available and affordable at scale. RD can be used in tandem with electrification for near term mitigation as well as for reducing emissions from dispersed sources, however the impact of RD may be limited by feedstock availability (see Chapter 11).
- **F-Gases**: Fluorinated gases (F-gases) represent a significant portion of present-day emissions, in large part because they have global warming potentials as high as 1000 – 3000 tCO_2e/t. F-gases are emitted from the building, industrial, and transportation sectors, with the majority of emissions coming from the building sector. As buildings electrify and switch to heat pump technology, it will be essential to develop technologies and policies to effectively mitigate these potential emissions. Responsible EOL F-Gas management is a solution available today, however deep F Gas emissions mitigation will require low-GWP refrigerants (e.g., CO_2, propane) that are currently unaffordable and unavailable at scale. Note that F-gas mitigation is included in CARB's Reference Case, but was incorporated into this exercise to illustrate the importance of the measure. F-gas emissions are discussed in more detail in Chapter 9.
- **LDV ZEV Sales**: LDVs (including passenger cars) make up 93% of the vehicle fleet in California and are responsible for 70% of transportation sector emissions and 28% of total emissions. As is shown in Chapter 7, the rate at which buyers convert to BEVs has a major impact on emissions, making it critical to set ambitious BEV sales targets. In addition, as will be shown in Chapter 13, further cost reductions to BEVs are amongst the highest leverage opportunities available to reduce the overall cost of the transition. Note the following measures are synergistic – LDV ZEV Sales, LDV VMT reduction, and LDV fuel efficiency; as such, when combined, the measures mitigate even greater emissions (50 Mt) than indicated in Figure 12.
- **Industrial CCS**: Industry is California's highest emitting sector by 2045 in CARB's Scoping Plan. Ensuring that there is a process for streamlining CCS project development in this sector will be critical to achieving neutrality in 2045. Note that the DECAL version of the CARB Proposed Scenario results in more emissions abated via CCS than the CARB Proposed Scenario (8 Mt). This is largely because in DECAL, refinery SMR's do not trend down with the phase-out of oil & gas, whereas in CARB's Proposed Scenario they do. Industrial CCS is discussed in more detail in Chapter 8.

- **Industrial Electrification:** Industrial fuel switching is still in its infancy, though this is an active area of R&D. In DECAL, petrochemical & mineral plants and food plants are electrified. In addition, it assumed that Industry Other cannot be decarbonized with CCS due to the dispersed nature of these plants, and so Industry Other is decarbonized via electrification. In general, electrification may be a necessary but expensive option for plants where CCS is logistically challenging.
- **Residential Electrification**: Emissions in the Residential sector are primarily due to the use of natural gas for space and water heating as well as cooking. Emissions abatement in this sector boils down to electrification of natural gas and propane appliances. More aggressive sales targets are needed to reach net-zero. Residential emissions are discussed in more detail in Chapter 10.

It is important to note however, that these eight high-impact areas are not necessarily the cheapest, as shown in the marginal abatement cost curve plot in Figure 13 (the eight that are discussed above are noted with a black star). Measures that cost $100/t or less will only account for about 39% of 2045 emissions mitigation. Even these measures will involve implementation challenges such as permitting, consumer preference, and more. Getting to net-zero will also inevitably require some more costly investments. The overall cost of abatement is $207/t[9].

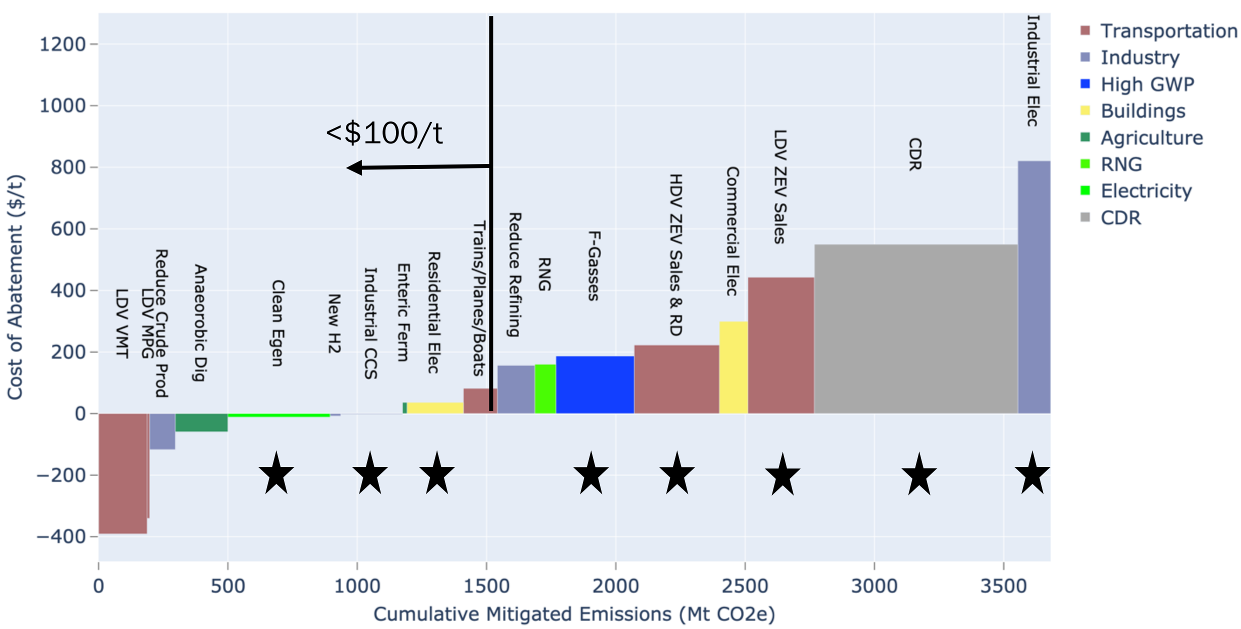


Figure 13: Marginal abatement cost curve (MACC) using the same 18 measures discussed in Figure 12.

Conclusion: What is it going to take to reach net-zero by 2045?

Eight key areas can get us ~80% of the way to net zero, but it will be expensive

[9] The abatement cost is calculated as the average annual emissions reduction divided by the marginal levelized cost, with both emissions and cost relative to the baseline (Decal version of CARB Reference Case).

Chapter 6: Model Insights for the Electricity Sector and the Grid

Questions that this section will address:

- *How much capacity needs to be added to the grid and from what resources?*
- *What is the cost and resource impact of a 100% clean generation constraint in 2045?*
- *How does a 100% renewable grid compare to a grid that maintains firm power resources (e.g., NGCCS)?*
- *What is the impact of shifting loads (e.g., day vs night EV charging)?*

Electrification and grid capacity expansion will be key drivers in meeting California's net-zero goal. To explore the bounds of the electrification space, low, medium, and high electrification scenarios were created. The DECAL version of the CARB Proposed Scenario was used for the medium case. The low electrification scenario was created by choosing non-electric technology options (CCS, biofuels, hydrogen) where possible and appropriate, as well as more efficient electric options (heat pump rather than electric resistance). By comparison, the high electrification scenario was created by choosing electric options where possible and appropriate, as well as less efficient electric options. Further details are shown in Table 9.

Scenario	Main Levers That Changed From CARB Proposed Scenario
Low Electrification	• Diesel used in Commercial Other is substituted with RD • Petrochemical & mineral plants, food plants, and Industry Other are decarbonized with H_2 • 30% LDV FCEV sales by 2045 (balance 40% BEV, 30% hybrid) • 70% HDV FCEV sales by 2045 (balance 30% BEV) • Planes are decarbonized using sustainable aviation fuel and H_2 only; trains are decarbonized using RD • New hydrogen production is satisfied with 50% SMRs with RNG & 50% Gasification with CCS (as opposed to 65% electrolysis and 35% Gasification with CCS)
Medium Electrification	• N/A
High Electrification	• Buildings: use ER heating instead of HPs • Industry: use ER heating instead of HPs • Transport: use BEVs instead of FCEVs, electricity used in trains/planes/boats • New hydrogen production is satisfied with 100% electrolysis

Table 9: Main levers used in each electrification scenario.

Figure 14 illustrates the 2045 load shape in the three cases, showing an average daily profile for each month of the year. The figure illustrates that in all scenarios, grid capacity will need to increase significantly. In fact, these results suggest about a 20-70 GW increase in peak load. Additionally, in all cases, a shift from a summer peaking system (current) to a winter peaking system is observed. This is partially due to electrification of space heating which peaks during the winter months.

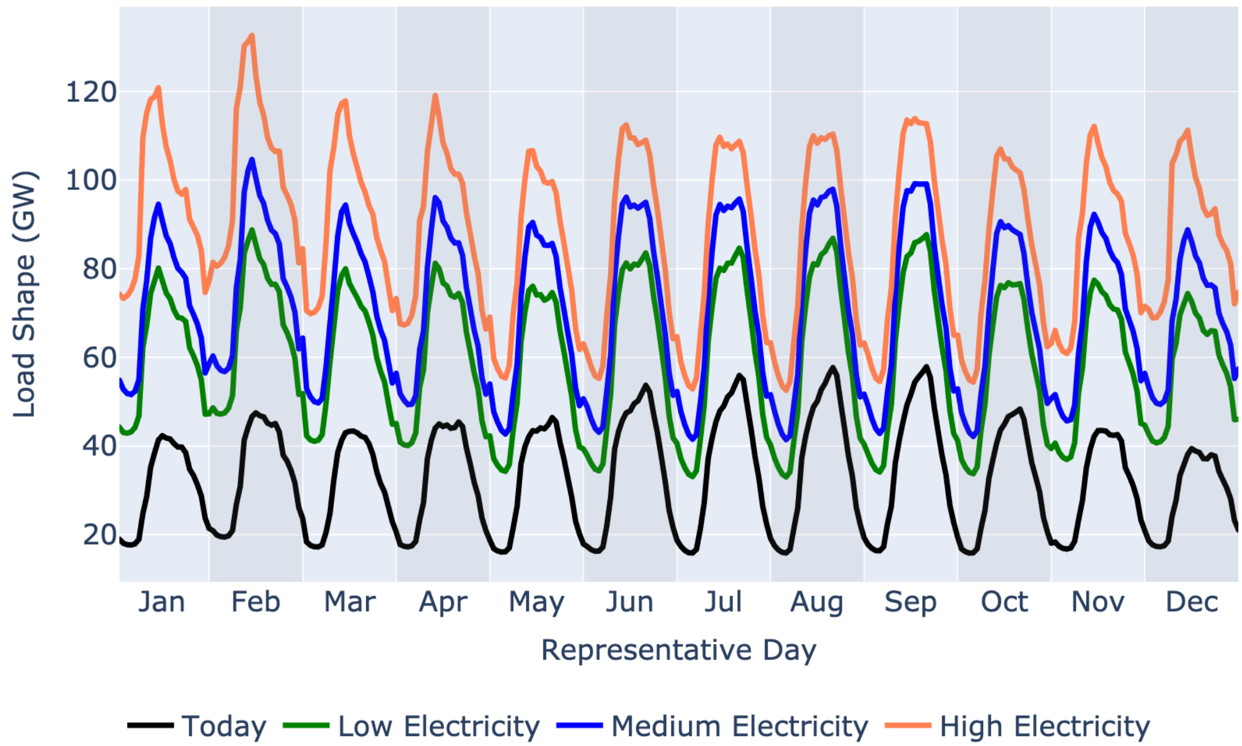


Figure 14: Electric load shape for an average day each month of the year. Current load (black) is compared to the DECAL results for a low, medium, and high electrification scenario.

Due to the intermittency of renewables, there is not a one-for-one relationship between peak load increase and capacity requirements. Figure 15 shows cumulative capacity added in the low, medium, and high electrification scenarios. In total, ~250-450 GW of capacity installation is needed, mainly in the form of solar, wind, Li Ion batteries, and NGCCS. To put this undertaking into perspective, there are currently 80 GW of generation capacity in the state, and only 30 GW have been added in the last 20 years. In other words, decarbonization will require that California increase the size of its grid by about 3 – 6 fold, and build approximately 8-15 times more capacity in the next 20 years than it did in the last 20 years. The orders of magnitude of these results are consistent with the Scoping Plan [37], which adds about 222 GW of electricity resources by 2045[10]. The enormity of these results cannot be overstated – meeting these goals will require infrastructure buildout to be streamlined as well as continued advancements in Li Ion batteries and NGCCS (or other clean dispatchable power). Impact on land-use will also be significant – these scenarios imply 0.6 to 2 million acres of suitable land for commercial solar arrays (assuming 5-10 acres/MW [42]), which equates to 0.5 to 2% of the land area in the state.

[10] Note the discrepancy in CARB results is likely due to 1) CARB utilizing more dispatchable power resources such as hydrogen, and 2) DECAL ramps down dirty electricity imports in the Reference Case and Proposed Scenario so as to fold decarbonized capacity buildout into the optimization framework.

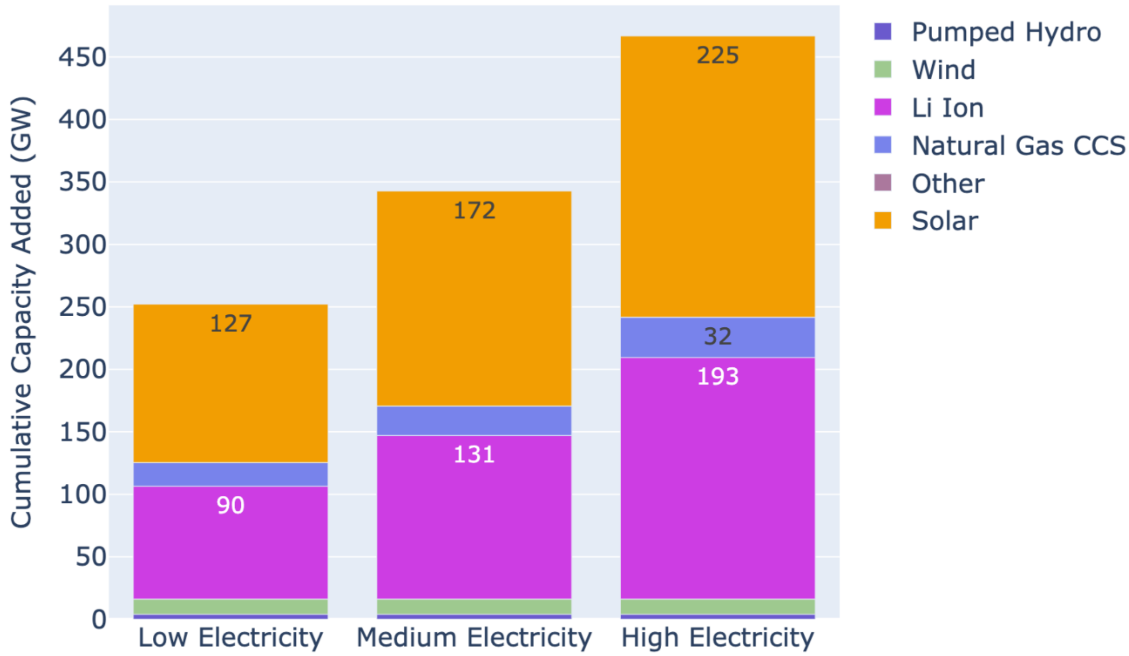


Figure 15: Cumulative capacity added by 2045 in the three electrification scenarios, by resource type. Note that a CGC of 99% was used here.

Conclusion: What is it going to take to reach net-zero by 2045?
Streamlining electric infrastructure capacity expansion

Impacts of Different Clean Generation Constraints

California's RPS program was established in 2002 by SB 1078 with a requirement that 20% of electricity retail sales be sourced from renewable resources by 2017. The program has been modified over the years and finally in 2018, SB 100 increased the RPS to 60% by 2030 and requires all the state's electricity to come from carbon-free resources by 2045 [43]. Using DECAL and the high, medium, and low electrification scenarios discussed previously, it is possible to assess the impacts of different clean generation constraints (CGC) on electricity sector emissions and costs.

To do so, the low, medium, and high electrification scenarios were run with 6 different CGC goals: 80.0%, 90.0%, 95.0%, 97.5%, 99.0%, 100.0%, each goal to be reached by 2045. Results are shown in Figure 16 which shows cumulative capacity additions and 2045 electricity emissions. The figure illustrates that in all three scenarios, moving from a CGC of 99.0% to 100.0% requires dramatically more capacity despite having a small impact on electricity emissions. Stepping out of the modeling exercise - whether in reality the value is 99%, 95%, or something else, the main takeaway is that there is likely a point at the extreme in which further emissions reductions are small but may require excess overbuilding, and as such the state should consider relaxing a policy constraint of 100% carbon-free by 2045.

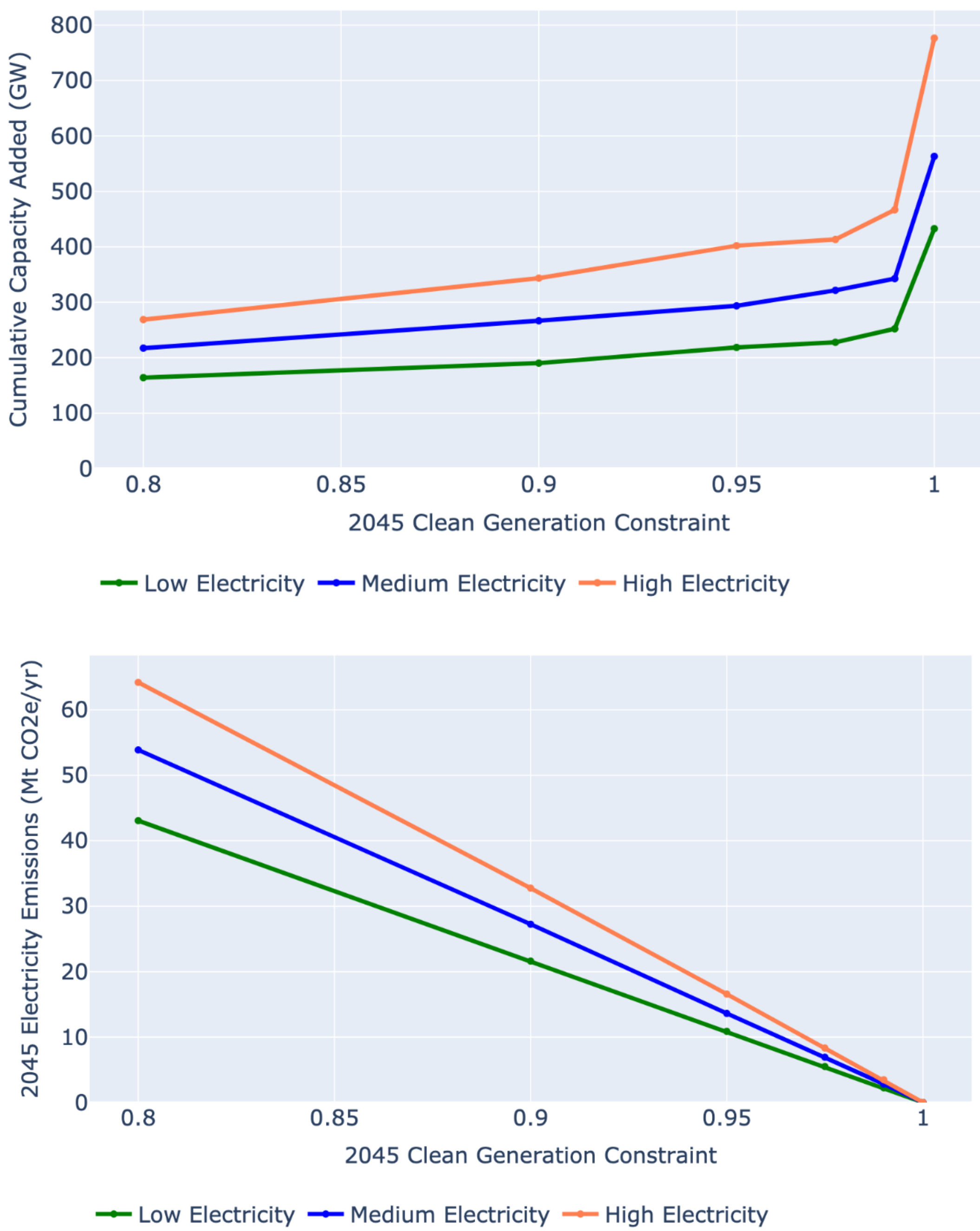


Figure 16: Capacity (top) and emissions (bottom) associated with the three electrification scenarios with a CGC of 80%, 90%, 95%, 97.5%, 99%, and 100% by 2045.

The reason for the dramatic increase in added capacity is explained in Figure 17 and Figure 18, which show annual and cumulative capacity additions in the 99% and 100% CGC medium electrification cases. The figures show that especially in later years, a 100% carbon-free grid cannot install very much NGCCS, which in DECAL is modeled as only 90% clean. To compensate, DECAL must add significantly more solar and Li Ion battery storage. Notably in the 99% CGC case, very little NGCCS is needed to prevent massive overbuilding.

In summary, while a clean grid is required and clearly the first step for decarbonizing California, a 100% clean grid may not be required nor the best use of capital.

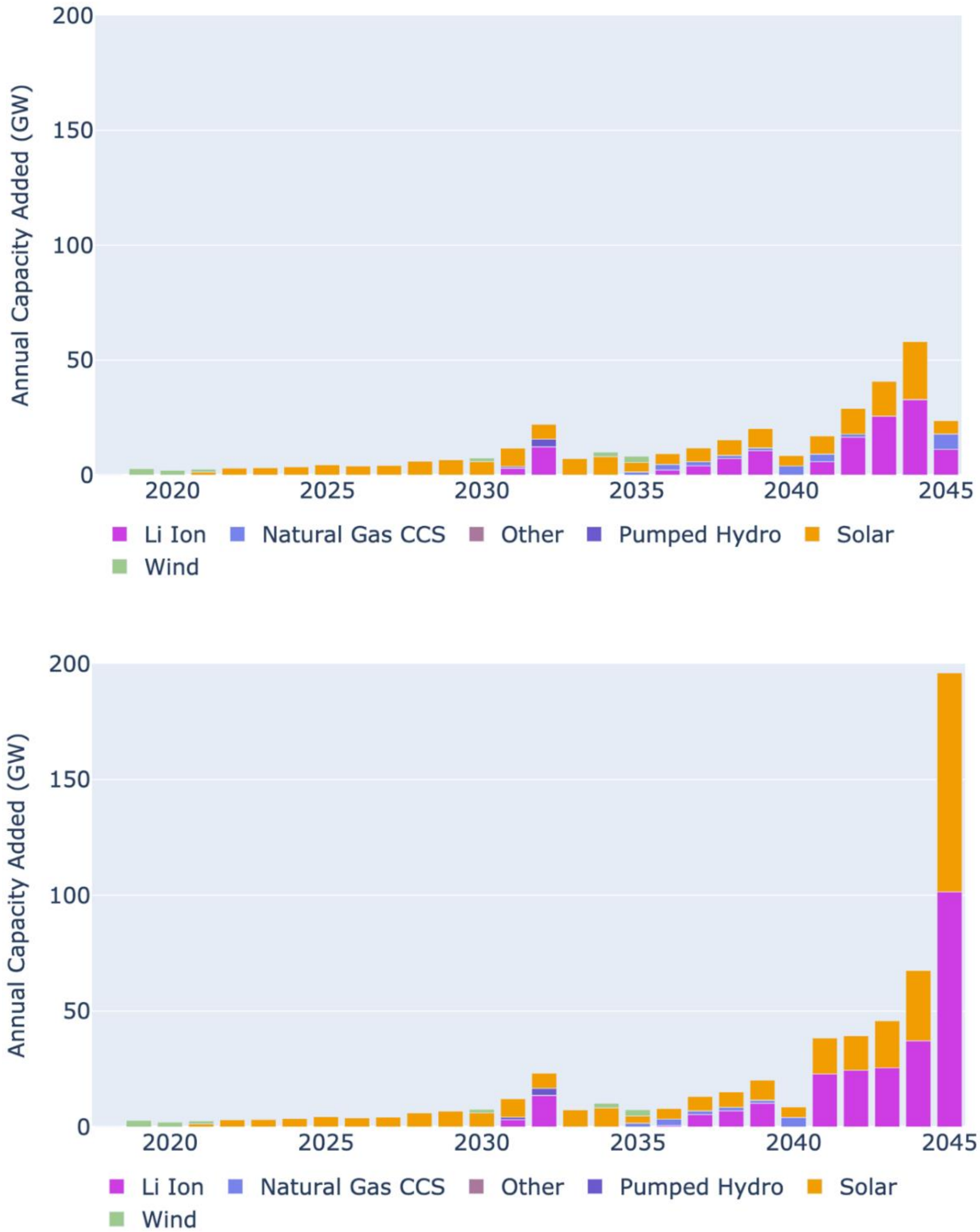


Figure 17: Electric capacity added with a CGC = 99% (top) versus a CGC = 100% (bottom), shown on annual basis. The 100% CGC does not allow for much NGCCS, resulting in a major buildout of solar and Li Ion storage.

Figure 18: Electric capacity added with a CGC = 99% (top) versus a CGC = 100% (bottom), shown on cumulative basis. The 100% CGC does not allow for much NGCCS, resulting in a major buildout of solar and Li Ion storage.

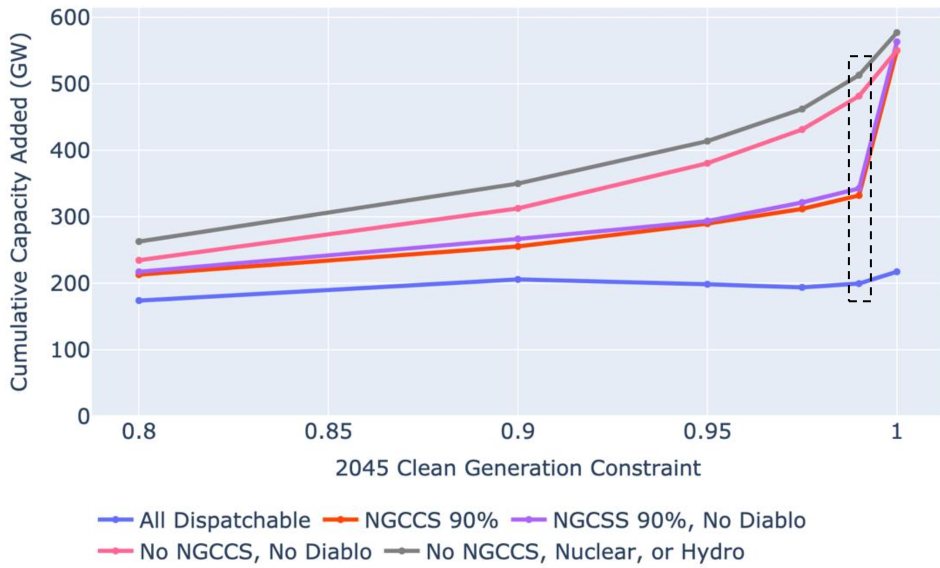
Conclusion: What is it going to take to reach net-zero by 2045?
A very clean grid, but perhaps not 100% clean

Importance of Clean Dispatchable Power

Dispatchable power refers to power plants that can be dispatched at any time and are notably not reliant on weather. DECAL considers the following plants to be dispatchable: nuclear[11], hydropower, geothermal[12]., and NGCCS. To assess the impact of 100% clean baseload power, five scenarios were created in DECAL. The first is the All Dispatchable scenario, which allows for maximum dispatchability, including 100% clean NGCCS (not commercially available). The remaining four scenarios stepwise remove one element of dispatchable power: first NGCCS was made 90% clean (currently available technology), then Diablo Canyon (California's major nuclear site) was removed, then NGCCS was removed entirely, and finally in-state hydropower and remaining in-state nuclear were removed (out-of-state hydropower and nuclear remain). These five scenarios were run with the same set of CGC's described previously (80.0%, 90.0%, 95.0%, 97.5%, 99.0%, and 100.0%, each by 2045).

The results are shown in Figure 19 which shows cumulative capacity additions for all 30 scenarios (five scenarios at six CGC constraints) and the 2045 energy generation for the 99% CGC cases. Figure 19 (top) illustrates that 1) the capture rate of NGCCS has a large impact across all CGCs, 2) Diablo Canyon has a small impact, 3) 90% clean NGGCS has a large impact especially beyond a CGC of 90%, and 4) hydropower has noticeable impact across all CGCs. Interestingly, when comparing the 'NGCCS 90%' scenario to the 'No NGCCS No Diablo' scenario, relatively little hydro and NGCCS generation (Figure 19 bottom) is needed to prevent massive capacity overbuilding (Figure 19 top). Overall, the analysis identifies NGCCS and hydropower as key technologies to reduce capacity expansion. The state should consider committing to dispatchable capacity, for which options include 1) funding NGCCS research and development, 2) streamlining NGCCS installations, and 3) more explicitly embracing NGCCS and hydropower in the RPS regulation.

[11] Note that in reality, due to thermal ramping constraints, nuclear is only partially dispatchable; this is not reflected in DECAL (DECAL should be considered optimistic).
[12] DECAL assumes limited geothermal growth potential.



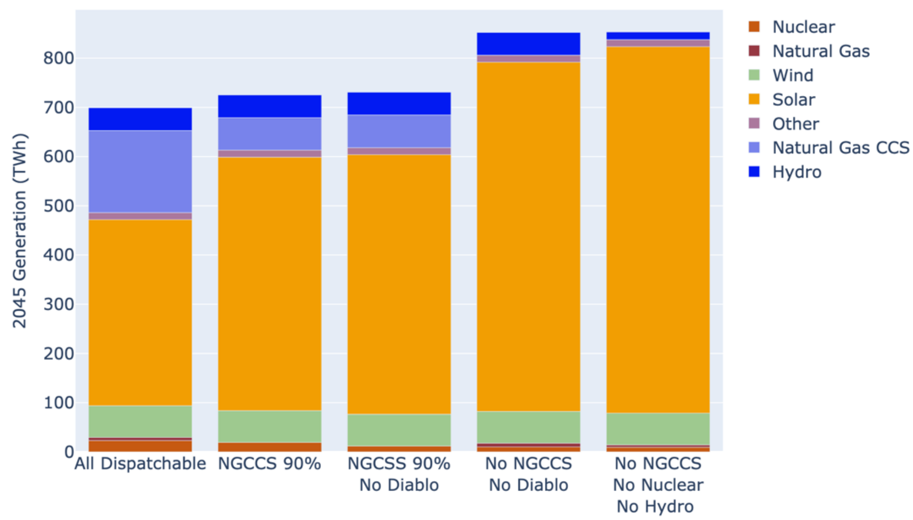


Figure 19: Electric capacity added at several CGCs (top); electric generation by resource for the 99% CGC case (bottom).

Conclusion: What is it going to take to reach net-zero by 2045?

Clean dispatchable power

Impacts of Demand Response

Demand response is a broad area that includes the ability to shift load, oftentimes to the middle of the day to maximally utilize cheap solar resources (without need for storage). As loads are electrified and more stress is put on the grid, research interest in demand response has continued to grow. Many of the benefits of demand response comes from general flexibility, helpful in case of abnormalities or extreme weather events. DECAL is not well set up to test the costs and benefits of demand response, as DECAL models every day of each month identically. That said, DECAL can offer some insight as to the value of demand response from a broad resource management perspective.

Limited demand response capabilities were implemented in DECAL to test the effect of load shifting, specifically for the following technologies: light duty BEV charging, residential electric water heaters, heavy duty BEV charging, and DAC. Shifting load poses a unique set of challenges for each of these technologies, and some would be more challenging (and costly) than others to implement. Below we describe how load shifting is modeled in DECAL for each of these technologies:

- **LDV BEVs:** Shifting light duty vehicle charging would likely imply BEV owners charging their cars during the day while at work, rather during the night while at home. The CEC published some scenarios for residential vs commercial charging as a function of plug-in electric vehicle (PEV) fleet share, as shown in Figure 20. Figure 20 was used in tandem with a stochastic load shape study [44] to inform LDV shifting in DECAL. Specifically, as BEVs are sold into the stock, the fraction of vehicles that charge residentially or commercially changes, as instructed by the curves in Figure 20. A low LDV shifting scenario, for example, would follow curve A, whereas a high LDV shifting scenario would follow curve B. As the fraction of home charging changes over time, the load shape used for BEV charging changes correspondingly, as described in Figure 21.
- **Residential electric water heating:** Shifting water heater load would imply concentrating water heating during the day, despite much of the water being used in the evening. The schema would likely necessitate a larger, more thermally resistant storage tank, and/or some amount of overheating (to be cooled later with a mixing point). Demand response water heaters are not yet commercially available, but they are an active area of research. In DECAL, a new technology was introduced called a demand response water heater (both electric resistance and heat pump), which can be sold into the stock over time just like any other water heater option. The demand response water heater has the same properties (annual energy usage, cost, etc.) as a standard water heater, except the demand response water heater follows a new load shape, demonstrated in Figure 22. Said load shape concentrates heating during the day while simultaneously accounting for the fact that standard water heaters within DECAL require less heat during the summer. These are optimistic assumptions, in that the demand response water heater would likely be more expensive, and it would almost certainly require some backup nighttime load. However, DECAL can still offer some intuition as to the optimistic impact of demand response water heating.
- **HDV BEVs:** As heavy duty BEVs are not yet commercially available, there is much less data and research on BEV load shapes. A lever was created to control the extent to which HDV BEV charging follows a flat versus solar load shape. DECAL proportionally overbuilds chargers in high solar scenarios to ensure peak charging demand can still be met.
- **Direct air capture:** It is theoretically possible to operate DAC plants during the day only, however, doing so while capturing the same amount of carbon would require overbuilding DAC plants. In DECAL, a lever was created to control the extent to which DAC plants follow a flat versus solar load shape. As the shape becomes more solar

focused, DECAL overbuilds DAC to ensure the desired rate of capture can still be achieved.

- **Rest of Industry:** A lever was implemented to control the extent to which industrial loads (cement plants, manufacturing plants, etc.) follow a flat versus solar load shape. Unlike other technologies listed above, it was not possible to account for the impacts overbuilding industrial plants. As such, this option should be strictly treated as a thought exercise, showing the benefits to the grid in an extreme demand response scenario, without showing overbuild costs.

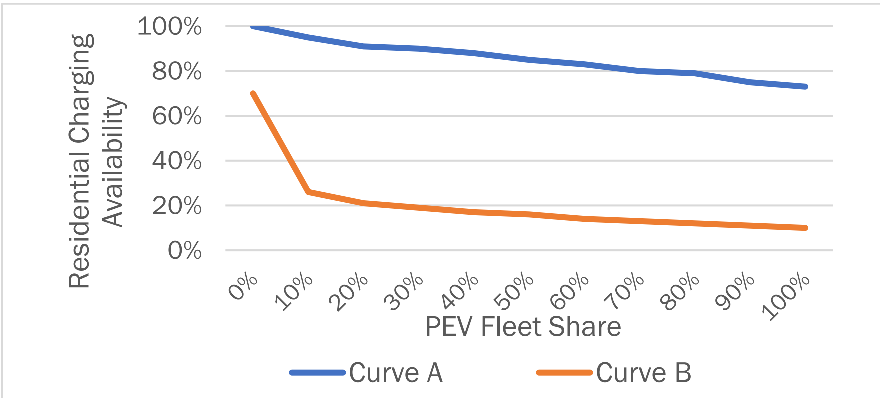


Figure 20:Two scenarios describing the relationship between PEV fleet share and access to home charging. Modified after CEC [45].

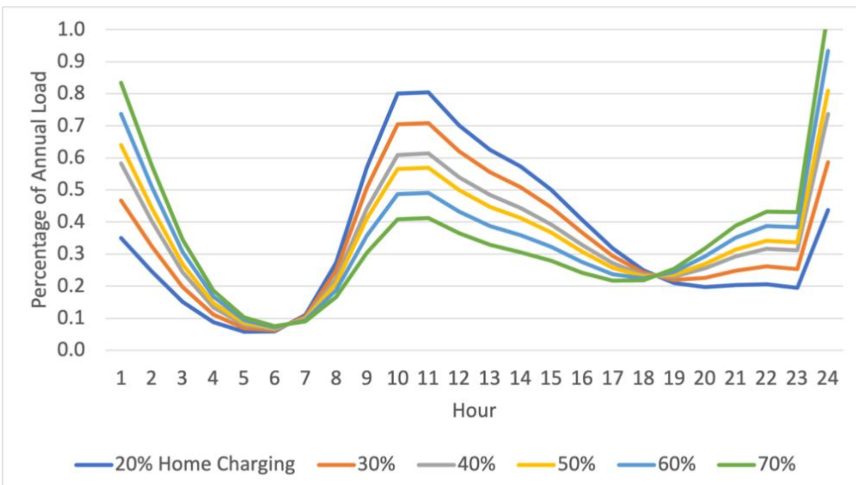


Figure 21: LDV charging load shapes as a function of home charging, made in collaboration with Powell et al [44].

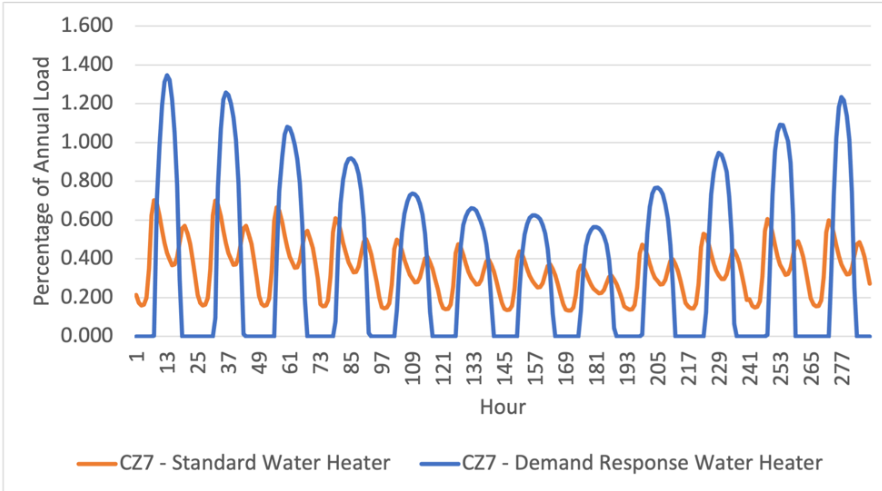


Figure 22: Standard water heater load shape compared to demand response water heater load shape, demonstrated for CZ7 (Los Angeles area).

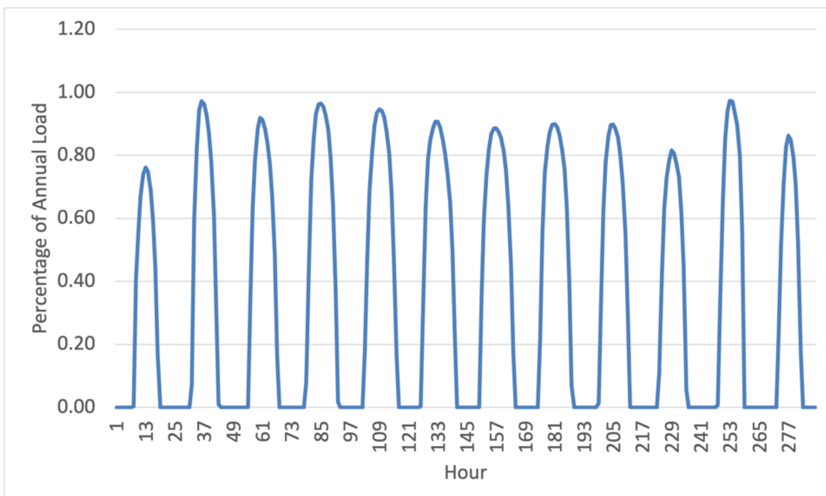


Figure 23: Solar load shape, constructed from the solar availability shape [24].

To test the impacts of demand response, six scenarios were implemented in DECAL, as described in Table 10. The scenarios build off of the DECAL Version of CARB Proposed Scenario with a 99% CGC. Demand response technologies are introduced sequentially; the most "shiftable" loads are added first, as in, the loads in which there is greater certainty that shifting would even be possible.

Scenario	Main Levers That Changed From CARB Proposed Scenario
No Shift	• Clean generation constraint set to 99% • LDV charging set to follow Curve A (Figure 20)
Shift LDVs	• In addition to the prior changes, LDV charging set to follow Curve B (Figure 20)

Shift WHs	• In addition to the prior changes, demand response heat pump water heaters are utilized instead of standard heat pump water heaters
Shift HDVs	• In addition to the prior changes, HDV charging reaches 100% solar load shape by 2045, with interpolation used in-between.
Shift CDR	• In addition to the prior changes, CDR reaches 100% solar load shape by 2045, with interpolation used in-between.
Shift Industry	• In addition to the prior changes, industry reaches a 100% solar load shape by 2045, with interpolation used in-between.

Table 10: Main levers used in each demand response scenario.

Figure 24 shows the impact to system-wide load shape and demonstrates that aggressive demand response measures are needed to substantially reduce nighttime usage. Figure 25 shows the impact on electric capacity additions. As expected, DECAL installs less Li Ion storage in high demand response scenarios, but even in the most aggressive demand response scenarios, Li Ion storage is still needed in a significant way. Finally, Figure 26 shows the impact to abatement cost – by in large, cost savings from lower storage are small, because Li Ion storage is a small driver of overall system-wide costs. By comparison, overbuilding CDR (DAC in this case) is exorbitantly expensive.

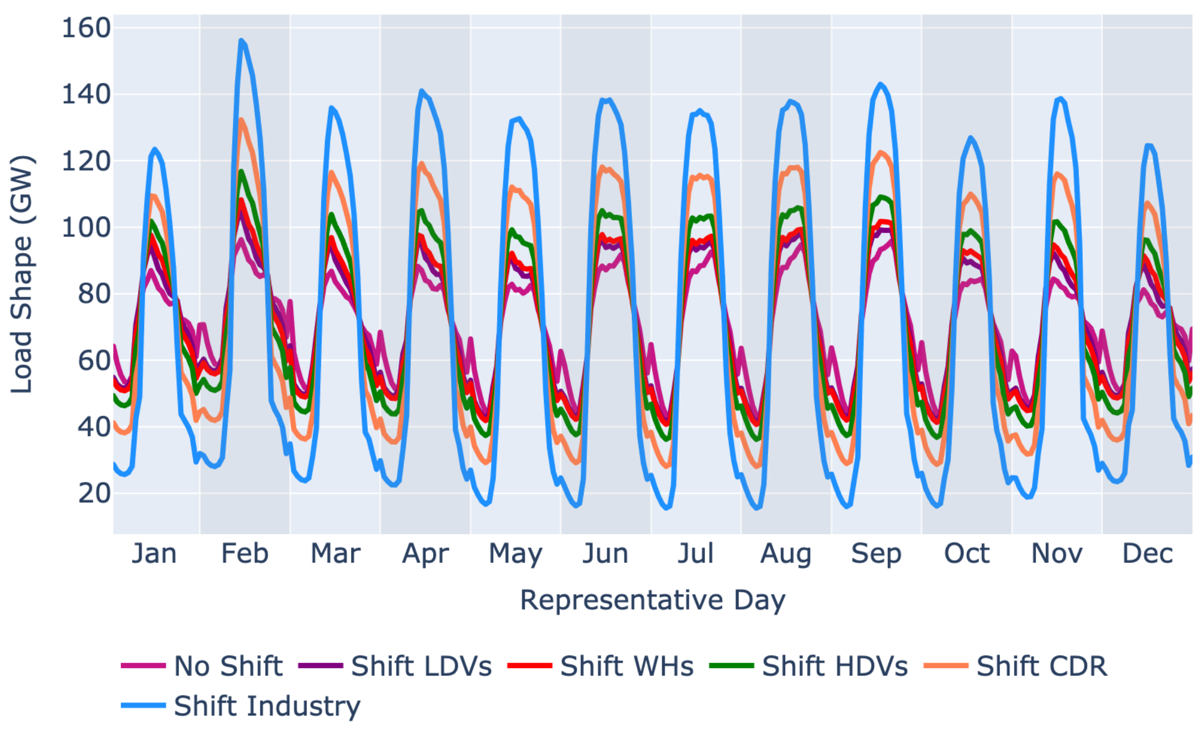


Figure 24: Load shapes, demand response analysis.

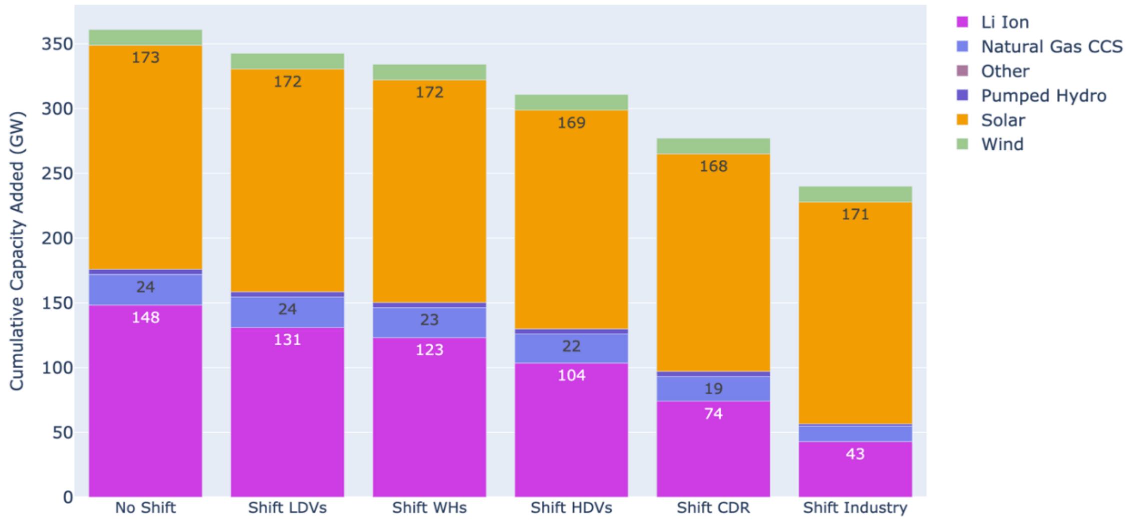


Figure 25: Cumulative electric capacity added, demand response analysis.

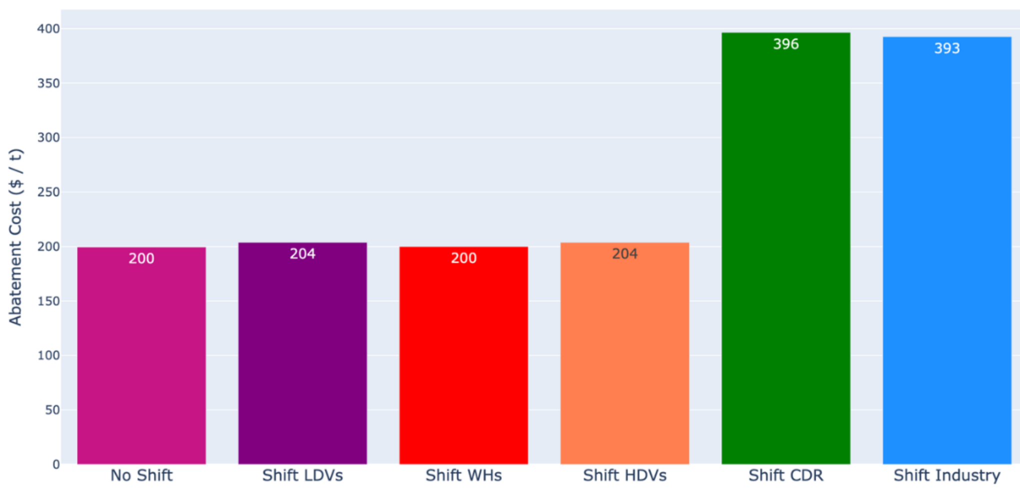


Figure 26: Abatement cost, demand response analysis.

There is much uncertainty related to the feasibility and cost of demand response. However, from the simple analysis here, we can conclude that demand response can be helpful to reduce storage capacity additions, but that expensive overbuilding of infrastructure (e.g., CDR) is likely not worthwhile. Furthermore, significant storage will inevitably be needed even in the most aggressive demand response scenarios. It is worth emphasizing, however, that much of the value of demand response is in grid flexibility (the ability to manage the volatility in the supply and demand of power at multiple timescales), and those effects are not captured here.

Conclusion: What is it going to take to reach net-zero by 2045?

Energy storage

Chapter 7: Model Insights for the Transportation Sector (and Fuels)

Questions that this section will address:

- *What is the impact of overshooting goals outlined in the Clean Cars II regulation and the Advanced Clean Truck program?*
- *How do costs and emissions of different vehicle fuel types (BEV, FCEV) compare?*

The Advanced Clean Cars II Regulation requires 100% of new passenger car and light-duty truck sales to be zero-emission by 2035 [4], with a ramp of increasing ZEV penetration before then as shown in Figure 27.

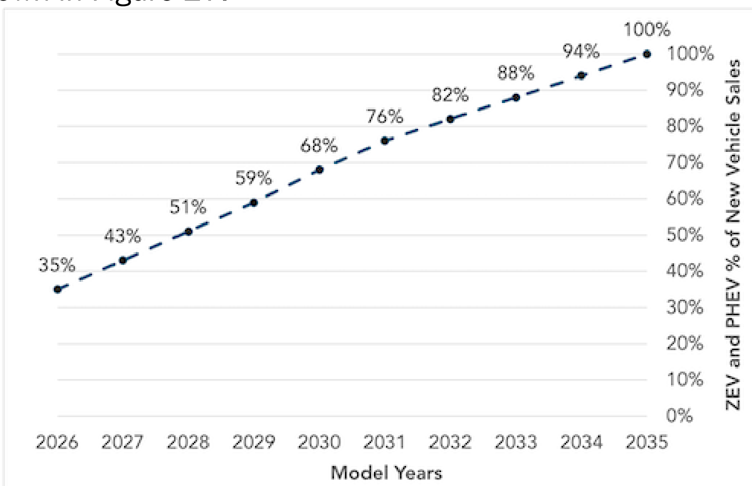


Figure 27: Percent of ZEV sales required by Advance Clean Cars II by model year [4].

Similarly, the Advanced Clean Truck Program requires all new medium- and heavy-duty vehicles sold in California to be zero-emission by 2045 [5]. While there is currently very low ZEV penetration in California, recent LDV adoption rates have increased, with BEVs making up 25% of new car sales in the state through the end of Q2, 2023 [46].

To assess the impact of a faster (earlier) and slower (later) 100% ZEV adoption rates of new LDVs and HDVs, four scenarios were set up in DECAL, reaching the 100% ZEV sales goal in 2025, 2035, 2045, and 2055 respectively (with linear interpolation between). Electricity and hydrogen production were also simultaneously cleaned[13]. Note that this analysis does not take into account whether infrastructure will be ready for an earlier transition to ZEVs, a concern raised in a recent report by the Energy Institute at UC Berkeley [47].

[13] CGC of 97% by 2045, existing SMRs receive CCS retrofits, new hydrogen plants consist of a mixture of Gasification with CCS (35%) and electrolysis (65%) (same assumptions used in Decal version of the CARB Proposed Scenario).

The results are shown in Figure 28 and Figure 29, which show emissions over time and an annual emissions snapshot by subsector.

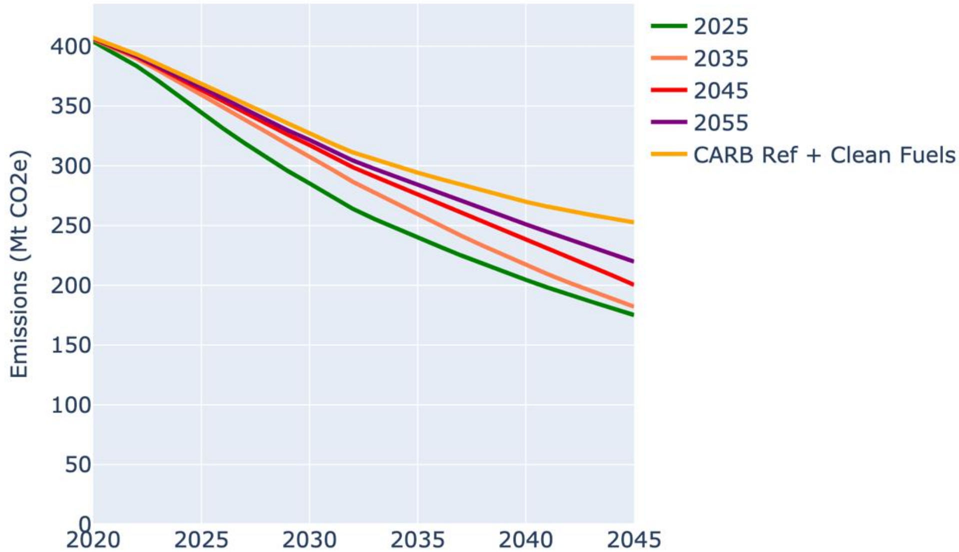


Figure 28: Emissions over time, varying the date in which 100% ZEV sales is reached.

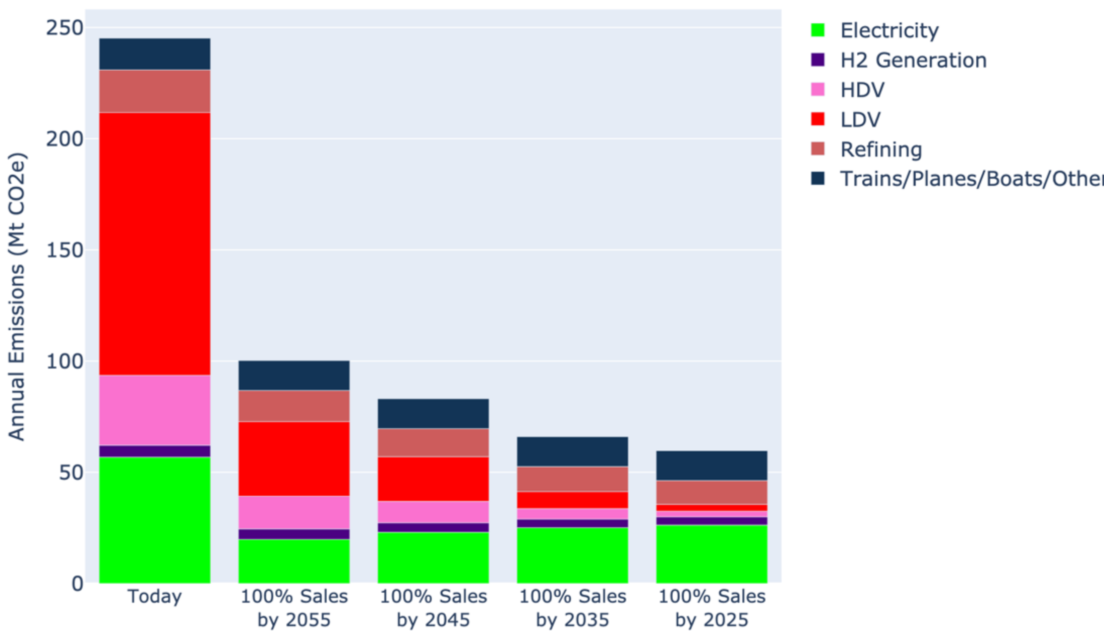


Figure 29: Annual emissions, varying the date in which 100% ZEV sales is reached.

The 2055 scenario should be seen as an overshoot, projecting emissions if we are late to reach ZEV sales goals by 10-20 years. Interestingly, even in this case, LDV and HDV emissions are both cut by more than half by 2045. That being said, if the state is steadfast about the net-zero by 2045 goal, any LDV and HDV emissions left over by 2045 would need to be handled via CDR. At the other end of the spectrum, the 2025 scenario should be seen as a thought exercise, projecting emissions if the state could move faster than realistically possible. In this case, LDV and HDV emissions reach near zero, but not quite zero. In a sense, the question is not *whether* CDR will be needed to bring transport emissions to zero, rather the question is *how much* CDR will be needed. Overall, the analysis simultaneously says the following: 1) gradual progress towards ambitious ZEV sales targets is an effective way to reduce economy-wide emissions, even if target dates are not met, 2) due to stock and flow dynamics, every year we overshoot said targets will inevitably lead to greater CDR requirements, assuming net-zero by 2045 is a binding constraint.

It is important to mention that adoption rate also has an impact on cumulative emissions, which in the end determines California's contribution to warming. As can be seen in Figure 30, the 2055 overshoot scenario results in 509 Mt less mitigation compared to the 2035 scenario (which is similar to the Proposed Scenario), whereas the 2025 scenario results in 380 Mt more. For reference, the DECAL Version of the CARB Proposed Scenario mitigates 3260 Mt cumulatively, and thus the 2055 and 2025 scenario respectively have about a -16% to +12% impact on cumulative emissions savings. This represents one of the larger swings in abatement seen throughout the analyses.

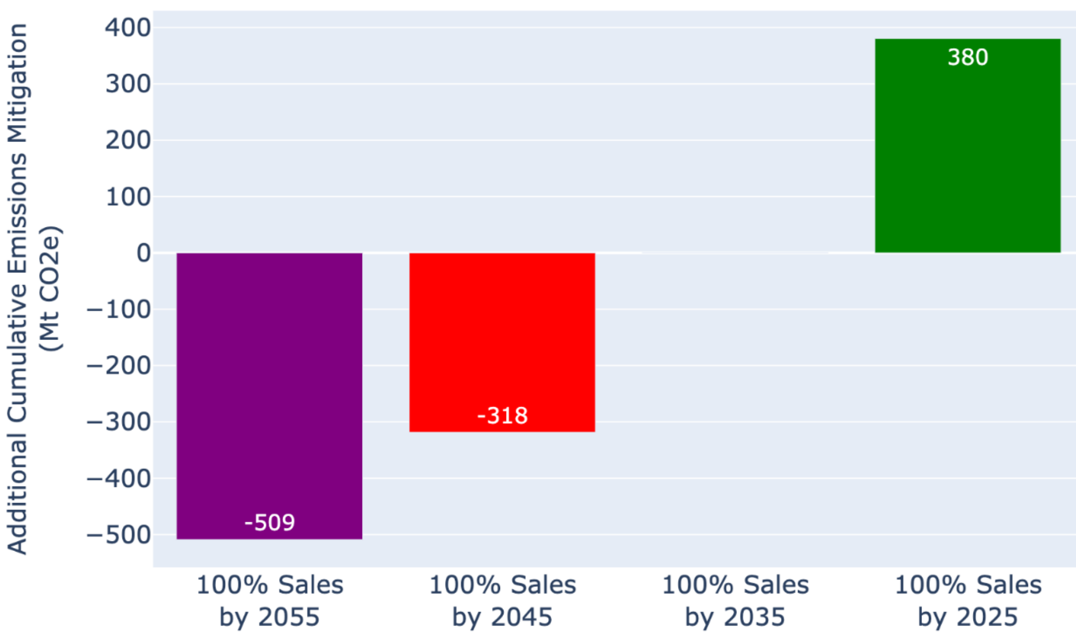


Figure 30: Marginal cumulative emissions, varying the date in which 100% ZEV sales is reached.

Conclusion: What is it going to take to reach net-zero by 2045?
Steady progress towards ambitious ZEV sales targets

BEVs versus FCEVs

While BEVs are currently the dominant ZEV type vehicle for LDVs, FCEVs are very slowly gaining market share. As of today, there are 63 light-duty retail hydrogen refueling stations in California with another 30 planned. Additionally, there are 6 heavy-duty refueling stations with another 4 planned [48]. These plans demonstrate California's commitment to FCEVs. Using DECAL, it is possible to test out scenarios to compare abatement costs associated with BEVs and FCEVs for both light and heavy-duty vehicles.

For both LDVs and HDVs, a low FCEV/high BEV scenario was compared to a high FCEV/low BEV scenario. The low FCEV/high BEV scenarios assume that 80% of clean vehicles sold into the stock are electric and the remainder (20%) are hydrogen powered. The high FCEV/low BEV scenario assumes the opposite, that 80% of clean vehicles sold into the stock are hydrogen powered, and the remainder (20%) are electric. Results are shown in Figure 31 and Figure 32, which respectively show the cost of abatement of each scenario, and the cost breakdown by subsector.

Figure 31 demonstrates that for both LDVs and HDVs, BEVs are more cost-effective option than FCEVs. Interestingly, Figure 31 also shows that HDVs are a "cheaper" problem than LDVs, even on a $/t basis. This is likely because heavy duty vehicles produce more emissions than light duty vehicles on a per vehicle basis; or in other words, fewer heavy duty ZEVs are needed to mitigate the same amount of CO_2. Figure 32 shows that the biggest drivers of cost/benefits are 1) the vehicles themselves, 2) hydrogen distribution & storage (D&S), and 3) resource savings from oil products. Notably, electricity and hydrogen production are not significant drivers of cost, nor are BEV chargers or FCEV refueling stations. Overall, the analysis tells us that as of today, BEVs are economically favorable, and that for hydrogen to become competitive, further cost reductions to FCEV vehicles and hydrogen D&S will be needed.

It should be noted that Figure 31 and Figure 32 only capture cost-differences from the point of view of the state. As such, some externalities, including payload, reliability and refueling time are not captured in this analysis. These externalities are particularly important for HDVs and could impact consumer preferences. Ultimately, businesses will need to weigh differences in reliability, payload, fuel-time, and cost. In addition, note that in Figure 31 and Figure 32, federal incentives are included in the capital costs; for example, the Clean Vehicle Credit is incorporated into LDV 'Transportation' bars, Commercial Clean Vehicle Credit is incorporated into the HDV 'Transportation' bars, and the Alternative Fuel Refueling Property Credit is incorporated into the 'Chargers/Refueling' bars.

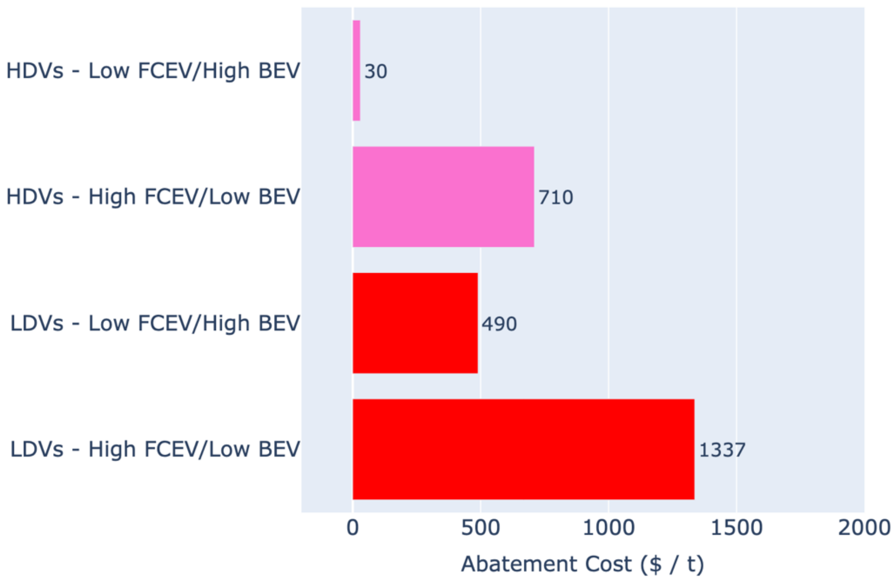


Figure 31: Abatement cost, high BEV versus FCEV for both HDVs and LDVs.

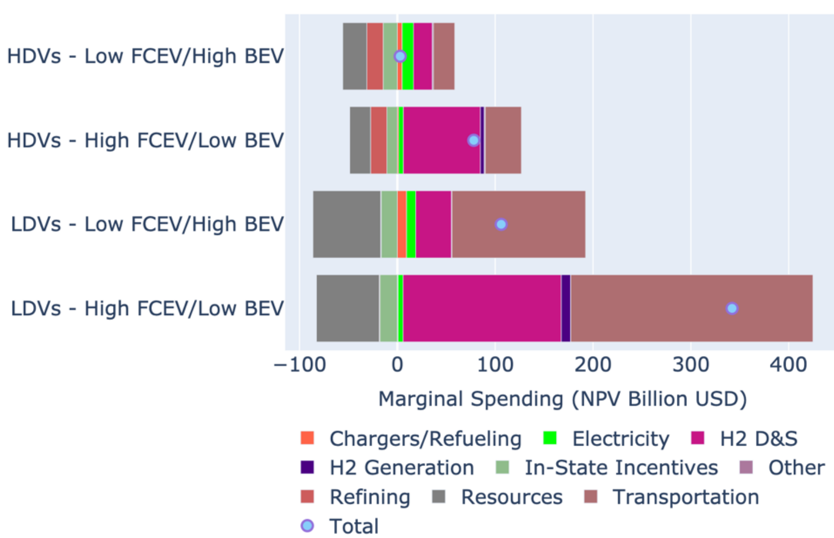


Figure 32: Cost by subsector, high BEV versus FCEV for both HDVs and LDVs. Note that the net cost (blue dot) is the right side minus the left side.

Conclusion: What is it going to take to reach net-zero by 2045?

BEVs

Chapter 8: Model Insights for The Industrial Sector

Questions that this section will address:

- *Which decarbonization technology is preferable for the industrial sector?*
- *What is the impact of incentives on CCS technoeconomics?*

Industry is California's highest remaining emitting sector by 2045 in CARB's Scoping Plan, in large part because the industrial sector contains some of the hardest to abate emissions [49]. In DECAL, industrial decarbonization options vary by subsector, but typically include either CCS, electrification (via electric resistance and/or heat pumps), or fuel switching to hydrogen. To test the efficacy of these options, one technology was deployed at a time in each industrial subsector (as applicable). The results are shown in Figure 33 which shows 2045 mitigated emissions and the cost of abatement.

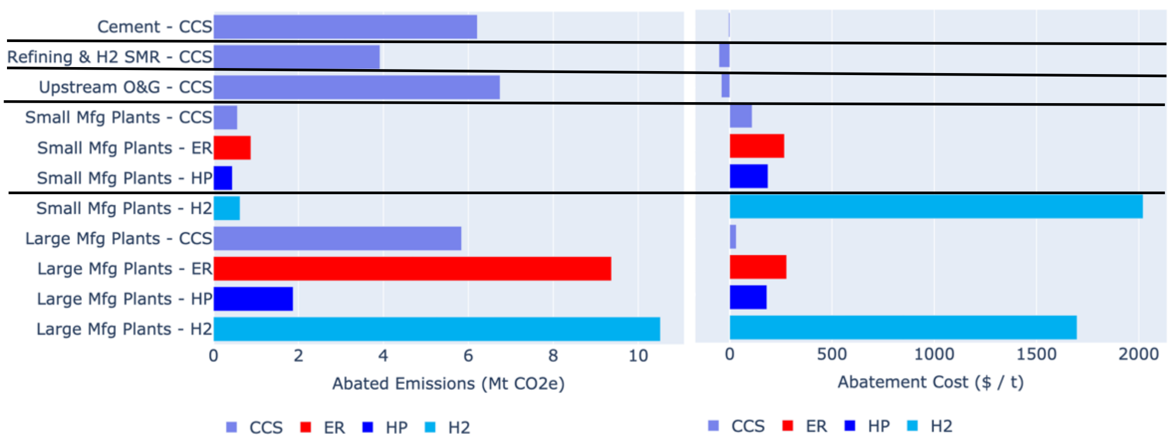


Figure 33: 2045 abated emissions and abatement costs for technologies in the industrial sector.

As can be seen in Figure 33 (left), CCS is the only modeled decarbonization option for the cement and upstream O&G subsectors. Due to high-temperature heating requirements, these subsectors are especially difficult to electrify, though this is an ongoing area of research with promising progress being made [22]. In the manufacturing subsector, abatement potential is a function of penetration potential. Specifically, it is assumed that 1) all manufacturing (petrochemical, mineral, food) plants can switch to ER and hydrogen, 2) deep deployment of CCS is unlikely because manufacturing plants are dispersed, and 3) food plants can switch to heat pumps, but petrochemical and mineral plants cannot (due to temperature constraints). Figure 33 (right) shows that CCS is a cost-effective option for all subsectors, and that hydrogen is much more expensive. Overall, Figure 33 shows that CCS has reasonable abatement potential while being more affordable, making it a less costly choice for the industrial sector under the assumptions made here.

Incentives, particularly 45Q and LCFS, play a key role in the cost effectiveness of CCS. The impact of these incentives is shown in Figure 34, which compares the cost of abatement under three scenarios: 1) standard incentive assumptions (used to produce Figure 27), 2) extending 45Q applicability from 2032 to 2045, and 3) turning off 45Q and LCFS entirely. In Figure 33, CCS penetration rates were set equal to those in the DECAL Version CARB Proposed Scenario, as those rates are reasonable guideposts as to how fast a particular subsector could move under aggressive decarbonization assumptions[14]. In some cases, such as refineries/SMRs, all CCS plants are installed prior to 2032, obviating the extension scenario. In other cases, such as upstream O&G, some CCS plants are installed after 2032, making the impact of a 45Q extension more material. In reality, penetration rates are highly uncertain, and the 45Q extension scenario is presented as a way to handle that uncertainty.

'Standard' and/or 'extended' scenarios can be compared to the 'off' scenarios to demonstrate the impact of 45Q and LCFS. It should be noted that LCFS only applies to subsectors that develop transportation fuels (refining/H2 SMRs and upstream O&G). In these subsectors, 45Q and LCFS can reduce the cost of abatement by over $100/t, shifting CCS from a net-cost to a net-benefit. Cement and large manufacturing plants only apply for 45Q, but still the incentive makes CCS much more attractive. Small manufacturing plants are assumed not to qualify for 45Q's emission thresholds, making this the most expensive subsector to implement CCS.

Overall, incentives such as 45Q and LCFS play a key role in enabling CCS, which is a promising option in a difficult-to-abate sector. In addition, there may be some rationale for extending the 45Q incentive to give more time to subsectors that may not be able to move as quickly.

[14] Note that the DECAL Version CARB Proposed Scenario does not use CCS in all industrial subsectors. However, for this analysis, CCS is deployed at the same rate and penetration as the alternative technology (e.g., electric resistance heating) is deployed in DECAL Version CARB Proposed Scenario.

Figure 34: Abatement cost of CCS with and without incentives.

Conclusion: What is it going to take to reach net-zero by 2045?

CCS and related incentives

Chapter 9: F-gas Mitigation

Questions that this section will address:

- *What is the impact of F-gases?*
- *What is the effect of EOL versus annual F-gas policies?*

F-gas emissions predominantly come from refrigerant leaks. Refrigerants are some of the most potent global warmers, with GWPs often as high as 2000 tCO_2e/t. Today, refrigerants are mainly used in air conditioners and refrigerators. However, heat pumps – which are likely to be an important electrification option in the buildings sector – also use refrigerants. As the economy turns to heat pumps to satisfy space and water heating needs, it will be essential to develop technologies and policies to effectively mitigate F-gas emissions.

Refrigerants can leak during unit operation and when the unit is retired. In fact, CARB's High GWP Emissions Inventory study [50] suggests that EOL leak rates can be quite high for residential technologies, implying that technicians often vent refrigerants during the retirement process. The assumed annual and EOL leak rates for California's 5 largest F-Gas emitters are shown in Table 11. Collectively the 5 technologies shown in Table 11 produced ~80% of the California economy's F-gas emissions in 2015 [50].

Technology	Contribution	Annual Leak Rate	EOL Leak Rate
Residential Central AC	32%	10%	80%
Commercial Central AC (small sized)	22%	10%	56%
Commercial Refrigeration (central, medium sized)	14%	18%	20%
Commercial Refrigeration (unitary, small sized)	7%	15%	34%
Commercial Refrigeration (unitary, medium sized)	7%	15%	20%

Table 11: Annual and EOL leak rates from CARB [50].

Efforts to produce air conditioners, refrigerators, and heat pumps that use low GWP refrigerants at scale are currently ongoing. Suitable gases may include CO_2 and propane, though the physical properties of these gases make the refrigeration process more difficult and expensive. SB 1013 established the Fluorinated Gases Emission Reduction Incentive Program which promotes *voluntary* adoption of low-GWP refrigerant technologies [18]. In addition, the AIM Act directs the EPA to phase down the production and consumption of HFCs in the US by 85 percent over the next 15 years [19]. For these reasons, low GWP refrigerants are assumed to be available in CARB's Reference Case, and thus by default in many of the scenarios used in the Scoping Plan. Given the current availability of low GWP refrigerants, it is important to examine CARB's assumptions surrounding F-gases and assess risk.

To do so, the DECAL version of the CARB Proposed scenario was run with four modifications: 1) no F-Gas measures are implemented, 2) EOL leak rates are linearly reduced to zero by 2045, 3) low GWP refrigerants are implemented in the same manner as in the CARB Reference Case and Proposed Scenario, and 4) both measures (reduce EOL leak rate and adopt low GWP refrigerant) are implemented. Results are shown in Figure 35, which shows F-gas emissions over time for the four scenarios.

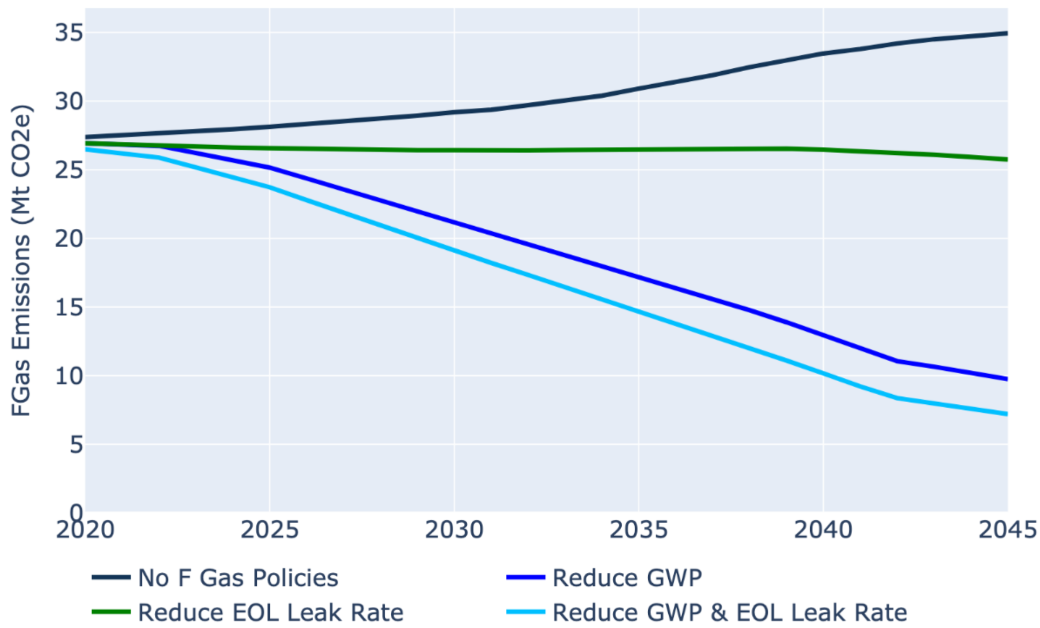


Figure 35: Emissions over time in several F-gas mitigation scenarios.

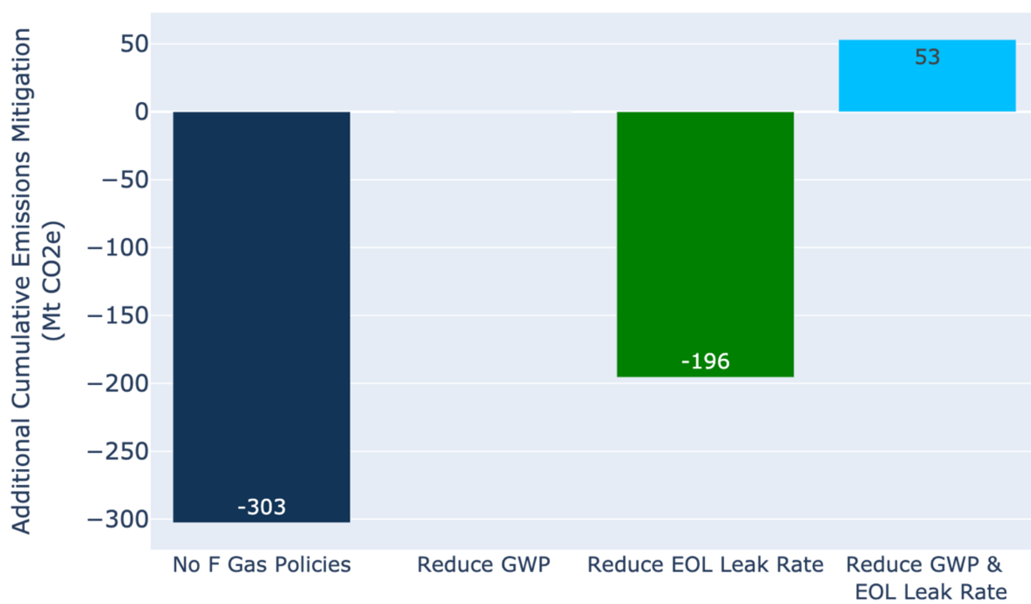


Figure 36: Marginal cumulative emissions in several F-gas mitigation scenarios.

The black line illustrates the potential F-gas emissions if no mitigation actions are taken and shows a potential net increase in F-gas emissions over time due to heat pump installations. The green line shows that just by reducing EOL leak rates – a lever that is readily available in the near term – the state can keep F-Gas emissions relatively constant despite installing millions of heat pumps. However, deep reductions will ultimately require low GWP refrigerants, as shown in the blue lines. On a cumulative emissions basis, the black line reduces emission savings by about 300 Mt compared to the Reduce GWP scenario (same as DECAL Version of the CARB Proposed Scenario), whereas the light blue line increases savings by about 50 Mt, as illustrated in Figure 36. Given that the DECAL Version of the CARB Proposed Scenario mitigates 3260 Mt of emissions over the whole modeling period, F-Gas measures can swing cumulative emission savings by -9% to +2%.

Overall, F-Gas emissions are a significant portion of present-day emissions and are particularly important to address given anticipated heat pump installations. Responsible EOL management is an available strategy for managing F-Gas emissions, but continued development of low GWP refrigerants will be needed to drive this sector to near net-zero.

Conclusion: What is it going to take to reach net-zero by 2045?
Low GWP refrigerants

Chapter 10: Model Insights for The Buildings Sector

Questions that this section will address:

- *What is the effect of changing the rate of electrification in the buildings sector?*
- *What are the costs, emissions, and resource implications of using heat pump versus electric resistance heating?*

The primary method for decarbonizing the buildings sector (residential and commercial) is electrification of gas appliances, mainly space and water heating and to a lesser extent stoves, ovens, and clothes dryers. Current building electrification policies are generally aimed at new homes and large retrofits only. CARB is in the process of defining zero-emissions standards for new sales of gas heaters, furnaces, and water heaters, with a likely implementation date of 2030. In addition, there is growing momentum at the local level to decarbonize buildings.

To assess the impact of a faster (earlier) and slower (later) 100% electric appliance adoption, four scenarios were set up in DECAL, reaching a 100% electric appliance sales goal by 2025, 2035, 2045, and 2055 (with linear interpolation between). A fifth scenario was added to reflect current policies aimed at new homes only. Electricity and hydrogen production were also simultaneously cleaned[15]. The results are shown in Figure 37 and Figure 38, which respectively show emissions over time and an annual emissions snapshot by subsector.

Figure 37 and Figure 38 demonstrate that existing policies aimed at new homes only will not have much impact on building emissions; this is because most California homes that will exist by 2045 already exist today [21]. The 2055 overshoot scenario still results in significant progress, but any leftover 2045 building emissions would need to be handled via

[15] CGC of 97% by 2045, existing SMRs receive CCS retrofits, new hydrogen plants consist of a mixture of Gasification with CCS (35%) and electrolysis (65%) (same assumptions used in CARB Proposed Scenario).

CDR. At the other end of the spectrum, 100% clean sales by 2025 brings the sector to near zero, but not quite zero. The conclusions here are the same as in Chapter 7 (Transportation): 1) it is important to make steady progress towards aggressive sales goals, and 2) due to stock-and-flow lagging effects, how fast California moves has a direct impact on the amount of CDR needed by 2045 (assuming that net-zero by 2045 is binding).

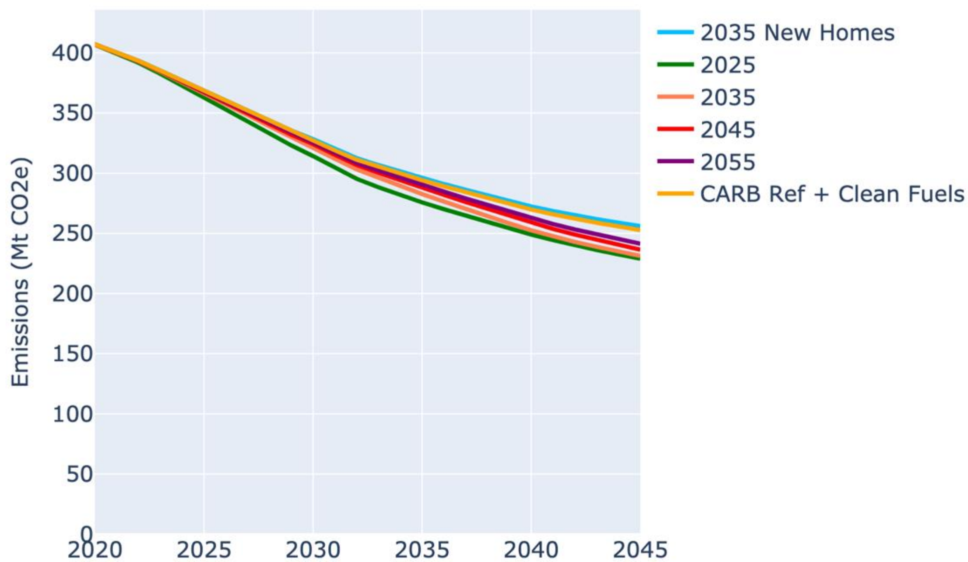


Figure 37: Emissions over time, varying the date in which 100% heat pump sales is reached.

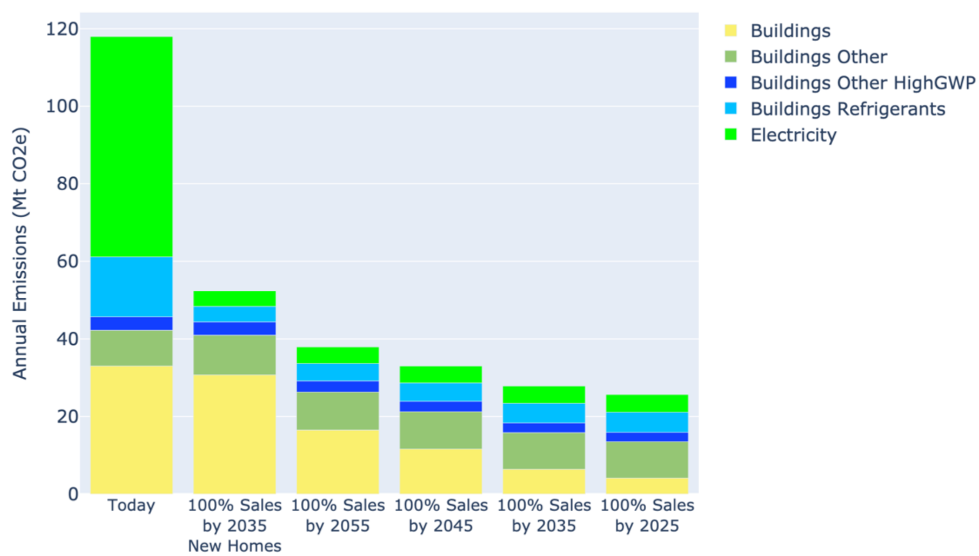


Figure 38: Annual emissions, varying the date in which 100% heat pump sales is reached.

Additionally, much like the transportation sector, the rate at which NG appliances are electrified has a significant impact on cumulative emissions mitigation, as shown in Figure 39.

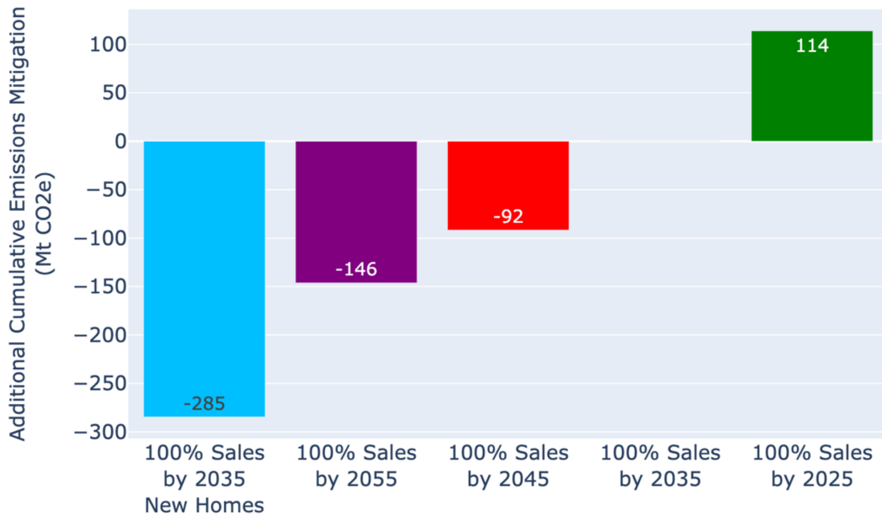


Figure 39: Marginal cumulative emissions, varying the date in which 100% heat pump sales is reached.

Conclusion: What is it going to take to reach net-zero by 2045?
Ambitious electric appliance sales targets and deployment

Heat Pumps versus Electric Resistance Appliances

Electrification of space heating can be done with either electric resistance appliances (including centralized forced-air electric furnaces as well as electric wall and baseboard heaters) or heat pumps. Electric resistance heaters are inexpensive to purchase and install. Heat pumps can achieve up to 200%-350% efficiency (by transferring heat between the building and the outside air or ground), significantly reducing electric load compared to resistance heating. Heat pumps can also dehumidify better than typical central air conditioners and replace the need for a separate air conditioning unit. Heat pump water heaters are also an alternative to electric water heaters in much the same way.

Using DECAL, it is possible to compare a scenario in which building electrification occurs via space and water heat pumps to a scenario in which electrification occurs via electric resistance appliances. Results can be seen below in Figure 40 and Figure 41.

As can be seen in Figure 40, heat pumps result in higher upfront cost and lower electricity costs, whereas electric resistance heaters result in lower upfront cost and higher electricity costs, overall resulting in similar costs to the state. It is important to remember that Figure 40 is *not* done from the perspective of the resident, and thus does *not* suggest that residents will spend similarly regardless of technology choice. In particular, as mentioned in Chapter 2, the cost of marginal electricity can be much lower to the state than it is for end-users. On a capacity basis (as opposed to a cost-basis), the electric resistance scenario requires about 40 additional GW of electric capacity added compared to the heat pump scenario. Overall, these results suggest that electric resistance can be a reasonable option, but in large quantities can add significant load to an already encumbered grid. As such, the state could consider options like incentives, subsidies, or relaxation of requirements for those unable to afford the capital cost of heat pumps.

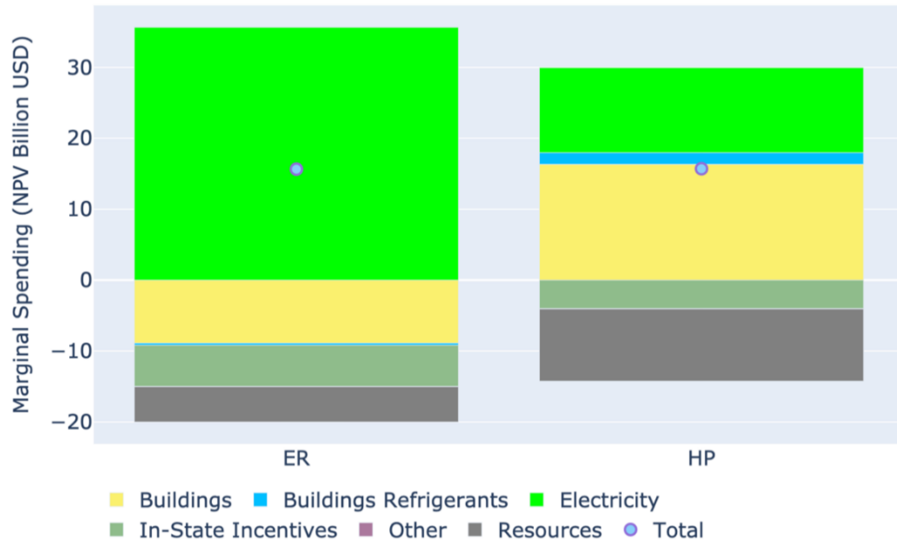


Figure 40: Cost by subsector for heat pumps and electric resistance heaters.

The same two scenarios were additionally run while iterating on two background assumptions: 1) a 'clean grid' vs 'dirty grid', and 2) 'clean F-Gases' vs 'dirty F-Gases'. In this analysis, a 'clean grid' assumes the same CGC as in the DECAL Version of the CARB Proposed scenario (97% by 2045), while a 'dirty grid' assumes the same CGC as in the DECAL Version of the CARB Reference scenario (82.5% by 2045). Similarly, 'clean F-Gases' assumes the same refrigerant assumptions as in the DECAL Version of the CARB Proposed scenario (roughly 85% reduction), whereas 'dirty F-Gases' assumes refrigerant GWPs remain unchanged from the start year. Results are shown in Figure 41, which shows 2045 abated emissions in the four cases. For example, the left side of the first blue bar shows abated emissions assuming heat pumps are used with a 'dirty grid' (and 'clean F-Gases'), and the right side of the first blue bar shows abated emissions assuming heat pumps are used with a 'clean grid' (and 'clean F-Gases'); the width of the first blue bar thus shows the synergy of heat pumps with the cleanliness of the grid.

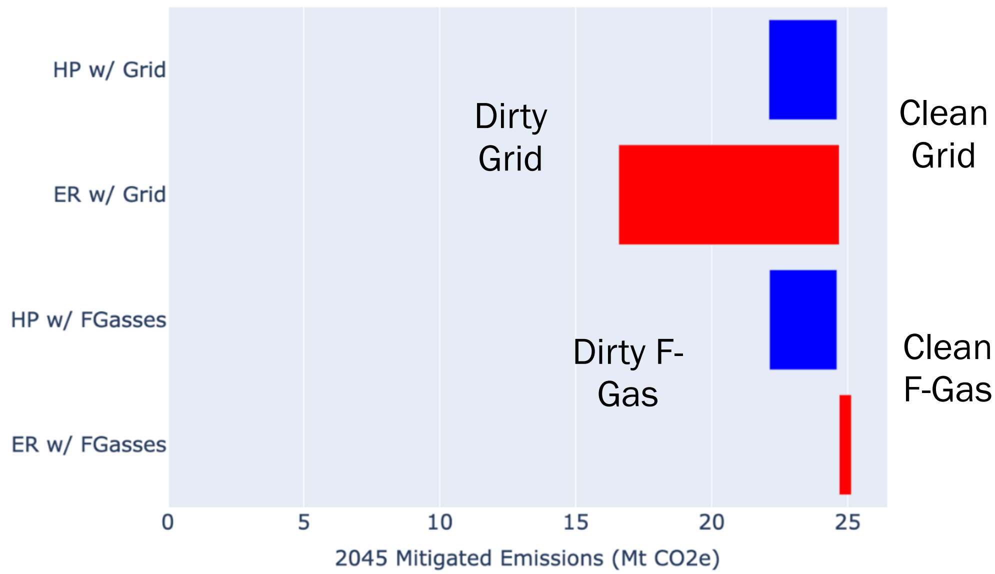


Figure 41: Mitigated emissions by scenario for heat pumps and electric resistance heaters.

Figure 41 shows that electric resistance heaters pose greater risk in case of a dirtier grid; this is because electric resistance heaters are far less efficient than heat pumps. Figure 41 also shows that heat pumps pose greater risk in case of dirtier F-Gases; this is because heat pumps use F-Gases whereas electric resistance heaters do not.

The synergy of heat pumps with F-Gases is particularly interesting. As previously mentioned, heat pumps serve both heating and cooling needs, and thus for every heat pump that is installed to replace a NG Furnace, a central air conditioning unit is additionally scrapped (if available). DECAL begins with roughly 10 million residential NG furnaces and 8 million residential central air conditioners. Thus, at the start of the modeling period, there are roughly 8 million residential devices that use F-gases (all air conditioners), and by the end, there are roughly 10 million residential devices that use F-gases (all heat pumps). If it were not for scrapping, there would instead be roughly 18 million residential devices that use F-gases, which would have a substantial impact on F-gas emissions. In this way, the dual-purpose nature of heat pumps significantly reduces the risk they pose to *adding* F-gases into circulation. This does not mean F-gases are unimportant. As discussed in Chapter 9, F-gases already account for roughly 27 Mt CO_2e; it just means that in the absence of F-gas measures, heat pumps stand to increase F-gas emissions by roughly 3 Mt CO_2e rather than 10+ Mt.

Overall, heat pumps and electric resistance heaters pose different pros and cons to the state and to end users.

Conclusion: What is it going to take to reach net-zero by 2045?

Both heat pumps and electric resistance heaters

Chapter 11: Model Insights for Alternative Fuels

Questions that this section will address:

- *What role can hydrogen play to decarbonize California and what is the impact of different generation methods on cost?*
- *What role can renewable diesel play to decarbonize California?*
- *What role can renewable natural gas play to decarbonize California?*

This chapter discusses the potential role of alternative fuels such as hydrogen, renewable diesel, and renewable natural gas. These fuel switch options are discussed in much more detail in [25] and [27]. In all cases, the volumes of these fossil fuel alternatives are currently limited, and careful planning will be needed to determine how and where to best utilize them most cost effectively.

Hydrogen

California currently produces around 1.83 Mt/yr of hydrogen. All of this capacity comes from SMR plants. Roughly 99% of this capacity is used for crude oil refining at the 14 refineries in-state, which are concentrated in the San Francisco Bay Area and Los Angeles [27]. SMRs can be retrofit with carbon capture equipment which, with current incentives, appear to be a cost-effective emissions mitigation solution [51].

A number of scenarios were run in DECAL to assess potential volumes of hydrogen that could be utilized by each sector as well as the associated costs. The results are shown in Figure 42. Each bar on the chart (except for the top 3 bars) represents a single scenario in which hydrogen was used as an alternative fuel in the sector (wherever applicable) at the indicated percentage, the balance set to electricity. For example:

- LDVs: 80% means that 80% of LDV ZEV sales are FCEV and 20% are BEV
- HDVs: 20% means that 20% of HDV ZEV sales are FCEV and 80% are BEV
- Industry: 60% implies 60% fuel switching to H2, 40% to electricity

In each scenario the sales/adoption rate is the same as the CARB Proposed Scenario, the only change is to technology choice. Hydrogen usage increases and electricity usage decreases moving up the chart, whereas hydrogen usage decreases and electricity usage increases moving down the chart. Results are shown in Figure 42 and Figure 43, which show 2045 hydrogen usage and the cost of abatement of each scenario, respectively.

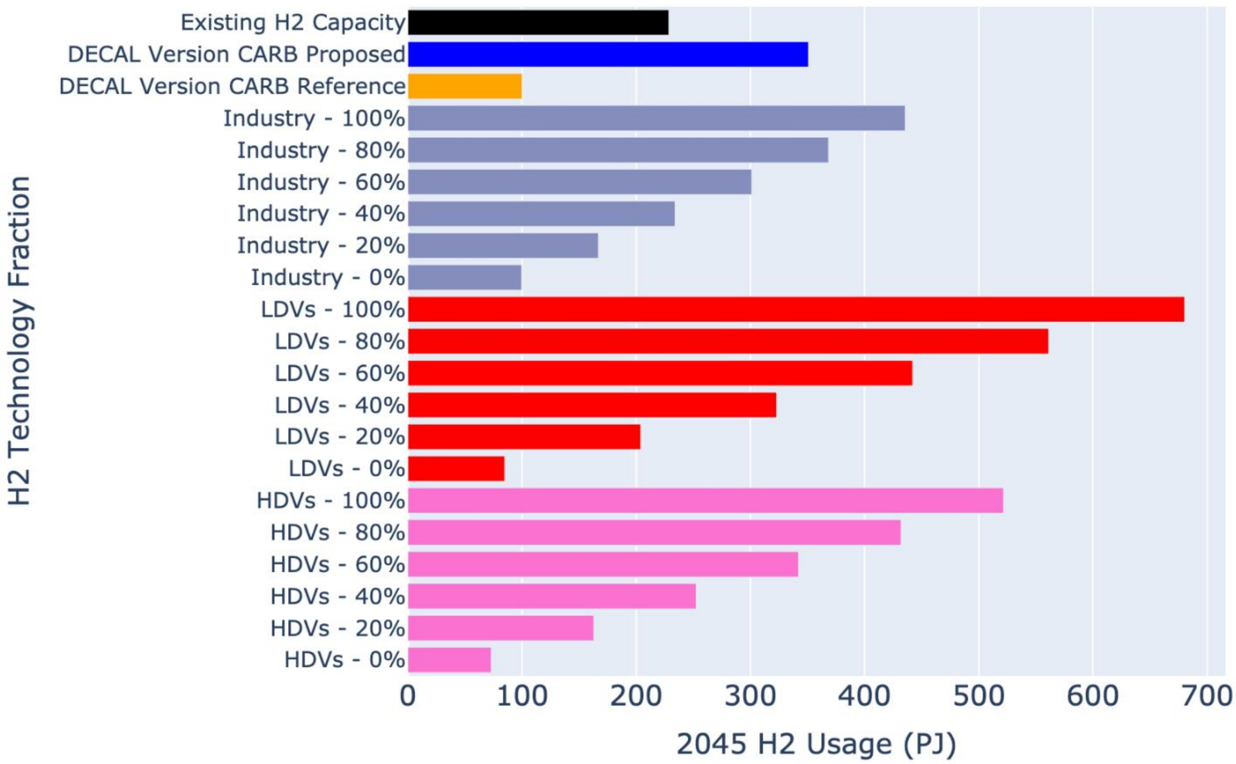


Figure 42: 2045 hydrogen usage for 18 scenarios.

Figure 42 is essentially a lookup table that can provide helpful 'guideposts' for planning. For example, if policymakers would like to use the same amount of hydrogen as current annual capacity, and furthermore would like to use all hydrogen in the HDV subsector, they might plan to set HDV sales fractions to about 40% over the modeling period. As another example, if policymakers would like to use the same amount of hydrogen as the DECAL Version of the CARB Proposed Scenario, and furthermore would like to use all hydrogen in Industry, they might plan to fuel switch roughly 60% - 80% of industrial heating to hydrogen. As hydrogen is a limited resource, these sorts of exercises could be used to help guide planning.

Figure 43 demonstrates that abatement costs increase as hydrogen usage increases (going up the plot), or equivalently, abatement costs decrease as electricity usage increases (going down the plot)[16]. As has been cited multiple times throughout this report, hydrogen is relatively expensive, largely due to distribution and storage costs[17]. For this reason, energy usage alone (Figure 42) should not be used alone for planning – policymakers should additionally take cost into account when planning. Figure 43 also suggests that HDVs may be the most cost-effective sub-sector to use hydrogen.

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[16] Figures 13, 43, and 55 are relatively consistent, if the technology fractions of LDVs and HDVs are considered. Interestingly, both Figures 43 and 55 show that HDV BEVs have a negative cost of abatement – this is because in this case, incentives and resource/refinery savings outweigh the costs of HDV BEVs and electricity generation.

[17] With the exception of refineries, DECAL assumes that hydrogen is created centrally and distributed, rather than created onsite.

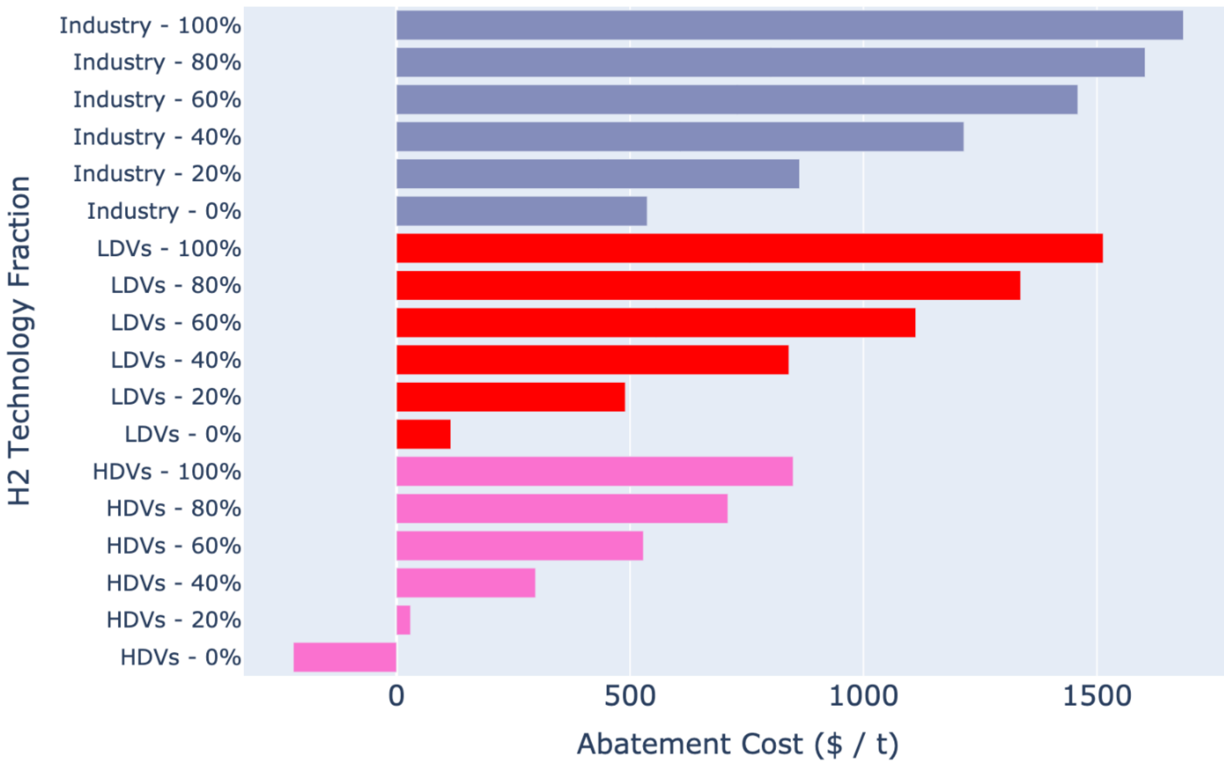


Figure 43: Cost of abatement for 18 scenarios.

DECAL was also used to assess the cost effectiveness of new hydrogen plants (new meaning, in addition to existing SMRs). To do so, a high hydrogen scenario was created, in which technology fractions were set to 60%, 40%, and 20% respectively for HDVs, Industry, and LDVs. This scenario was run while iterating on 11 hydrogen generation options. For both SMRs and ATR, four arrangements were tested: the base technology on its own, with CCS, with RNG, and with both CCS and RNG. Gasification with and without CCS was additionally tested, along with Electrolysis. Results are shown in Figure 44, which shows marginal spending compared to the DECAL Version of the CARB Reference Case. The figure illustrates that hydrogen generation (dark blue bar) is not the driving cost in high hydrogen pathways. Rather, the cost of FCEVs (brown), and hydrogen distribution and storage (D&S, cherry color) are much more significant. Overall, the marginal costs associated with these different hydrogen generation pathways are quite similar, illustrating that how the hydrogen is made is less important than the decision of whether or not to use hydrogen in the first place.

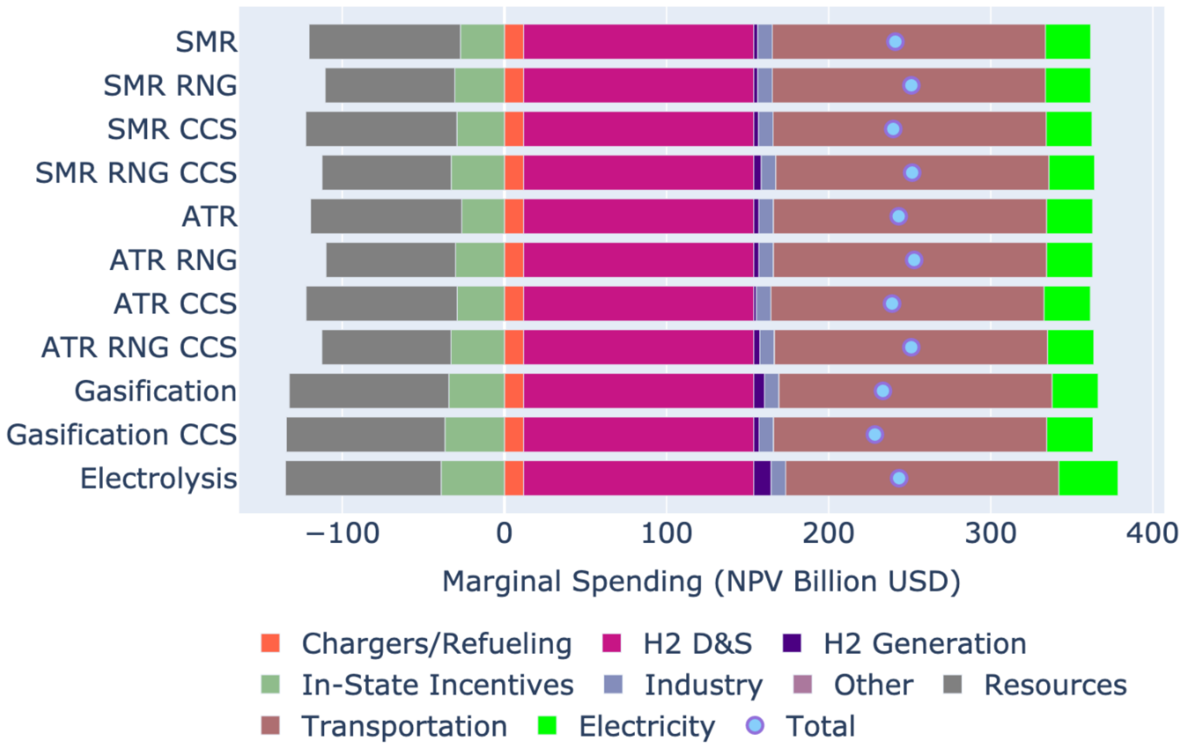


Figure 44: Costs by sector for several hydrogen generators in a high hydrogen scenario.

Renewable Natural Gas

RNG is chemically equivalent to fossil-sourced natural gas and can be mixed into any natural gas stream. Decarbonizing the natural gas supply with RNG is therefore an effective way to accommodate for stock and flow lag effects (e.g., reduce emissions in buildings that have not yet converted to electric appliances), and can be helpful in subsectors that are hard to electrify (e.g., cement).

Similar to prior analyses done for hydrogen, DECAL can be used to create helpful guideposts for RNG planning. To do so, economy-wide blend percentages were set to 5%, 10%, 20%, 30%, 40%, 50%, 60%, 80, and 100% from both the DECAL version of the CARB Reference Case and the DECAL version of the CARB Proposed Scenario. Note that in these scenarios, RNG is used mainly in Demand sectors, and is explicitly not used in the electricity and hydrogen sectors. Results are shown in Figure 45, which shows RNG usage over time in the two cases. Figure 45 additionally includes two resource proxies: the in-state capacity of RNG [25][18], and NREL's projected US capacity for RNG [52]. Capacity projections like these are highly uncertain but can be useful guideposts to aid planning.

The plots show that both the Reference Case and Proposed Scenario stay within in-state capacity. In the Reference Case, RNG blends should not exceed ~10% to stay within in-state

[18] Note that [25] assumes that food waste is diverted to compost as part of SB 1383 (reducing RNG capacity), whereas DECAL assumes that food waste can instead be diverted to anaerobic digesters.

production capacity, and should not exceed roughly 30% to stay within the US potential for RNG. Due to aggressive electrification in the DECAL Version of the CARB Proposed Scenario, higher RNG blend fractions can be reached in the Proposed Scenario while using less RNG. In particular, a blend of 60% can be achieved by 2045 while staying within in-state production, and even a blend of 100% would not exceed the US potential for RNG. It is worth mentioning, however, that these results change substantially if RNG is used in the electricity sector and to make hydrogen (see Figure 46). Overall, RNG can be a useful plug-and-play resource to mitigate leftover or hard to decarbonize emissions in 2045. However, policymakers will need to carefully consider resource constraints, rising global demand, and ongoing decarbonization efforts when making plans for RNG.

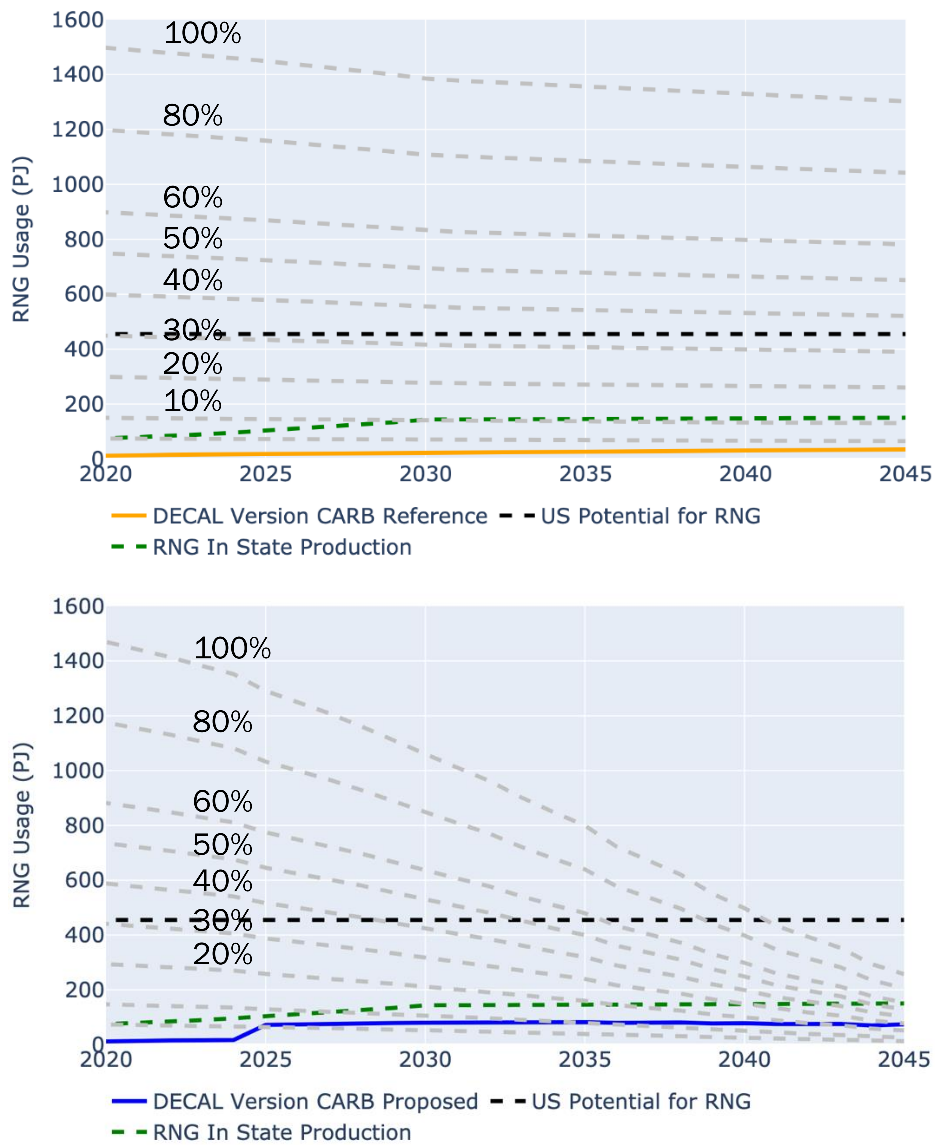


Figure 45: RNG demand over time. DECAL version of CARB Reference Case (top) and Proposed Scenario (bottom) compared to estimated in-state production [25] and US potential for RNG [52]. Grey contour lines show RNG demand over time using different blends of RNG in the NG system.

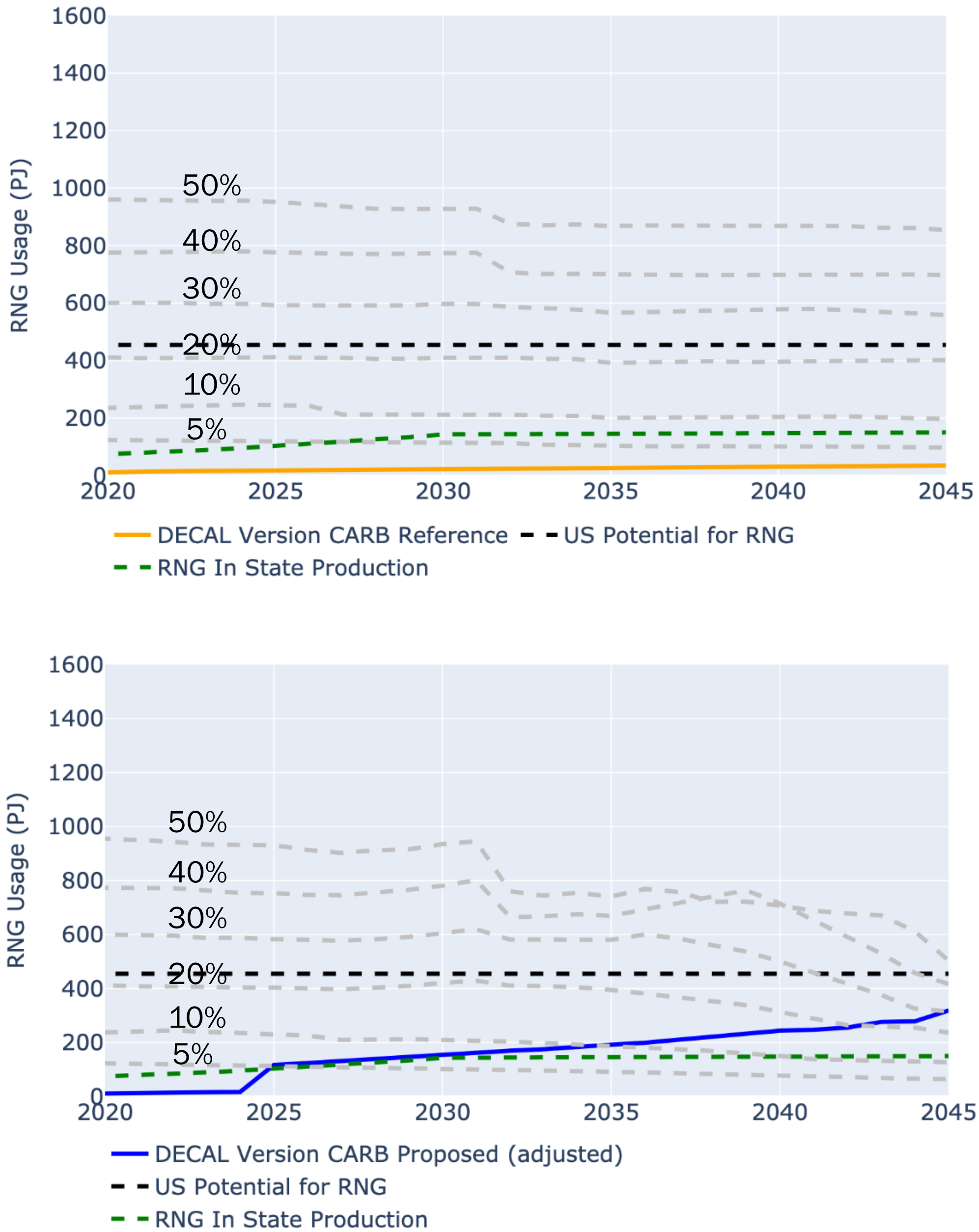


Figure 46: RNG demand over time. DECAL version of CARB Reference Case (top) and Proposed Scenario (bottom), adjusted to allow RNG in electricity and hydrogen sectors. The scenarios are again compared to estimated in-state production [25] and US potential for RNG [52]. Grey contour lines show RNG demand over time using different blends of RNG in the NG system, with RNG allowed in the electricity sector and to make hydrogen.

Renewable Diesel

Renewable diesel (RD) is a fuel made from fats and oils (e.g., soybean oil, cottonseed oil, canola oil, corn oil); recycled cooking greases or oils; animal fats (beef tallow, pork lard); or

various combinations of these feedstock types and is processed to be chemically the same as petroleum diesel. Decarbonizing the diesel supply with RD is therefore an effective way to reduce emissions in cases where diesel vehicles are still on the road by 2045.
Since a limited volume of these materials is available locally, much of the feedstock volume necessary to satisfy the demand is sourced elsewhere in the world and transported to California.

A very similar set of analyses done for RNG was also done for RD. Economy-wide blend percentages were set to 25%, 50%, 75%, 30%, and 100% from both the DECAL version of the CARB Reference Case and the DECAL version of the CARB Proposed Scenario. Results are shown in Figure 47, which show RD usage over time in the two cases. Figure 47 additionally includes a resource proxy - the current global demand for RD [53]. RD capacity projections (in-state, nationwide, etc.) are sparse in literature, but the current state of global demand still provides a helpful order-of-magnitude comparison. Interestingly, California already accounts for a large fraction of global demand, in large part due to the LCFS program.

Due to aggressive electrification in the DECAL Version of the CARB Proposed Scenario, higher RD blend fractions can be reached in the Proposed Scenario compared to the Reference Case while using less RD than is being used now. In fact, given deep electrification, RD could eventually replace fossil diesel entirely (near 100% blend) while about doubling current California demand for renewable diesel. As electrification and decarbonization proceed, policymakers should use analyses like these to ensure California does not overburden a limited global feedstock supply.

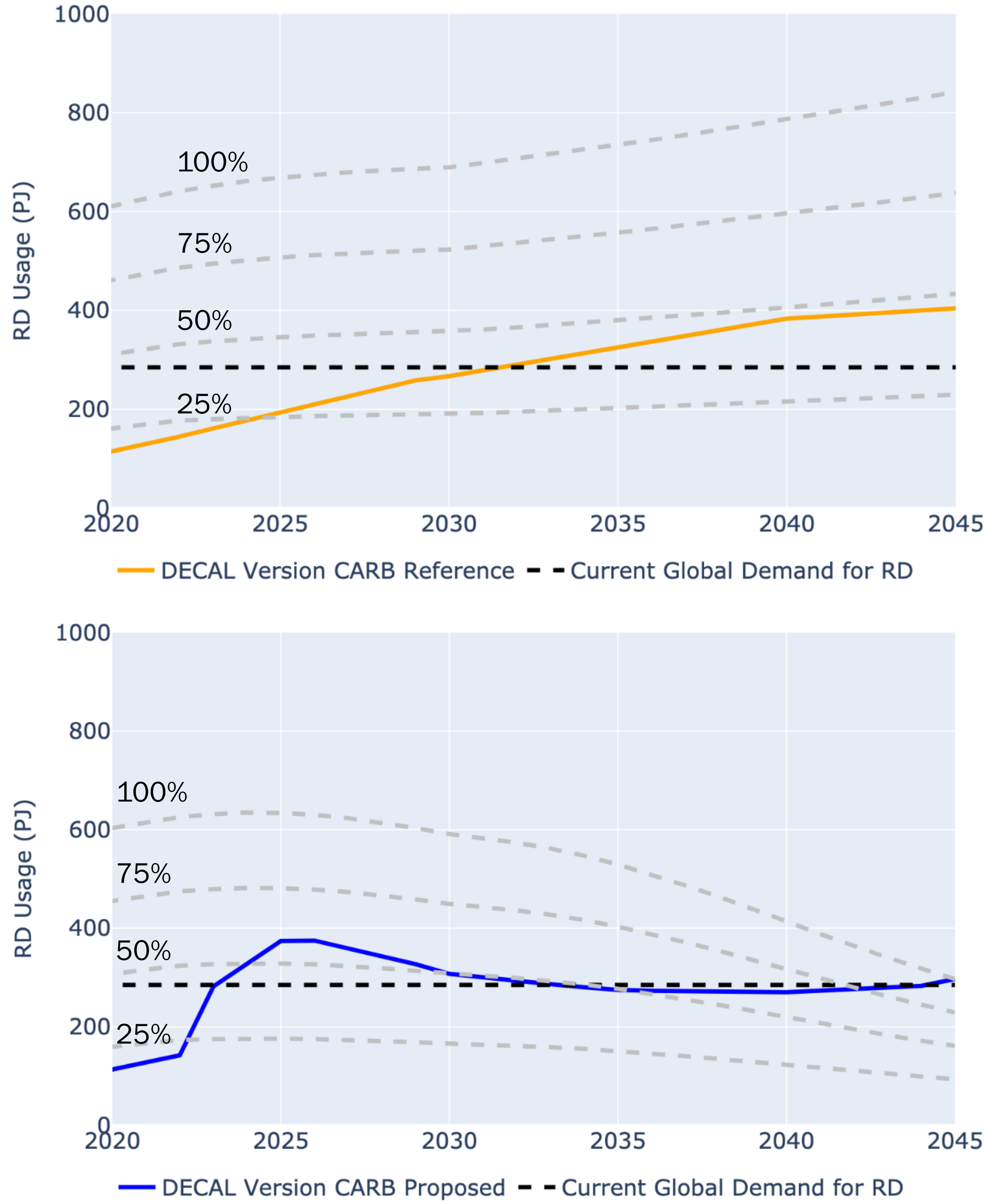


Figure 47: RD demand over time. DECAL version of CARB Reference Case (top) and Proposed Scenario (bottom) compared to estimated present-day global demand for RD [54]. Grey contour lines show RD demand over time using different blends of RD in the diesel system.

Conclusion: What is it going to take to reach net-zero by 2045?

Careful planning of hydrogen, RNG, and RD

Chapter 12: Model insights for Carbon Dioxide Removal

Question that this section will address:

- *What is the minimum amount of CDR/DAC required while still meeting a net-zero goal?*
- *How much electric load will CDR/DAC add to the grid?*

The Proposed Scenario in the 2022 CARB Scoping Plan relies on 75 Mt of CDR to reach net-zero by 2045. CDR encompasses a suite of technologies including DAC with carbon storage, biomass carbon removal with carbon storage (BiCRS, also known as bioenergy with CCS, or BECCS), contributions from natural and working lands (NWL), and other technologies. The contributions assumed by CARB from DAC, BiCRS, and NWLs are listed in Table 12.

CDR technology	CO_2 emissions mitigated in 2045 (Mt)
DAC	64.4
BiCRS	9.1
NWL	1.5
Total	75

Table 12: 2045 mitigated emissions by CDR technology in CARB's Scoping Plan.

There are currently 18 DAC plants operating globally (mainly serving the carbonated beverages industry) capturing 0.01 Mt of CO_2 per year. A 1 Mt/yr plant is in advanced development in TX, and 11 more large scale plants are in early development. The International Energy Agency [40] forecasts that there will be 5.5 Mt/yr of DAC onstream globally by 2030. The 2022 Scoping Plan requires 2.3 Mt of DAC in 2030. Clearly, DAC development and deployment will need to scale significantly if California is to achieve its carbon neutrality goals. Additional research funding to find ways to reduce the cost and energy requirements of DAC will be essential.

The future development and deployment of BiCRS technology is also quite uncertain. The BiCRS term was introduced in 2021 and refers to technologies that use plants and algae to remove CO_2 from the atmosphere and store it geologically or in long-lived products [55]. It is estimated that there is 2.5 Mt/yr carbon removal via BiCRS today (globally), with perhaps up to 25 Mt/yr associated with projects in planning and development [55]. A recent Lawrence Livermore National Lab report suggests that there is more than enough waste biomass in the State and by 2045 it would be possible to remove significantly more than the Scoping Plan requires [56].

Finally, as discussed earlier, the 2022 Scoping Plan suggests that NWL are a net source of a significant volume of emissions. Additionally, emissions from NWL are not included in CARB's annual GHG inventory [36]. For these two reasons, NWL emissions and NWL as a potential mitigation option are not included in DECAL.

To simplify the modeling effort, DAC is the only CDR technology utilized by DECAL. DAC requires significant energy inputs to power the system, and those energy requirements (and associated emissions) are also captured by DECAL.

To assess the minimum CDR needed while reaching net-zero by 2045, a minimal DAC scenario was developed. The main levers that were adjusted for this scenario are listed in Table 13 and the results are shown in Figure 48, which shows emissions by subsector over time for both scenarios.

	DECAL version of CARB Proposed Scenario	Minimum DAC Scenario
Electricity	• 97% clean generation by 2045 • NGCCS is 90% clean • RNG is not used in the electricity sector	• 99% clean generation by 2045 • NGCCS is 98% clean • The electricity sector reaches the same RNG blend as the rest of the economy, 30% by 2045
Transportation	• 100% LDV sales ZEV by 2035 • 100% HDV sales ZEV between 2035-2040 • 100%/50%/25% reduction in emissions from planes/trains/boats	• 100% LDV sales ZEV by 2030 • 100% HDV sales ZEV by 2030-2035 • 100% reduction in emissions from planes/trains/boats
Buildings	• 100% clean sales by 2035/2045 Residential/Commercial	• 100% clean sales by 2030
Industry	• 90% CCS capture rate • 65% deployment of CCS in refining subsector • 50% electrification of "Industry Other"	• 98% CCS capture rate • 100% deployment of CCS in refining subsector • 100% electrification of "Industry Other"
Hydrogen Production	• RNG is not used to make hydrogen • New hydrogen production consists of 35% Gasification with CCS and 65% Electrolysis.	• Hydrogen SMRs reach the same RNG blend as the rest of the economy, 30% by 2045 • New hydrogen production consists of 50% Gasification with CCS and 50% SMR RNG with CCS.
Agriculture	• Seaweed: 50% eligibility, 30% reduction in emissions	• Seaweed: 85% eligibility, 60% reduction in emissions
CDR	• **75 Mt DAC in 2045**	• **35 Mt of DAC in 2045**

Table 13: Changes made to CARB Proposed Scenario to develop a 'minimal DAC' scenario.

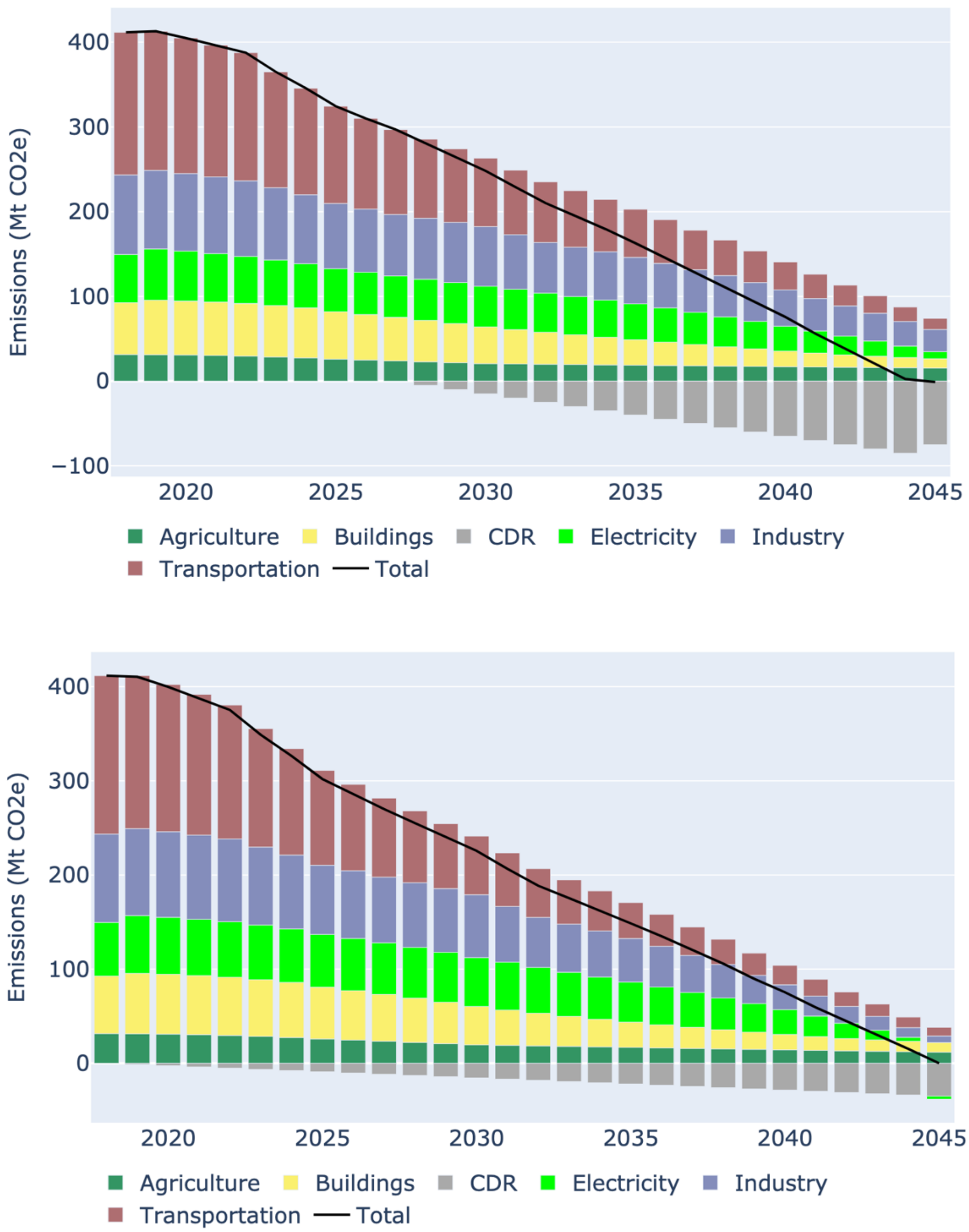


Figure 48: Emissions by sector in the DECAL version of the CARB Proposed Scenario (top) and the minimum DAC scenario (bottom).

While it may be possible to reduce the necessary contribution from CDR (by close to 50%), it will require pushing every other decarbonization option to limits that are likely beyond achievable. Furthermore, while the difference between 75 Mt and 35 Mt is significant, in either case, CDR will need to be scaled and costs will need to be reduced.

Figure 49 shows where these leftover emissions come from. First and foremost, roughly 17 Mt are from the “unleverable” emissions previously discussed in Chapter 2. These emission sources do not have solutions readily available – it is fair to say that either the state will either need innovation in these areas, or otherwise the state will need CDR to compensate. The next largest chunk of emissions (7.4 Mt) comes from refrigerants, as it is roughly assumed refrigerants see an 85% reduction in GWP by ~2050 (importantly, not 100% reduction). Leftover enteric fermentation emissions account for another 5.6 Mt. Another slice of emissions comes from the LDVs (4.8 Mt), HDVs (1.6 Mt) and the building sectors (2.5 Mt), due to stock-and-flow lag effects. As discussed previously, some CDR will be needed to compensate for leftover emissions in these sectors, the question of *how much* CDR is directly tied to *how fast* the state can move towards 100% electric sales goals. A final portion of industrial emissions comes from NG leaks (2.3 Mt), and from assuming that some small and dispersed industrial plants will not be able install CCS or fuel-switch (0.9 Mt); in reality, leftover emissions from these plants will likely be much higher than either scenario presented here. It is easy to argue for less CDR in the abstract, however this analysis demonstrates its crucial role in meeting net-zero goals.

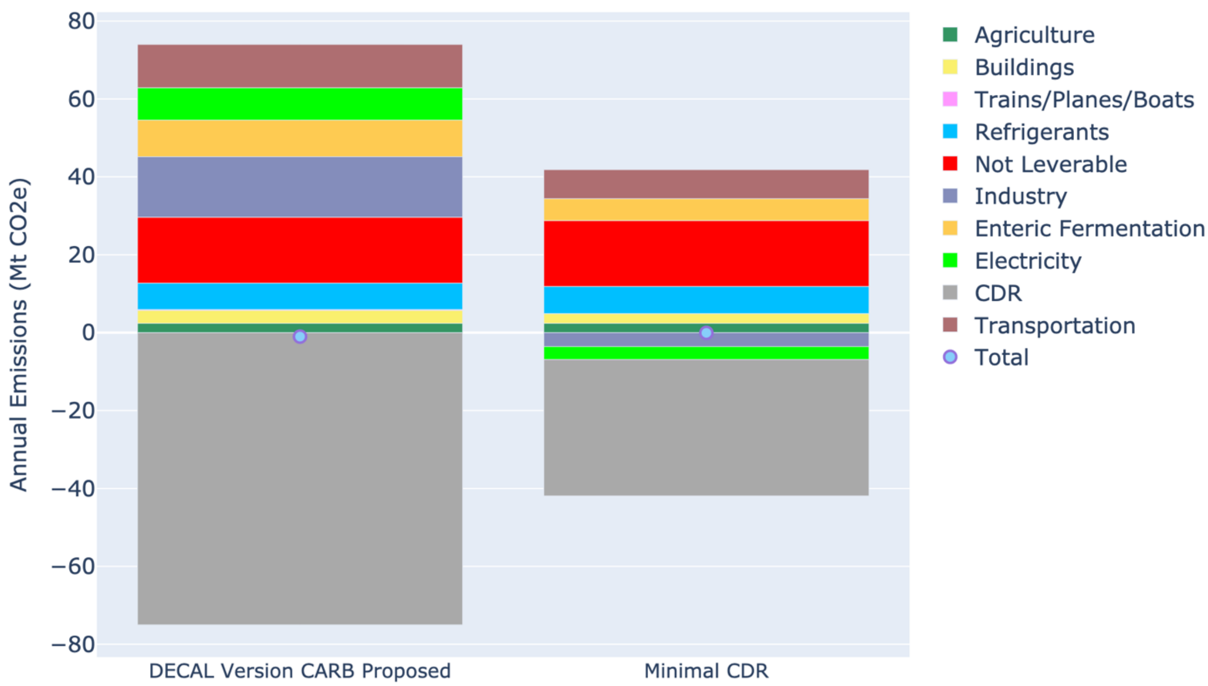
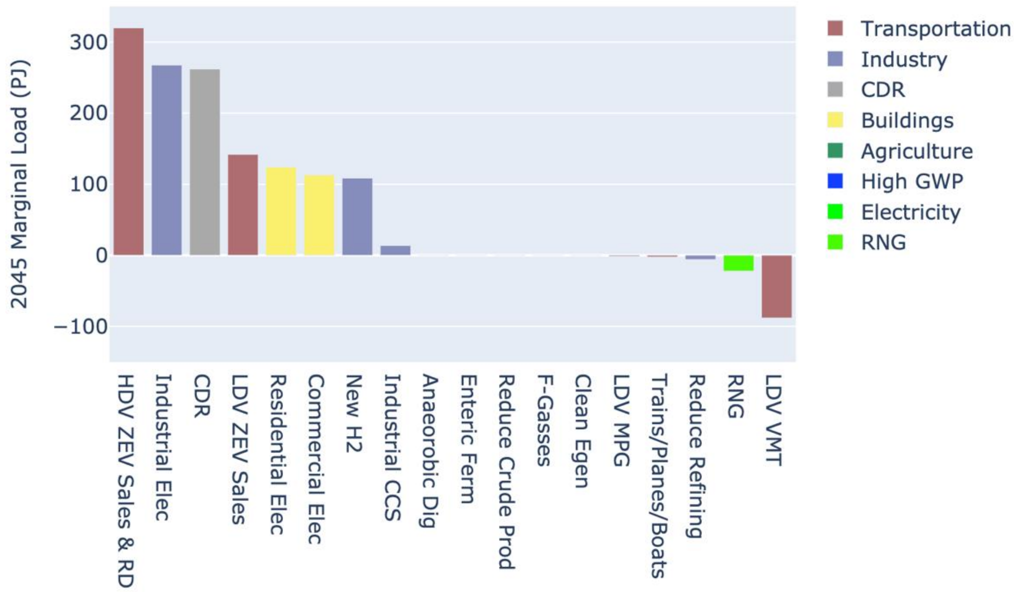


Figure 49: 2045 Annual emissions in the DECAL version of the CARB Proposed Scenario compared to the minimal CDR scenario.

Indeed, it is difficult to imagine a net-zero world in the mid-to-near term without CDR playing a major role. Realistically, less CDR could be more readily achieved by extending the net-zero timeline, or by utilizing offsets in other states and countries.

Regardless of the amount of CDR (or DAC) that is needed in 2045, it is worth noting that DAC requires electricity to operate, and the amount of required CDR will have a large impact on the future electric load. Figure 50 shows the 2045 marginal electric load in the same 18 areas originally discussed in Chapter 5 as well as the 2045 load by sector. While buildings are and will remain the largest sectoral electric load, CDR will have a growing impact as well.



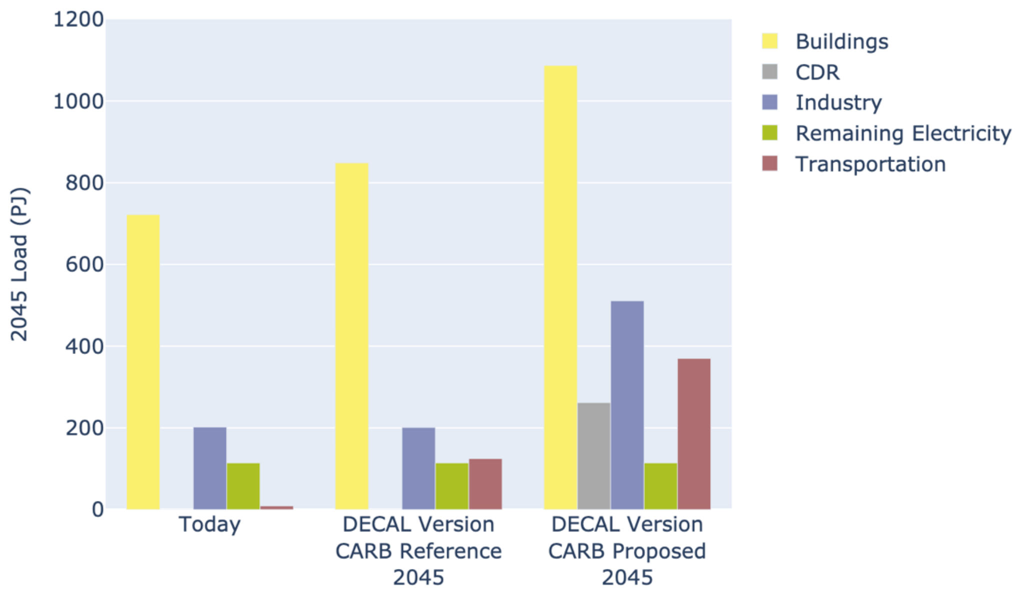


Figure 50: 2045 marginal electric load in 18 key areas discussed in Chapter 5 (top) and load by sector today and in the Reference Case and Proposed Scenario (bottom).

Conclusion: What is it going to take to reach net-zero by 2045?
Significant volumes of CDR

Chapter 13: Sensitivity Analysis

Questions that this section will address:

- *Where a choice is available, which technology is most effective?*
- *What are the 'next best' options in case the first fails?*
- *How will cost reductions over time affect overall costs?*
- *How sensitive are overall system costs to fuel prices?*
- *How important are incentives?*

Technology Choice

The technology choice sensitivity analysis involved starting with the DECAL version of the CARB Reference Case and adopting one technology/policy at a time at the same rate as the CARB Proposed Scenario and comparing emissions reductions and abatement costs. The analysis can be helpful to identify the technologies that impact emissions and cost the most – these are possible policy and R&D focus areas. In addition, the analysis can be helpful to identify tradeoffs between technologies, where a choice exists. The results of this analysis for the whole economy are shown in Figure 51 and Figure 52.

At the economy-wide level, Figure 51 confirms that CDR and transportation technologies and policies will have the largest impact on total emissions. Industrial and residential measures have the next largest impact. Overall, the distributed nature of emissions abatement is notable – outside of a few key measures, reaching net-zero will require making progress in several areas. Figure 52 shows that hydrogen solutions are relatively expensive under the assumptions made here. Some more affordable measures include HDV BEVs, CCS, reduced crude production, residential water heating, and anaerobic digestion. See Appendix B for a more detailed sector by sector breakdown of Figure 51 and Figure 52.

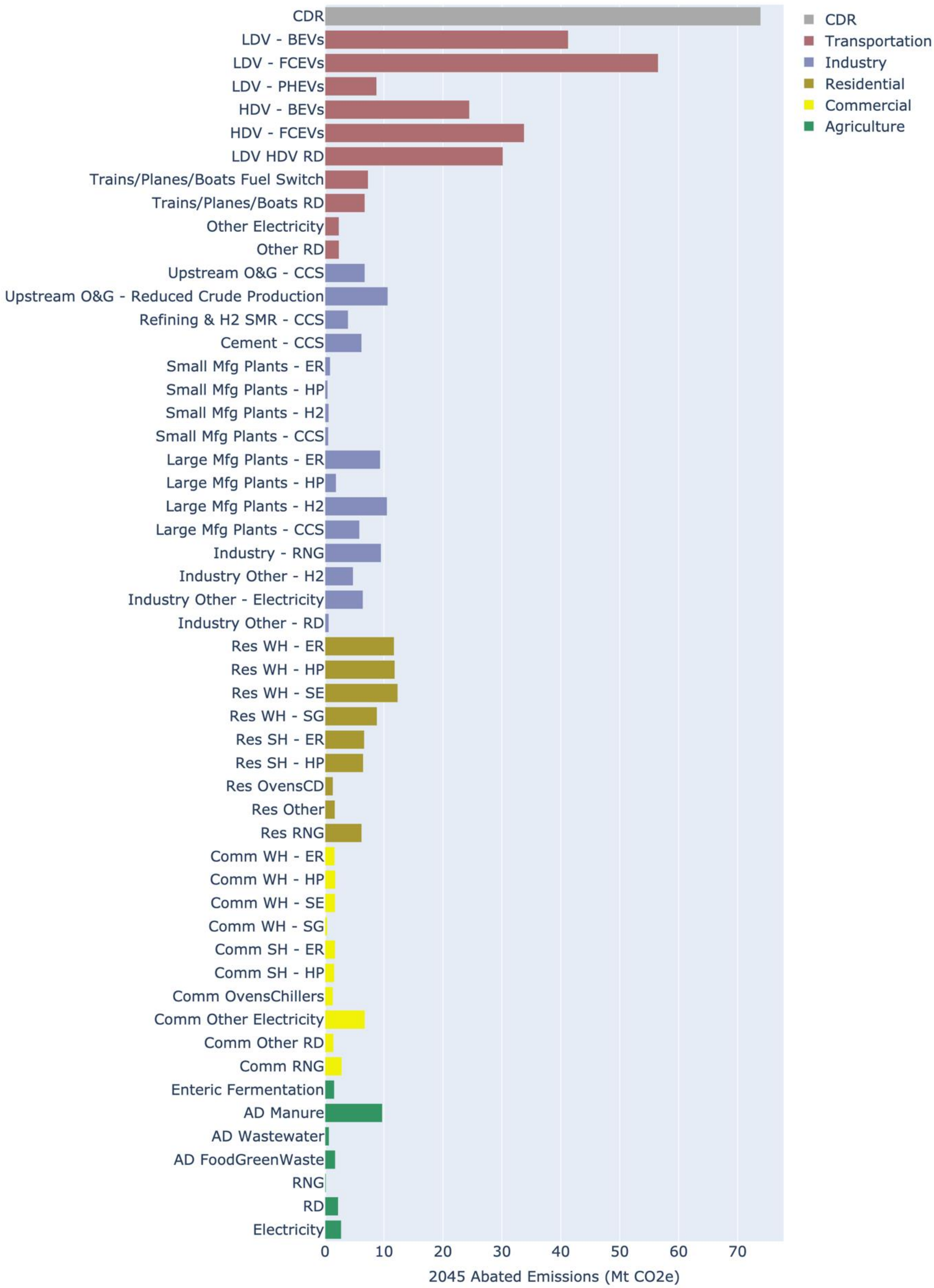


Figure 51: Technology choice sensitivity analysis for the whole economy, 2045 abated emissions (Mt).

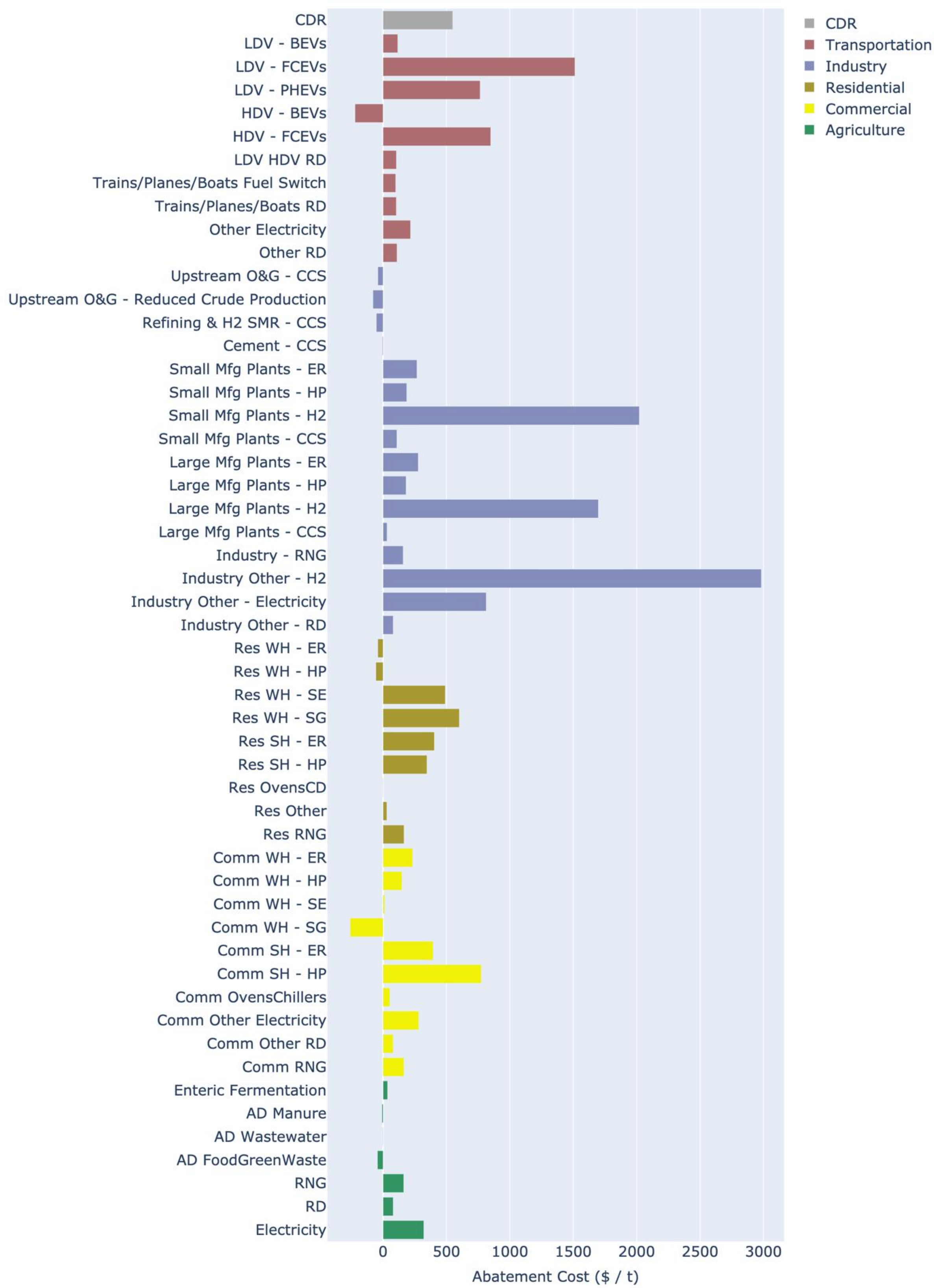


Figure 52: Technology choice sensitivity analysis for the whole economy, abatement cost ($/t).

Cost

As mentioned in Chapter 2, cost estimates are among the most uncertain data entries in DECAL, especially cost projections into the future. A sensitivity analysis was performed to explore this uncertainty. The analysis involved starting with the DECAL version of the CARB Proposed Scenario and fully adopting one technology at a time (similar to the Technology Choice sensitivity), once with aggressive learning assumptions and again with less aggressive learning assumptions (see Chapter 2 for more details). In the electricity sector, cost assumptions are iterated on, and DECAL decides which technologies to deploy. The sensitivity analysis helps identify those technologies that impact system-wide cost the most. In addition, it helps ensure that conclusions regarding technology tradeoffs are robust to assumptions made about learning. Results are shown in Figure 53.

In Figure 53, the left side of each bar shows marginal cost under high learning assumptions, whereas the right side of each bar shows marginal cost under low learning assumptions. In this way, the width of the bar shows how sensitive the overall system is to cost reductions to a particular technology. In addition, each scenario in the figure is compared the LEAP Version of CARB Proposed Scenario (the zero line) – thus, technologies that are further right are more expensive than the option chosen in LEAP Version of the CARB Proposed Scenario, whereas technologies that are further left are less expensive.

At the economy wide-level, Figure 53 confirms that system costs can be driven furthest left via cost improvements to LDVs and CDR. In other words, the figure argues that R&D effort is likely best spent on LDVs and CDR, as cost reductions here drive down overall decarbonization cost the most. Note that the figure attempts to account for the fact that some technology costs are easier to reduce than others by making learning rates a function of maturity.

The system is next most sensitive to cost reductions to following technologies (from top to bottom): solar, electricity T&D, F-gas mitigation, HDVs, industry other, and hydrogen D&S. It is particularly interesting that several of these costs are represented in a top-down manner (electricity T&D, F-gas mitigation, industry other, and hydrogen D&S), indicating that further technoeconomic modeling in these areas could be worthwhile.

See Appendix B for a more detailed sector by sector breakdown of Figure 53.

Figure 53: Results of the learning rate sensitivity analysis for the whole economy. Bars are color coded by technology maturity level.

Conclusion: What is it going to take to reach net-zero by 2045?

Reducing the costs of BEVs and CDR

Chapter 14: Action Items

The findings of this study have been consolidated into a tangible list of action items, both in terms of research and development and policy opportunities.

Areas that would benefit from additional research and development include:

- **CDR**: R&D is needed to reduce the cost and parasitic load for DAC technologies. CDR is the largest contributor to 2045 abated emissions in the CARB Proposed Scenario despite being amongst the highest cost. DAC also becomes a very large user of electricity by 2045 in the DECAL Version of the CARB Proposed Scenario.
- **F-Gases**: Low GWP refrigerants will be needed at scale to achieve deep reductions in this sector.
- **Biofuel feedstocks**: Identifying new RNG and RD feedstocks could help these fuels play a larger role, easing the burden on electrification.
- **Hydrogen Costs**: Hydrogen is expensive, driven by high end-use (fuel cell vehicles, industrial hydrogen heating, etc) and D&S costs. R&D to reduce these costs could allow hydrogen to play a larger role in decarbonization.
- **Battery costs**: In this study, LDV ZEV sales is one of the largest contributors to emissions reductions, but has a high abatement cost. Although costs of BEVs are already coming down, additional reductions would have a substantial impact on statewide costs. In addition, all electrification scenarios explored here necessitated a significant amount of grid-scale Li Ion storage, and thus reducing the cost of grid-scale electricity will be crucial.

Areas that would benefit from policy interventions include:

- **Electric home appliances**: Most homes that will exist by 2045 already exist today; as such, existing policies aimed at new homes are not sufficient – more rapid deployment of electric appliances are needed for existing homes as well.
- **Grid emissions requirements:** Current regulations require a 100% carbon-free grid by 2045. This study shows that a CGC of 99% reduces overbuilding while having a negligible impact on emissions. Clean baseload power sources such as NGCCS (90% capture) and hydropower also reduce cost. An evaluation of this regulation is suggested.
- **45Q incentive**: While some subsectors may be able to install CCS retrofits in the nearer term (e.g., power plants, SMRs) other manufacturing subsectors (e.g., petrochemicals, food) may only be able to after 2032, when 45Q expires. This expiry date has been extended twice so far, and a case can be made that it should be extended even longer.
- **Permitting**: Climate change is an infrastructure problem. Given the speed and scale with which new infrastructure (electric generators, T&D, BEV charging, CDR, CCS, building appliances, and more) will be required, it is critical that the state find ways to eliminate red tape and streamline permitting activities.

Chapter 15: Future Work

The work done here helped identify additional opportunities that could and should be addressed in future modeling studies. Some of these ideas are listed below:

- **Equilibrium modeling:** DECAL is an entirely exogenous model, in that the user controls both cost and buildout. In a more sophisticated and realistic model, the user could specify costs and allow the model to respond to economic conditions.
- **Optimization modeling:** The work done here explores part of the vast problem space using storylines and logic, leading to helpful insights. Instead, nonlinear optimization could potentially be used to find "optimal" pathways.
- **Multiagent modeling (multiple perspectives):** DECAL only considers cost from the perspective of the state via the Total Resource Cost test. A more sophisticated model could simultaneously consider the cost to the state as well as to other agents, such as business owners and residents.
- **Risk-based modeling:** Systematically defining technology risks, and exploring scenarios according to said risks.
- **Higher model resolution**: The electricity sector currently uses one geographic node and assumes each day of the month is the same. Greater fidelity could allow better characterization of grid service issues that are not explored in this study.
- **Model Scope:** It may be useful to expand the model scope and consider impacts to neighboring states and countries, especially those that trade with California directly.
- **More Impacts:** This study only focuses on impacts to emissions, cost, and resources. More sophisticated models could examine other impacts, such as to criteria air pollution, soil pollution, water pollution, equity, and more.
- **Energy distribution infrastructure:** Energy distribution infrastructure – i.e., poles and wires for electricity and pipelines for gaseous products (NG, hydrogen, CO_2) – was handled in DECAL using top-down costs. These costs are significant, thus analysis that explicitly models these entities could be warranted.
- **More technologies:** DECAL considers a wide range of technologies, but further work could be done to explore up-and-coming technologies, for example, proposed high-grade industrial heating options, new electric storage technologies and battery chemistries, modular nuclear reactors and more. In addition, the impacts of energy efficiency measures, such as retrofits to buildings and industrial processes, are difficult to capture in DECAL, but are thought to be some of the most economically compelling.

There are many additional questions that can be addressed using DECAL directly (or with minor modifications) that were outside the scope of this study but would make for interesting and valuable future analysis. Some specific questions that could be considered in future studies include:

- **Timing**:
    - What are the resource and cost implications of delaying the net-zero target past 2045, or accelerating it to earlier than 2045?
    - How low could emissions realistically get by 2030, and at what cost?
- **Electricity Sector**

- What is the impact of peaker and NGCC plant retirements (current modeling in DECAL does not address plant retirement)?
- At what cost point does NGCCS become a more favorable option to Li Ion storage? What about hydrogen fuel cells?

- **Transportation Sector**
  - How many EV charger stations will be required, and of what type (residential vs commercial)?
  - How much cheaper do FCEVs, hydrogen distribution and storage, and/or refueling stations need to be to achieve cost parity with BEVs, especially for HDVs?
- **Industrial Sector**
  - How would a state limit on CCS impact industrial emissions and statewide costs?
- **F-Gases**
  - How much should the state be willing to incentivize development and procurement of low-GWP F-Gas systems?
  - How much should the state be willing to incentivize end-of-life F-Gas programs?
- **Buildings Sector**
  - What is the impact of using different assumptions regarding electric panel installations and costs?
  - Where should we act first – i.e., which geographic zones?
- **Fuel Switching**
  - What are the emissions/cost implications of using excess solar capacity to make hydrogen, store it geologically, and then convert back to electricity to meet later demand?
  - What would it take for E85 to disrupt the planned transportation decarbonization strategy? What impact would this have to scope 1 & 3 emissions and land use?
  - Where should alternative fuels be prioritized – i.e., which subsectors?
- **CDR**
  - Which CDR technology is more economically attractive low-temperature solid sorbent or high-temperature aqueous solution?
- **Other**
  - On a volumetric basis (not accounting for location and dispersion), what impact do measures explored here have on other pollutants (SOx, NOx, particulate matter)?

Chapter 16: Conclusions

This chapter summarizes sector-by-sector conclusions that are made at the end of each sub-chapter, all aimed to answering the question “What is it going to take to get to net-zero emissions by 2045?”

Economy Wide

- A diversified portfolio of resources and technologies will be needed
- A few policies/technologies are key, though some have high costs

Electricity Sector

- The state must become proficient, timely, and responsive at permitting and building electric infrastructure
- A clean grid is key, but 100% clean may not be needed
- Clean dispatchable power reduces capacity requirements
- Demand response can be helpful but will not replace energy storage

Transportation Sector

- It is important to make steady progress towards ambitious ZEV sales goals
- BEVs are more cost effective than FCEVs

Industrial Sector

- CCS is an effective and relatively affordable option
- Incentives have a large impact on CCS technoeconomics

F-Gases

- EOL programs are helpful but not enough on their own to limit significant emissions of high GWP gases
- Innovative low-GWP refrigerants are needed at scale for deep reductions in refrigerant emissions

Buildings

- It is important to make steady progress towards ambitious electric appliance sales goals
- ER and HP are both effective options with different tradeoffs
- California should consider new programs to accelerate retrofitting of older residences.

Alternative fuels (Hydrogen, RNG, RD)

- Careful resource planning will be required, for instance, prioritizing hydrogen in more cost-effective areas (HDVs), or prioritizing RNG and RD in hard-to-decarbonize subsectors.
- Hydrogen is relatively expensive, with cost driven by end-use technologies (FCEVs, industrial heating) and hydrogen delivery and storage costs.
- RNG and RD will likely have limited feedstocks

CDR

- Net-zero will be difficult to impossible without significant CDR

Appendix A: Additional Emissions Comparisons

Additional emissions comparisons were made in the model start year, specifically between DECAL and the CARB Scoping Plan, as well as between DECAL and CARB's GHG Inventory. Agreement is reasonable in both cases (see Figure 54 and Figure 55).

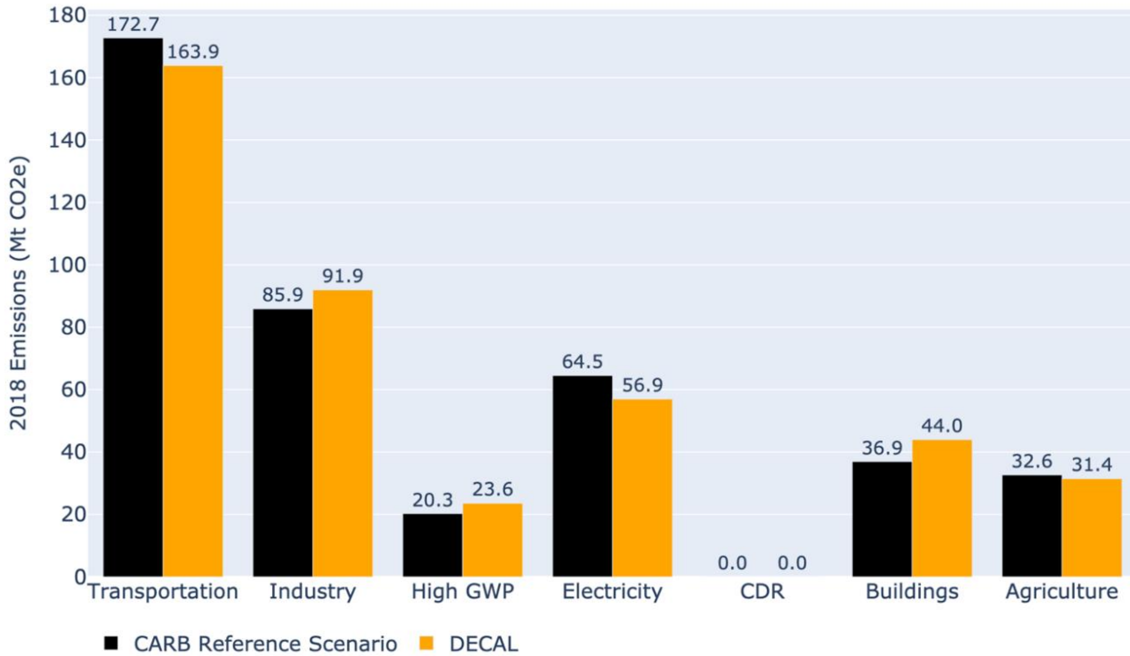


Figure 54: 2018 emissions comparison between DECAL and the CARB Scoping Plan.

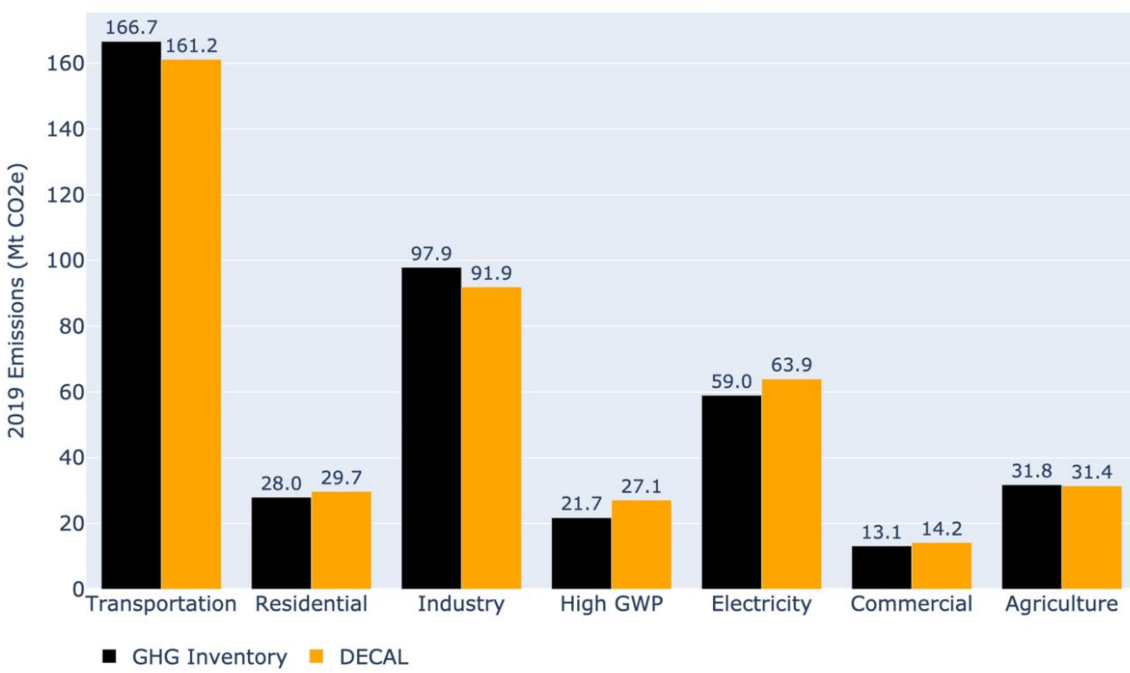


Figure 55: 2019 emissions comparison between DECAL and CARB's GHG Inventory [41].

Appendix B: Additional Insights from Sensitivity Analysis

This appendix lists additional insights (on a sectoral basis) from the sensitivity analysis.

Technology Choice

Transportation (Figure 56)

- LDVs are a larger source of emissions than HDVs, but also more expensive to decarbonize on a $/t basis.
- Incentives and resource/refinery savings drive negative abatement costs for HDV BEVs.
- BEVs and FCEVs lead to larger emissions reductions than PHEVs. PHEVs are expensive from an abatement cost perspective because they mitigate fewer emissions.
- BEVs and FCEVs have similar emissions reductions, but BEVs are significantly cheaper.
- Significant estimated reductions in emissions result from the DECAL assumptions for renewable diesel fuel.
- Top-down modeling objects such as Trains/Planes/Boats and Transportation Other overall account for a small portion of emissions abatement.

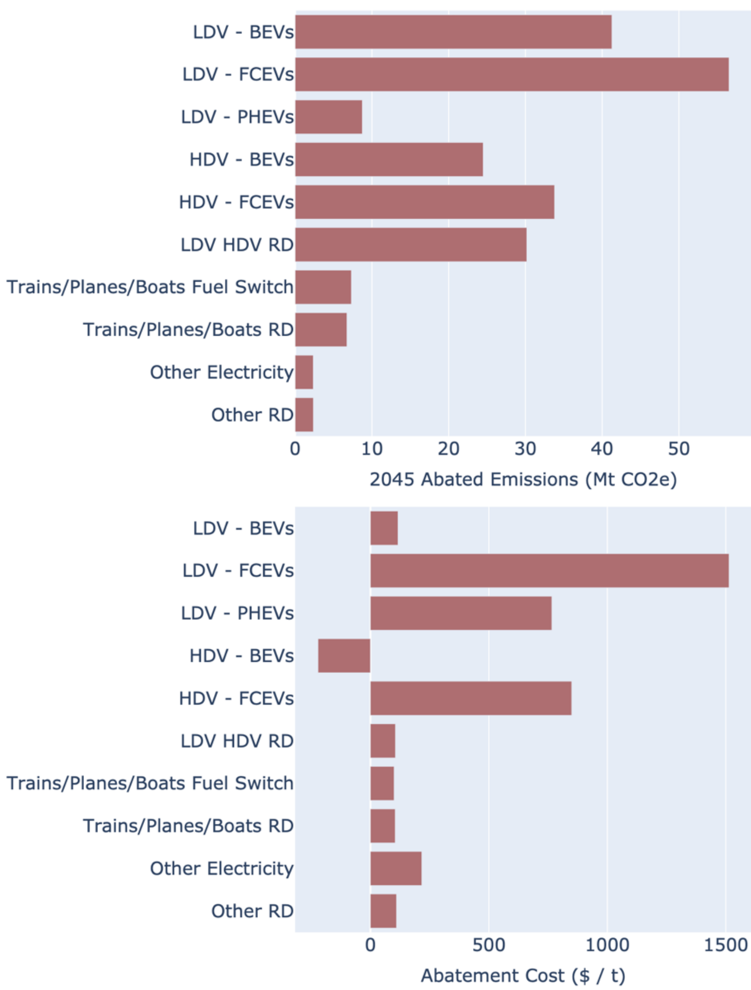


Figure 56: Results of the technology choice sensitivity analysis for the transportation sector.

Industry (Figure 57)

- Emissions from small manufacturing plants are small compared to those for large manufacturing plants and oil & gas.
- HPs have a smaller abatement potential in the large manufacturing sub-sector because petrochemical and mineral plants cannot use HPs due to the heating grade limitations.
- CCS is effective in both emissions reductions and cost.
- Hydrogen is more expensive than other available options.
- Industry "other" is a material portion of Industrial sector emissions. Only a small portion of these emissions come from diesel fuel combustion, so a fuel switch to RD is only a partial solution.

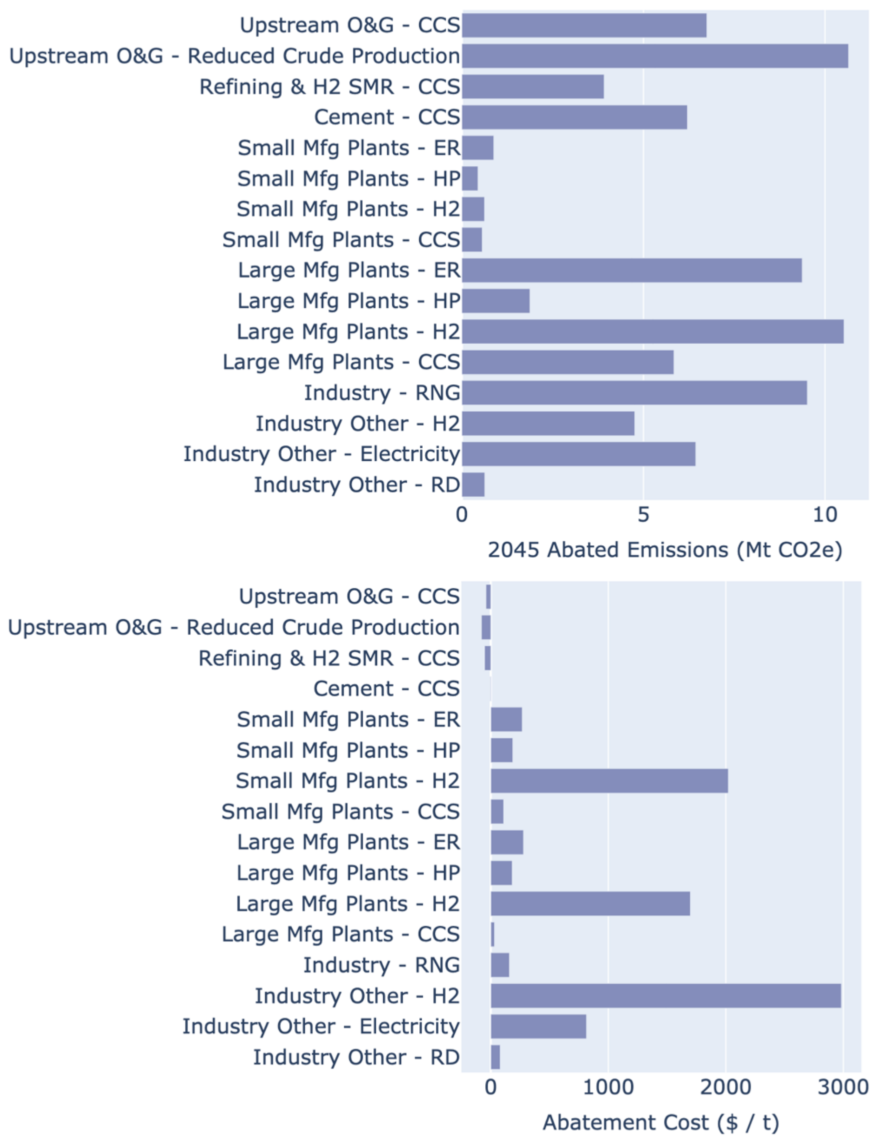


Figure 57: Results of the technology choice sensitivity for the industrial sector.

Buildings (Figure 58)

- Residential emissions are larger than commercial.

- Water and space heating is much more important than ovens and clothes dryers, and water heating is more important than space heating.
- Decarbonizing water heating is cheaper than decarbonizing space heating.
- Residential solar water heating is relatively expensive, but commercial solar water heating is more economical.
- Residential "other" is relatively small portion of buildings sector emissions, but Commercial "other" is relatively large. Only a small portion of Commercial "other" emissions come from diesel burning, and so a fuel switch to RD is only a partial solution.

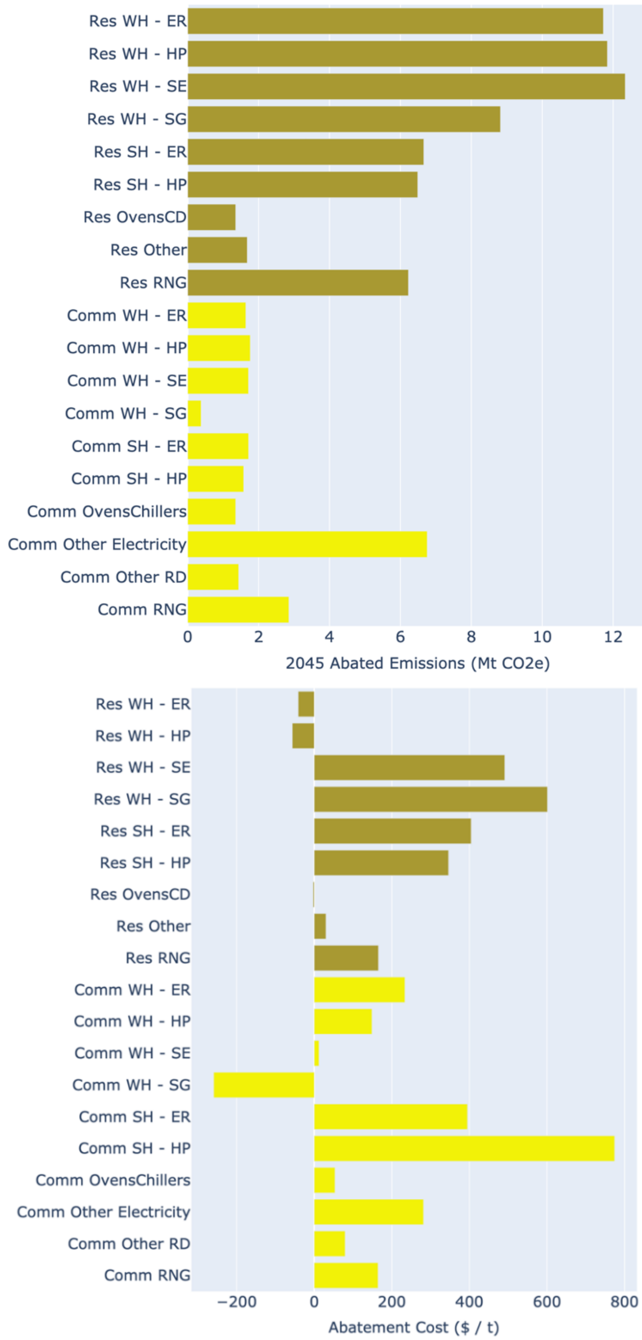


Figure 58: Results of the technology choice sensitivity analysis for the buildings sector.

Agriculture (Figure 59)

- Methane reductions are generally cost effective on $/t basis.
- AD Manure has the highest potential emissions savings.
- Seaweed feed augments are limited in abatement potential due to low eligibility and burp reduction rates.
- Burning of fuels used in agriculture is a relatively small portion of Agricultural sector emissions, with most emissions in this sector coming from Non-Energy sources (methane leaks). However, most agricultural combustion emissions come from diesel fuels. Therefore, RD can be an effective carbon mitigation option.

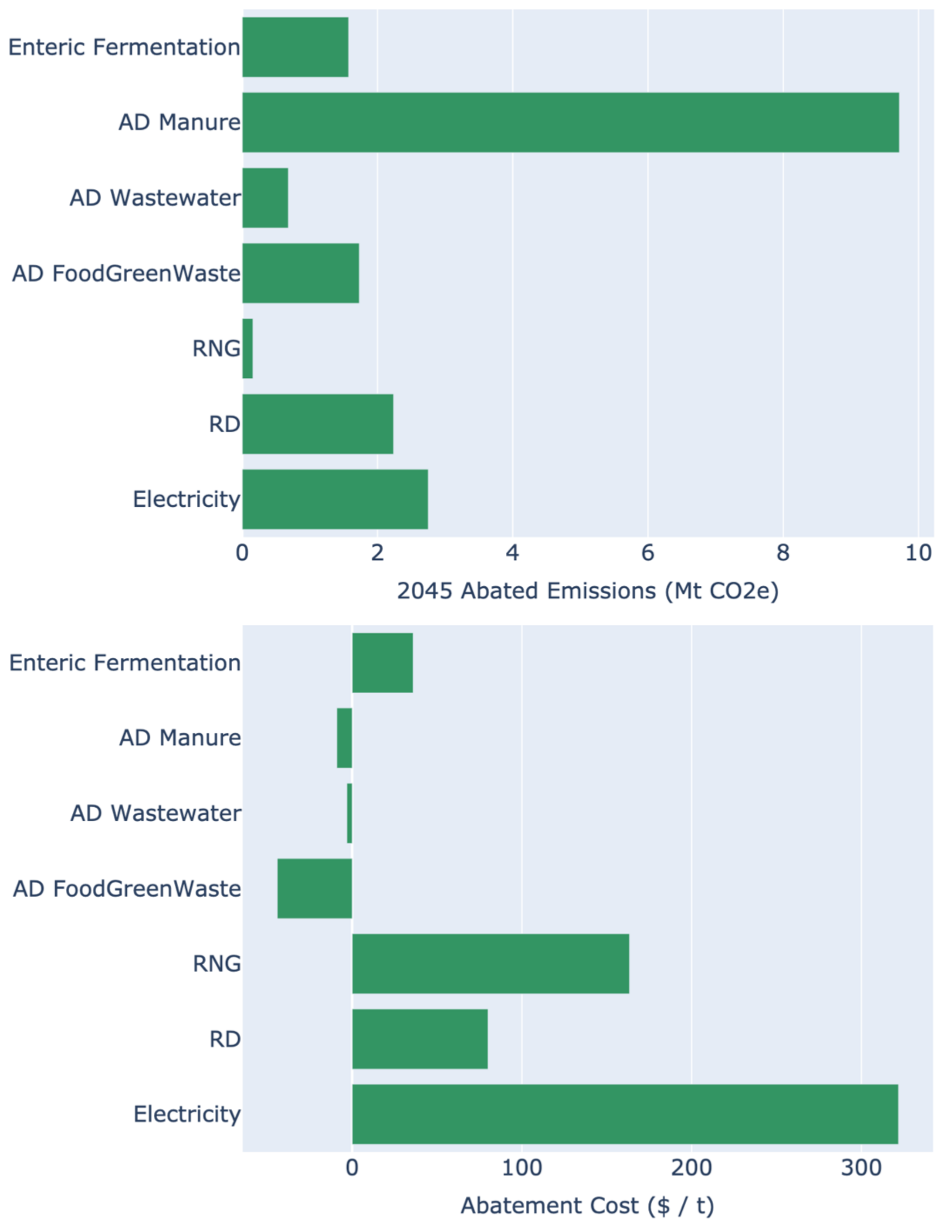


Figure 59: Results of the technology choice sensitivity analysis for the agricultural sector.

Cost

Electricity (Figure 60)

- Overall system costs are most sensitive to T&D, solar, and NGCCS costs.
- Next most sensitive are Li Ion storage and onshore wind.

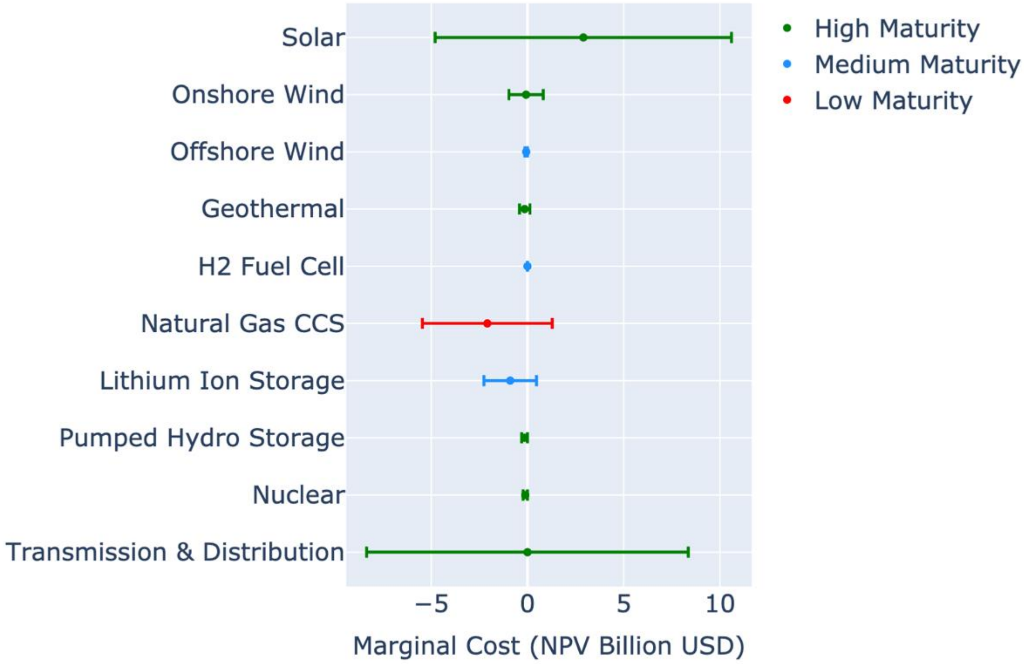


Figure 60: Results of the learning rate sensitivity analysis for the electricity sector.

Buildings (Figure 61)

- Solar thermal water heating is relatively expensive regardless of learning rate assumptions.
- Heat pump water heaters are more cost effective than electric resistance water heaters, regardless of learning rate assumptions.
- Space heat pumps and electric resistance heaters have somewhat comparable costs, with space heat pumps having a larger uncertainty range.
- Overall system costs are not too dependent on electric panel costs.
- Commercial “other” costs are material; more technoeconomic modeling could be warranted.

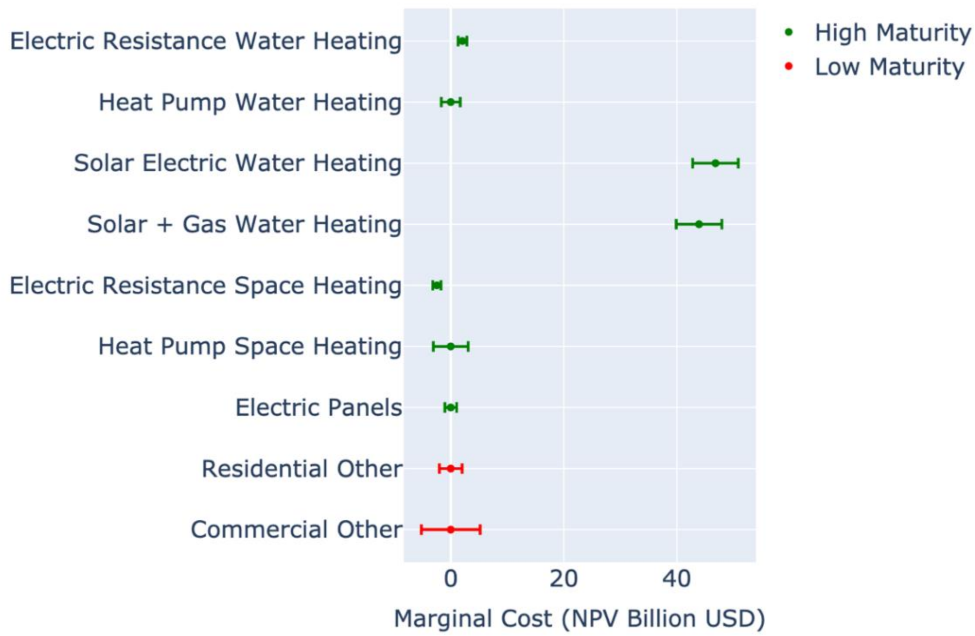


Figure 61: Results of the learning rate sensitivity analysis for the buildings sector.

Transportation (Figure 62)

- FCEVs are more expensive than BEVs regardless of learning rate assumptions.
- Overall system costs are most sensitive to the cost of the vehicle itself. Hydrogen D&S costs are also significant. Charger and refueling station costs are less significant.
- Top down costs of trains/planes/boats as well as "Transportation-other" are relatively insignificant.

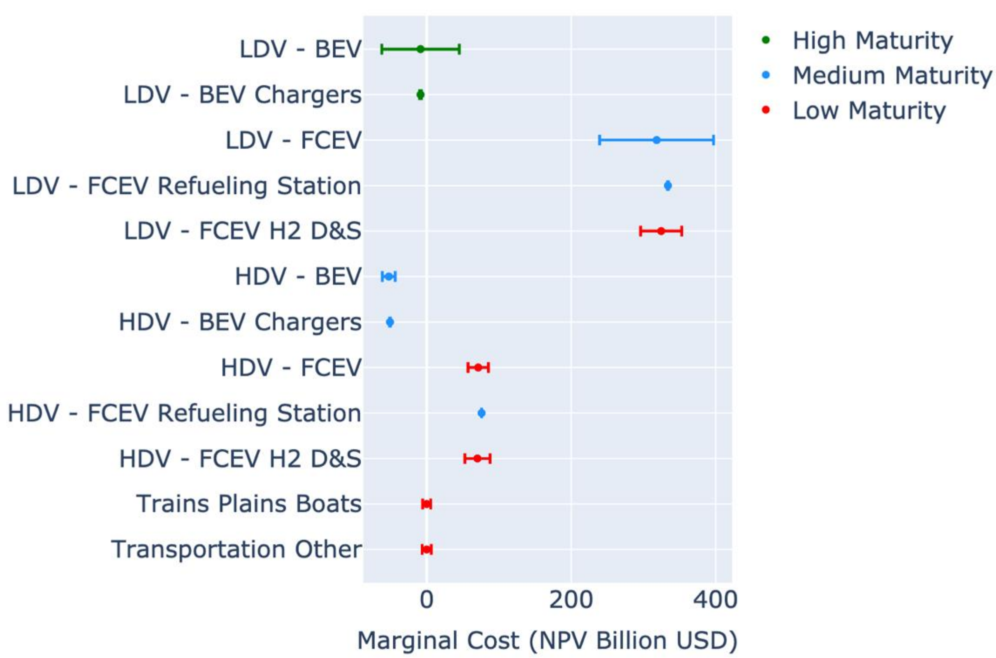


Figure 62: Results of the learning rate sensitivity analysis for the transportation sector.

Industry (Figure 63)

- Uncertainty bounds are insignificant compared to the difference in costs between different technology options.
- CCS and electric resistance are cost effective options (particularly the prior), and hydrogen is more expensive; this is true regardless of learning rate assumptions.
- Top-down industrial costs, which are used in "Industry-other", are material; more technoeconomic modeling could be warranted.

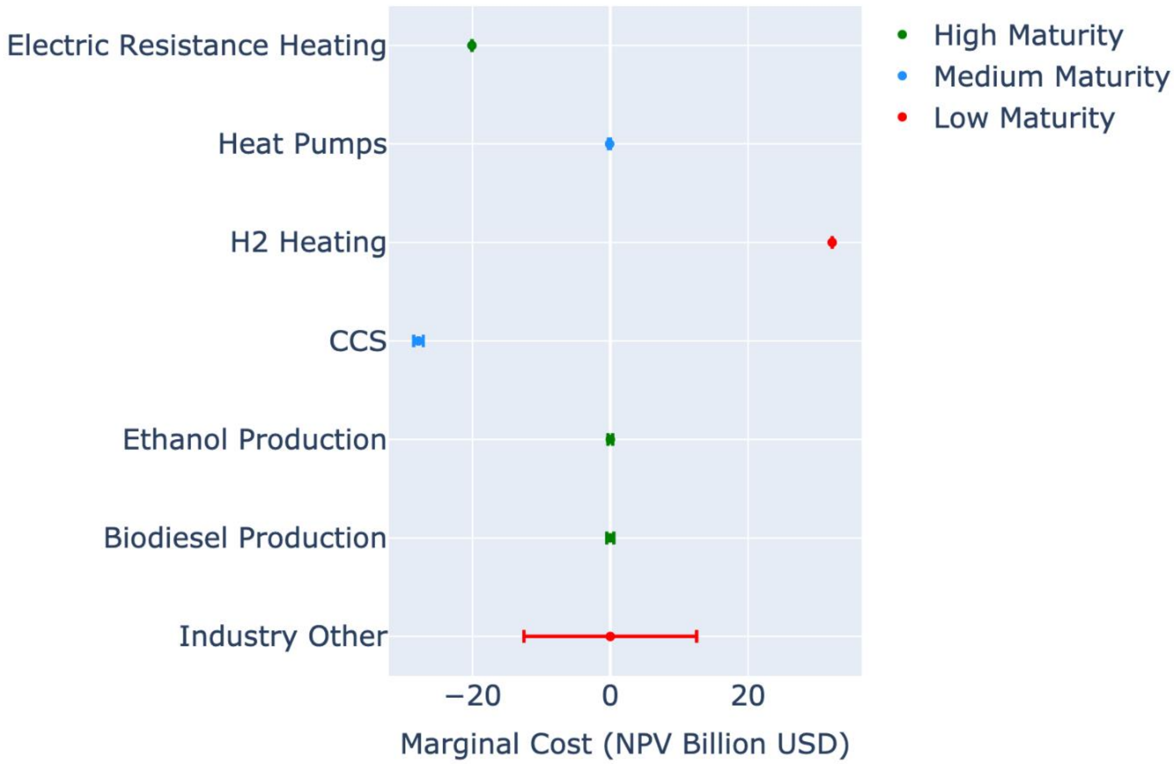


Figure 63: Results of the learning rate sensitivity analysis for the industrial sector.

Hydrogen (Figure 64)

- Hydrogen D&S is the largest driver of cost (assuming that hydrogen is created centrally and then distributed).

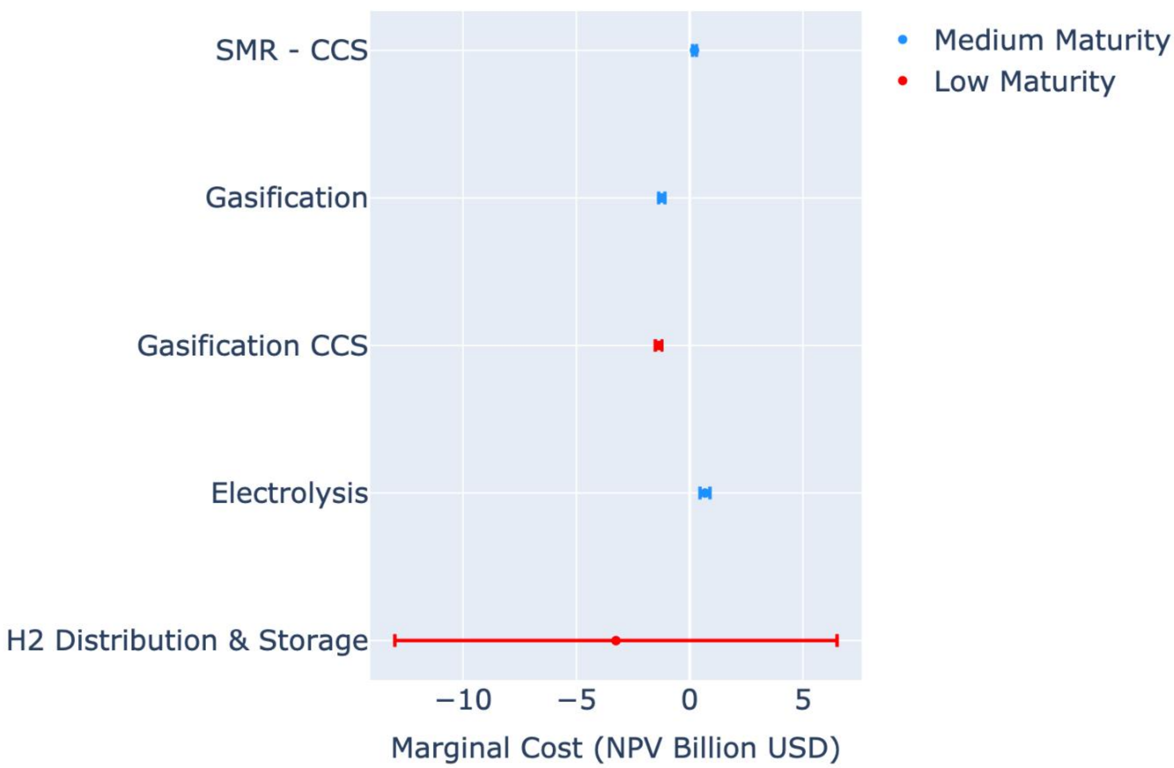


Figure 64: Results of the learning rate sensitivity analysis for the hydrogen sector.

Fuels

Fuel prices are subject to vary based on a multitude of factors including but not limited to global economic conditions, political relations, resource constraints, technological breakthroughs, and more. For these reasons, fuel prices represent a significant uncertainty. A third sensitivity analysis was done to explore the relative importance of fuel prices on system-wide costs. This was done by running the CARB Reference Case and Proposed Scenario while changing the price of key fuels (one at a time) by +/- 50%. Results are shown in Figure 65.

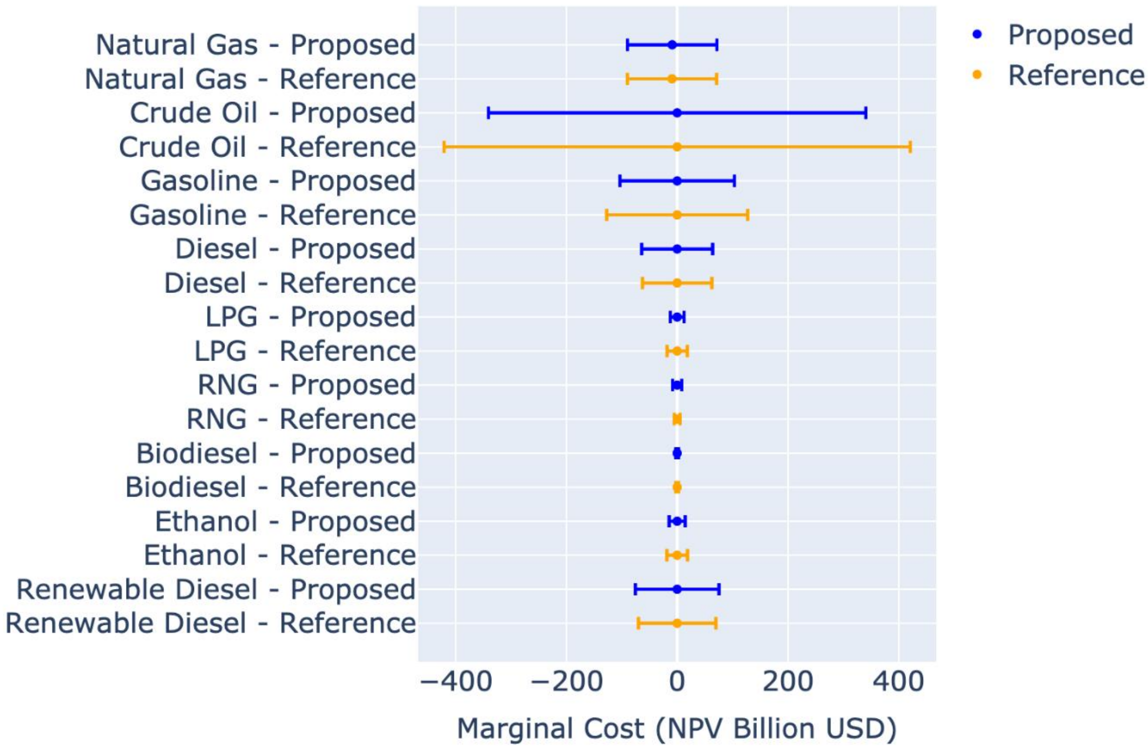


Figure 65: Results of the fuel price sensitivity analysis.

Comparing Figure 65 to the overall marginal cost of LEAP Version of CARB Proposed ($359 billion) it is clear that fuel price uncertainty is significant. In fact, comparing Figure 53 and Figure 65, system-wide costs are generally more sensitive to fuel prices than they are to learning rates. This is true in both the Reference Case and the Proposed Scenario. The price of crude oil has the largest impact on costs (larger than even CDR). The next most important are the costs of gasoline, diesel, and then RD.

Incentives

A final sensitivity analysis evaluated the relative impact of incentives on system-wide costs. To do this, the DECAL version of the CARB Proposed Scenario was estimated with each incentive turned on and off. For those incentives with an end date, a separate evaluation assessed the impact of extending the incentive to the model end year (2045). The results of this analysis are shown in Figure 66.

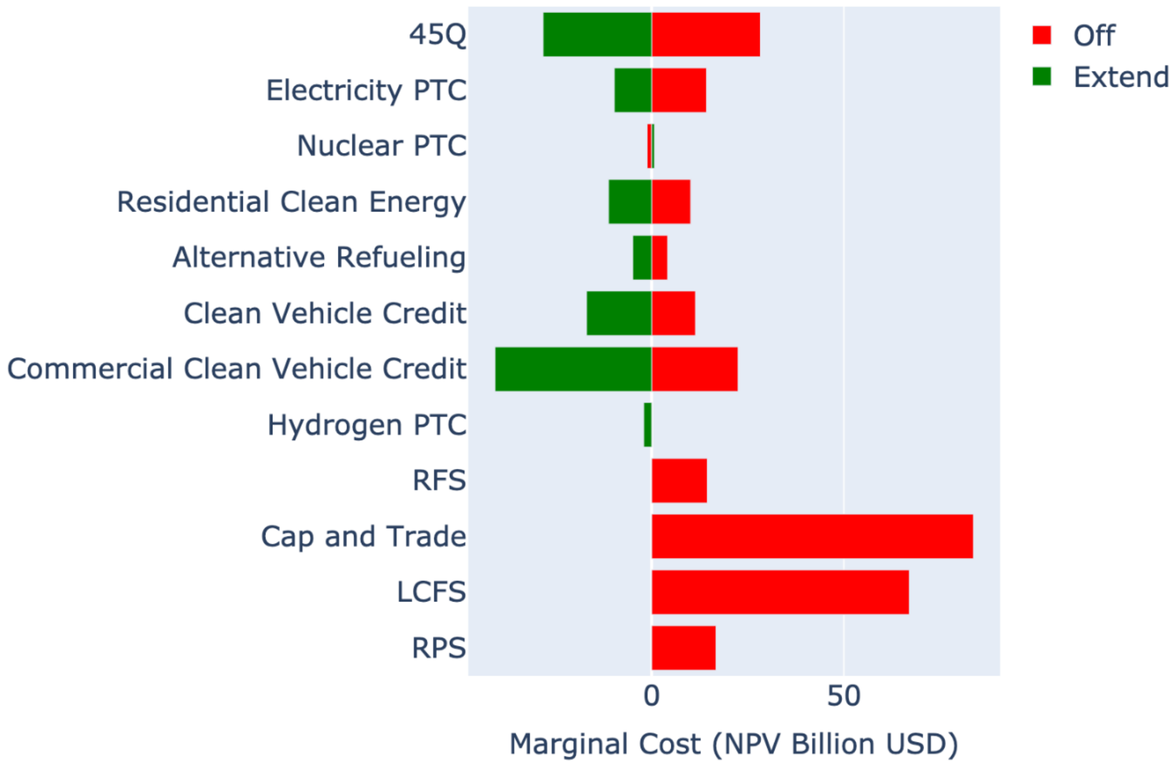


Figure 66: Results of sensitivity analysis on incentives.

Comparing Figure 66 to the overall marginal cost of LEAP Version of CARB Proposed ($359 billion) with incentives on – it is clear that incentives are significant. The highest impact incentives include Cap and Trade, LCFS, 45Q, and the Commercial Clean Vehicle program. Notably, emissions guidelines proposed in the hydrogen PTC guidelines appear to be too stringent for the regulation to have much of an impact.

Appendix C: Modeling Frameworks in LEAP

When selecting the last branch of a tree, LEAP offers several modeling framework options. Each of these frameworks varies in complexity, requires a different set of data inputs, and is governed by a different set of equations. That said, each framework follows the same basic calculation structure, shown below:

$$Result(t) = Volume(t) * Rate(t) \quad (\boldsymbol{Eq.1})$$

In equation 1, the $Result$ is the variable of interest - typically, energy, emissions, or cost – at a particular end branch. The $Volume$ is the number of relevant processes at the end branch, and the $Rate$ is the degree to which said process produces/creates/accounts for the $Result$. Each of these variables may change as a function of time as the model progresses, in response to user-defined levers (see Chapter 2).

A basic example of Eq. 1 is as follows:

$$Energy\ Consumed\ By\ Residential\ Furnaces\ in\ Old\ Dwellings\ in\ CZ1\ in\ 2025 = Number\ of\ Residential\ Furnaces\ in\ Old\ Dwellings\ in\ CZ1\ in\ 2025 * Energy\ Consumed\ Per\ Furnace\ in\ Old\ Dwellings\ in\ CZ1\ in\ 2025\ (\boldsymbol{Eq.2}).$$

To calculate emissions, an additional emission factor is added on:

$$Emission\ Produced\ By\ Residential\ Furnaces\ in\ Old\ Dwellings\ in\ CZ1\ in\ 2025 = Number\ of\ Residential\ Furnaces\ in\ Old\ Dwellings\ in\ CZ1\ in\ 2025 * Energy\ Consumed\ Per\ Furnace\ in\ Old\ Dwellings\ in\ CZ1\ in\ 2025 * NG\ Emissions\ Per\ Unit\ Energy\ (\boldsymbol{Eq.3}).$$

However, Eq. 3 is essentially another form of Eq. 1, if written as follows:

$$Emissions\ Produced\ By\ Residential\ Furnaces\ in\ Old\ Dwellings\ in\ CZ1\ in\ 2025 = Number\ of\ Residential\ Furnaces\ in\ Old\ Dwellings\ in\ CZ1\ in\ 2025 * Emissions\ Produced\ Per\ Furnace\ in\ Old\ Dwellings\ in\ CZ1\ in\ 2025\ (\boldsymbol{Eq.4})$$

Where,

$$Emissions\ Produced\ Per\ Furnace\ in\ Old\ Dwellings\ in\ CZ1\ in\ 2025 = Energy\ Consumed\ Per\ Furnace\ in\ Old\ Dwellings\ in\ CZ1\ in\ 2025 * NG\ Emissions\ Per\ Unit\ Energy (\boldsymbol{Eq.5}).$$

As another example, for the cost of heat pumps, the equation essentially looks as follows:

$$Cost\ of\ Heat\ Pumps\ in\ Old\ Dwellings\ in\ CZ1\ in\ 2032 = Number\ of\ Heat\ Pumps\ Sold\ in\ Old\ Dwellings\ in\ CZ1\ in\ 2032 * Cost\ Per\ Heat\ Pump\ in\ Old\ Dwellings\ in\ CZ1\ in\ 2032\ (\boldsymbol{Eq.6})$$

In this way, Eq. 1 provides the basic rationale of LEAP calculations, which is that a variable of interest can be calculated using a volume and a rate. LEAP's modeling frameworks allow users to either add or subtract variables – and correspondingly add or subtract detail/complexity –into Eq. 1. This is a basic and powerful paradigm used by many models, bearing strong resemblance, for example, to the Kaya Identity [57].

Demand

Modeling frameworks used in DECAL's Demand Area are listed in Table 14.

Modeling Framework	Description
Top-down	This is the most basic modeling method, in which the $Volume$ is the Number of California's – equal to 1 – and the $Rate$ is the amount of energy/emissions produced per California's. In this way, the relevant amount of energy/emissions is essentially specified in a top-down fashion. This method is relevant for areas where bottom-up modeling could not be done, either due to data sparsity or bandwidth issues, but it is well-known that energy consumption/emissions production exists. Good examples are trains, planes, and boats, where energy consumption and emissions are tracked by CARB, but the team did not do a deep dive in these areas.
Technology With Energy Intensity	This is LEAP's standard modeling method. The $Volume$ is entered in directly, or in some cases, it is helpful to break down $Volume$ into an $Activity\ Level$ and a $Percent\ Share$ or $Saturation$. For example, to define the number of residential pool pumps in CZ1, we first define the number of homes in CZ1, and then the percentage of those homes that have pool pumps.
Stock and Flow	In this modeling method, LEAP asks users for the number of processes/devices in the start year, projected sales, the age distribution of the current fleet, and the statistical likelihood of retirement in each year, and then LEAP calculates the $Volume$ over time endogenously. A major benefit of stock and flow is users can specify the sales variable, rather than the $Volume$ directly, which is more reflective of real-life policy. Stock and flow also helps capture the effect of market resistance/lag time.
Transportation Stock and Flow	In addition to breaking down $Volume$ as described in Stock and Flow, LEAP also breaks down $Rate$ into $Vehicle\ Miles\ Traveled$ and $Fuel\ Economy$.

Table 14: DECAL Modeling Frameworks, Demand Area.

Transformation

LEAP's Transformation area operates on the same basic principle described in Eq. 1, but with the added complexity that the Demand Area drives the Transformation Area. To reconcile this complexity, LEAP calculates the $Output\ Required$ for a given process, and then calculates the amount of energy needed to meet that output. The $Output\ Required$ for a given process is calculated based on fuel demand, imports/export adjustments, the stock of capacity, and the dispatch rule.

For example, say that 100 GJ/yr of gasoline are demanded in the Demand Area, there are 20 GJ/yr of export requirements, and there are two available processes, each capable of producing 70 GJ/yr of gasoline. Utilizing a user-selected dispatch rule, LEAP determines how to dispatch the 140 GJ/yr of capacity. For example, the user can tell LEAP to deploy all capacity, which would result in 100% capacity factors for both processes, but 20 GJ/yr of excess exports (40 GJ/yr of exports in total). Or the user can tell LEAP to utilize process 1 completely, and then utilize process 2, resulting in 100% capacity factor of process 1, a ~70% capacity factor for process 2, and 0 excess exports (20 GJ/yr of exports total). Or the user can tell LEAP to dispatch both processes equally, resulting in ~85% capacity factors for both processes, and 0 excess exports (20 GJ/yr of exports total). Of course, many other configurations are possible. In the end, however, calculating the $Output\ Required$ for each process allows us to think about Transformation processes in a similar manner to Eq. 1.

Once the $Output\ Required$ for each process is known, LEAP can calculate feedstock requirements and auxiliary energy demand. Feedstock is the raw material needed in units of energy, for example, the amount of crude oil needed to produce a given amount of gasoline. Auxiliary fuel is the energy used in the process itself, for example, the amount of electricity used in the process of turning crude oil into gasoline. LEAP roughly calculates process-based and auxiliary energy demand as follows:

$$Feedstock(t) = \frac{Output\ Required(t)}{Process\ Efficiency(t)}\ (\boldsymbol{Eq.7})$$

$$Auxilary\ Fuel\ Demand(t) = Output\ Required(t) * Auxilary\ Energy\ Required\ Per\ Unit\ Ouput(t)\ (\boldsymbol{Eq.8})$$

As previously mentioned, feedstock and auxiliary fuel demand create additional demand for Transformation processes lower in the tree. Emissions can be calculated by adding emission factors onto Auxiliary Fuel Demand, in a similar manner to Eq. 3 – 6 above. Cost is calculated by charging capital costs upon installing new capacity, as well as variable and fixed O&M costs for ongoing operations.

$$\begin{aligned} Cost(t) = {} & Capacity\ Added(t) * Capital\ Price(t) + \\ & Capacity(t) * Fixed\ OM\ Price(t) + \\ & Output\ Required(t) * Variable\ OM\ Price(t) \end{aligned}\ (\boldsymbol{Eq.9})$$

Transformation calculations follow the same basic pattern shown in Eq. 1. In the case of Transformation calculations, the $Volume$ is simply the $Output\ Required$, and the $Rate$ is entered via $\frac{1}{Process\ Efficiency}$ as well as via $Auxilary\ Energy\ Required\ Per\ Unit\ Ouput$. In the case of emissions, an emissions factor is added, which can easily be fit to the form of Eq. 1, as done in Eq. 3 – 6. In the case of cost, the $Volume$ is the $Capacity\ Added$, $Capacity$, and $Output\ Required$, and the $Rate$ is capital, fixed, and variable OM prices. One major difference between the Demand and Transformation areas is that in the Demand Area, $Volume's$ are exogenous to the system (they are essentially entered by the user), whereas in the Transformation Area, $Volums$ are endogenous to the system (they are calculated internally). This is another way of saying that in LEAP, the Demand Area drives the Transformation Area.

As in the Demand area, LEAP has different modeling frameworks available in the Transformation area, which allow users to add or subtract complexity to the basic structure described above. In addition, the modeling frameworks differ in how they add new capacity into the system, and how they dispatch generators. Modeling frameworks used in DECAL's Transformation Area are listed in Table 15.

Modeling Framework	Description
Transmission & Distribution	This modeling framework only allows for one process, which must exactly meet demand without any export/import adjustments ($Output\ Required$ comes directly from the Demand Area). The only relevant data-entry is the process efficiency, which is effectively used to increase the amount of energy required by later Transformation modules. For example, if 100 GJ/yr of electricity is demanded in the Demand Area, and T&D is 98% efficient, then the electricity sector will be required to produce ~102 GJ/yr of electricity. This framework has no concept of capacity, cost, or auxiliary fuel use (only Eq. 7 is relevant).
Cost Without Capacity	In this modeling framework, LEAP will always exactly meet demand plus exogenous import/export adjustments (0 excess imports/exports). There is no concept of capacity, and instead, users must tell LEAP the proportion of output that comes from each process (on a fractional basis) as a function of time. In DECAL, if there is more than one process, the process share is controlled with a lever. As there is no concept of capacity, all costing is baked into the Variable O&M price (Eq. 7 – 9 all apply, but Eq. 9 is abstracted).
Cost and Capacity	This is LEAP's standard modeling framework, unchanged from Eq. 7 – 9 above. With this framework, users instruct LEAP exactly how to add or subtract capacity, and how to dispatch. In DECAL, capacity additions and subtractions are mostly handled via user-defined levers, whereas the dispatch rule is hard coded. Note that controlling capacity in this way can lead to a mismatch in supply and demand, which will result in imports/exports.
Optimization	Optimization is fundamentally different than other modeling techniques in that the model is given information about generators and constraints, and then it decides how to build out capacity and dispatch plants. With other transformation modules, the user tells LEAP how to build out capacity and dispatch. The optimization model has perfect foresight (it can see all information for the whole modeling period in the start year), and then adds and deploys capacity so as to minimize cost subject to the following constraints: 1) the clean generation constraint [19], 2) load shape constraints [20], 3) availability constraints [21], 4) maximum capacity constraints [22], and 5) a planning reserve margin [23]. Once the optimization model has made its decisions, Eq. 7 – 9 still apply.

Table 15: DECAL Modeling Frameworks, Transformation Area.

[19] The Clean Generation Constraint defines the portion of electricity generation that must be created from "clean" sources; each resource is assigned a "clean qualified" fraction (e.g., 100% for renewables, 90% for NGCCS by default to match its carbon capture rate, etc.).
[20] The timing of electricity demand is calculated in the demand area, which forms a constraint on electricity supply; fundamentally this is because electricity supply must always equal electricity demand.
[21] This constraint accounts for the fact that renewables (solar, wind, hydro) are not always available on a diurnal and/or seasonal basis.
[22] This constraint accounts for the idea that some generators are limited by resource availability or political constraints, such as hydro, nuclear, and geothermal.
[23] The 17.5% planning reserve margin attempts to capture resilience and reliability constraints.

Non-Energy

The Non-Energy area has only one modeling framework, that is to enter top-down emissions and costs. The top-down emissions and costs can be made a function of other variables within DECAL, and thus are not necessarily hard-coded. We will call the prior methodology Non-Energy Top-down – data that is truly hard coded – and the latter methodology Non-Energy Bottom-up – results that are a function of other variables within DECAL.

Disclaimers

Please note that the information provided here was intended only as an introduction to LEAP's internal mechanisms to provide a feel for how LEAP works, and overall aid understanding. While some detail/complexity was left out, LEAP's internal calculations do follow the basic principles outlined above. In the end, LEAP's internal calculations are not actually too complex – they stem from Eq. 1 and differ in how the $Volumes$ and $Rates$ are calculated. Additionally, please note that this discussion/explanation was somewhat catered to DECAL, in that some modeling configurations that are available in LEAP but not used in DECAL are not discussed. Finally, please note that some internal vocabulary was used to aid dialogue (for example, terms like $Volume, Rate$, $Output\ Required$ would not be found in LEAP's documentation). For further details on how each modeling framework works, refer to LEAP's website (https://leap.sei.org/), help page (https://leap.sei.org/help/leap.htm#t=Demand%2FDemand_Properties_Wizard.htm), and online tutorials.

Appendix D: DECAL Modeling Methodologies & Raw Data Inputs

The table below is a guide for data sources which were used to populate DECAL. The excel workbooks loaded into LEAP can be found at this link: https://sccs.stanford.edu/california-projects/pathways-carbon-neutrality-california. These excel workbooks contain the raw data as well the data manipulations that were needed to prepare for entry into DECAL. Raw data sources are linked throughout the excel sheets and are also summarized in the table below.

Top Folder	Workbook	Data Contained in the Workbook	Major Raw Data Sources
Buildings	Residential.xlsx	• Number of existing homes • Projections for new homes • Percent saturation • Energy intensity • Electric load profiles • Vintage profiles • Survival profiles • Cost • Efficiency conversions • F Gases: Annual charge size, annual leak rate, EOL charge size, EOL leak rate, GWP	• US Census Bureau [link] • California Department of Finance Population Projections [link] • 2019 Residential Appliance Saturation Study [link] • California Energy Commission Energy Consumption Database [link] • EIA Updated Buildings Sector Appliance and Equipment Cost and Efficiency [link] • CARB's California's High Global Warming Potential Gases Emission Inventory, Technical Support Document, "HFC Emission Factors.xlsx" CARB F-Gas Inventory, May 2021 (made privately available)
	• 8760 Load Shape Calc.xlsx • 8760 normalized.xlsx • 8760 to 288 Load.xlsx • Demand Response Water Heater.xlsx	• Residential load profiles	• NREL Commercial and Residential Hourly Load Profiles for all TMY3 Locations in the United States [link]
	1 – Commercial Summary.xlsx	• Summary of workbooks in row below • Square footage • Commercial Other electricity & NG • Vintage profiles • Survival profiles • Cost • Efficiency conversions • F Gases: Annual charge size, annual leak rate, EOL charge size, EOL leak rate, GWP	• California Energy Commission Energy Consumption Database [link] • EIA Updated Buildings Sector Appliance and Equipment Cost and Efficiency [link] • CARB's California's High Global Warming Potential Gases Emission Inventory, Technical Support Document, "HFC Emission Factors.xlsx" CARB F-Gas Inventory, May 2021 (made privately available)
	• College.xlsx • Food Store.xlsx • Health.xlsx • Large Office.xlsx	• Number of devices • Energy per device • Percent saturation (sf basis) • Energy per square-foot	• 2006 CEC Commercial End Use Survey (CEUS) [link] • Commercial Buildings Energy Consumption Survey (CBECS) [link]

	• Lodging.xlsx • Misx.xlsx • Refrigerated Warehouse.xlsx • Restaurants.xlsx • Retail.xlsx • School.xlsx • Small Office.xlsx • Unrefrigerated Warehouse.xlsx		• EIA Updated Buildings Sector Appliance and Equipment Cost and Efficiency [link] • NREL Commercial and Residential Hourly Load Profiles for all TMY3 Locations in the United States [link]
	• LADWP.xlsx • PGE.xlsx • SCE.xlsx • SDGE.xlsx • SMUD.xlsx	• Commercial load profiles	• NREL Commercial and Residential Hourly Load Profiles for all TMY3 Locations in the United States [link]
	ResComm Panel and AdjFactors.xlsx	• Residential and commercial panel upgrade costs	• Various online sources (provided)
Electricity Generation	• Electricity Generation.xlsx	• Installed capacities, minimum capacities, maximum capacities • Generator efficiencies • Costs (CAPEX, VOM, FOM, fuels) • Electricity imports • Availability shape • Top-down remaining electricity • Natural gas emission factor • Availability shapes	• Decarbonizing the Electricity Sector [24] • California GHG Inventory [link] • CEC 2019 Total System Electric Generation [link] • CEC Electric Generation Capacity and Energy [link]
	• 2019 Renewable Profiles CAISO.xlsx • 2020 Renewable Profiles CAISO.xlsx • 2021 Renewable Profiles CAISO.xlsx	• Availability shapes for current solar, wind, and hydro	• CAISO Supply [link]
	Distributed PV and Storage.xlsx	• Behind-the-meter solar PV and Li-ion battery capacity	• Distributed Generation Interconnection Program Data [link]
Transportation	• automobiles.xlsx • emfacCalcs.xlsx • hybridVMT.xlsx • LDV technoeconomics.xlsx	• Vehicle stocks • Vehicle sales volumes • Vehicle fuel efficiencies • Vehicle miles travelled • Vintage profiles • Survival profiles • VMT degradation profiles • Total cost of ownership • Fraction of miles driven by electric motor vs combustion engine Cost of hydrogen refueling stations	• Kelley blue book [link] • Car and driver [link] • Decarbonizing the Transportation Sector [23] [link] • CARB – EMFAC [link] Argonne National Laboratory - Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains [link]
	• LDV_load_shapes.xlsx • EVSE Rates.docx • bevChargingCostTemplate.xlsx	• Electric vehicle charging load shape Cost of electric vehicle chargers	• CEC - Home Charging Access in California [link] • ScienceDirect – Scalable probabilistic estimates of electric vehicle charging given

			observed driver behavior [link 1], [link 2] • Home Advisor – How much does an electric car charging station cost [link] • US DOE – Costs Associated With Non-Residential Electric Vehicle Supply Equipment [link] • Alternative Fuels Data Center [link] CEC CALeVIP Cost Data [link]
	• FCEV_refueling.xlsx	• Cost of FCEV refueling stations Number of refueling stations per vehicle	• MarketWatch - How Many Gas Stations Are In U.S.? How Many Will There Be In 10 Years? [link] • Zippia - How Many Cars Are In The Us? [link] US DOE – Hydrogen Fueling Stations Cost [link]
Industry	refiningAndSMR.xlsx	• FCCU and CHP CCS technoeconomics • Refinery inputs, outputs, and auxiliary fuels • SMR CCS technoeconomics • SMR input and output fuels' Refineries and Steam Methane Reformers	• CEC Petroleum Watch, March 2020 [link] • CARB fuel inventory [link] • CARB GHG inventory [link] • Argonne National Laboratory – Assessment of Potential Future Demands for Hydrogen in the United States [link] • Decarbonizing the Industrial Sector [link] • The Hydrogen Opportunity [link] • EPA FLIGHT [link] Hydrogen Tools [link]
	renewableDiesel.xlsx	• Renewable Diesel refining input fuels, output fuels, auxiliary fuels, and costs	• Diamond Green Diesel presentation [link] • Oil and Gas Journal – Diamond Green Diesel to build new Port Arther Plant [link] • Darling Ingredients 2021 Annual Report [link] • Darling Ingredients Sept. 2021 ESG Report [link] • Phillips66 News Releases [link] • CARB LCFS Renewable Diesel Fuel Pathway Reports [link 1], [link 2]

			• REG Carbon Intensity Report: Renewable Diesel [link]
	chpsAndSgs.xlsx	• Crude oil production – CHP energy use and technoeconomics • Crude oil production – steam generator energy use and technoeconomics	• Decarbonizing the Industrial Sector [link] • ScienceDirect – Boiler Efficiency [link] • CARB fuel inventory [link] • CARB GHG inventory [link] • US EPA – eGRID [link] • EIA – Today in Energy [link]
	mfg_td.xlsx	• Technoeconomics and energy use for food production, petrochemical and mineral production, timber drying, natural gas transmission and distribution, and other manufacturing	• Decarbonizing the Industrial Sector [link] • PG&E - California Industrial Energy Efficiency Market Characterization Study [link] • NREL - Potential Cost-Effective Opportunities for Methane Emission Abatement [link] • CARB fuel inventory [link] • CARB GHG inventory [link]
	• New Hydrogen.xlsx	• Plant costs • Plant efficiency • Plant auxiliary fuel use • Emission factors	• The Hydrogen Opportunity [27] • Comparison of Commercial, State-of-the-Art, Fossil-Based Hydrogen Production Technologies [link] • Electrofuel Synthesis from Variable Renewable Electricity: An Optimization-Based Techno-Economic Analysis [link] • Techno-economic analysis and life cycle assessment of hydrogen production from different biomass gasification processes [link]
	• Cement.xlsx • Cement Technoeconomics (Original).xlsx	• Plant activity level • Plant energy intensity • Process emissions per unit energy • Cost of CCS retrofits. The original technoeconomics includes fuel prices and incentives. The abatement costs inputted into DECAL do not include fuel prices and incentives, as they are endogenously included in other places in the model.	• Decarbonizing the Industrial Sector [22]
Bioenergy	Bioenergy.xlsx	• Existing capacity (biogas, ethanol production, biodiesel production) • Biogas potential • Process efficiency • Cost	• The Bioenergy Opportunity [25]

		• Auxiliary fuel use	
Prices	Fuels.xlsx	• Fuel prices	• Index Mundi [link] • World Bank [link] • Alternative Fuels Data Center [link] • IEA Bio-jet Fuel costs [link] • American Gas Foundation [link]
	Incentives.xlsx	• Incentive prices	• Cap and Trade Dashboard [link] • LCFS Monthly Activity Reports [link] • EPA RIN Trades and Price Information [link] • Internal Revenue Code [link] • Alternative Fuels Data Center [link]
	LCFS.xlsx	• LCFS carbon intensity by fuel	• LCFS Pathway Certified Carbon Intensities [link] • LCFS Data Dashboard [link]
Other	2022-sp-PATHWAYS-data-E3.xlsx	• Data outputs from E3's/CARB's scoping plan report. Used to help set some levers and miscellaneous variables.	• Draft 22 Scoping Plan Documents [link]
	Calibrate Other.xlsx	• Used to calculate abatement price of Residential, Commercial, Transportation, and Industry "Other"	N/A
	DR Overbuilding.xlsx	• Used to calculate the amount of overbuilding necessary in demand response scenarios	N/A
	Efs.xlsx	• Emission factors in cases where LEAP defaults are not used	• EPA Emission Factors for Greenhouse Gas Inventories [link]
	RNG Blend.xlsx	• Setting the current blend fraction of RNG	• LCFS Data Dashboard [link]
	Technology Maturity Survey.xlsx	• Results from the technology maturity survey. Poll was sent to expert staff on the Pathways team. Results helped define maturity buckets described in Chapter 2.	N/A
	Transport_Industrial_ BottomUp_FGasses.xlsx	• F Gases: Annual charge size, annual leak rate, EOL charge size, EOL leak rate, GWP (for Industrial and Transport sectors)	• CARB's California's High Global Warming Potential Gases Emission Inventory, Technical Support Document, "HFC Emission Factors.xlsx" CARB F-Gas Inventory, May 2021 (made privately available)
	HFC Emission Factors 2021 May 10.xlsx	• Raw bottom-up F-gas data provided by CARB staff (Glenn Gallagher). Used in other spreadsheets in this database.	• CARB's California's High Global Warming Potential Gases Emission Inventory,

			Technical Support Document (made privately available)
	TopDown_Compare.xlsx	• Used to set top down energy usage and non-energy emissions. Done by comparing to GHG inventory.	• California GHG Emission Inventory Data, Fuel Combustion and Heat Data [link]

Table 16: DECAL Data Sources.

Appendix E: DECAL's Tree

DECAL's full tree structure is shown in Table 17. Branches are shown exactly as they appear in DECAL up to the terminal branch, where raw data is ultimately inputted. Detail is only redacted when repetitive – for example, all climate zones in the residential sector have the same sub-tree structure. Recall that LEAP performs calculations at the end branch, and then has the ability to sum up to higher levels for summary purposes.

- Demand
  - Residential
    - Old Dwellings
      - CZ1
        - Lighting
          - Indoor Lighting
          - Outdoor Lighting
        - Misc Equipment
          - Pool Pump
          - Spa
          - Electric Spa Heat
          - Well Pump
          - Electric Misc
          - Gas Pool Heat
          - Gas Spa Heat
          - Gas Misc
          - Gas Pool Heat RNG
          - Gas Spa Heat RNG
          - Gas Misc RNG
        - Appliances
          - Microwave
          - TV
          - PC
          - Home Office
        - SF Appliances
          - Electric Clothes Dryer
          - First Refrigerator
          - Second Refrigerator
          - Freezer
          - Electric Range Oven
          - NG Clothes Dryer
          - NG Range Oven
          - Clothes Washer
          - Dishwasher
          - Electric Range Oven Replacement
          - Electric Clothes Dryer Replacement
          - New Electric Panels
        - Space Heating
          - SH ER
          - SH HP
          - SH Aux ER
          - SH NG
          - SH Aux NG
          - SH HP Replacement
          - SH ER Replacement
        - Water Heating

            - ER WH
            - NG WH
            - HP WH Replacement
            - ER WH Replacement
            - Gas Solar WH Replacement
            - Electric Solar WH Replacement
            - DR HP WH Replacement
            - DR ER WH Replacement
          - Cooling
            - Central AC
            - Room AC
            - Evaporative Cooling
            - HP Cooling
          - Fans
            - Furnace Fan
            - Ceiling Fan
        - CZ2
        - CZ3
        - CZ4
        - CZ5
        - CZ6
        - CZ7
        - CZ8
        - CZ9
        - CZ10
        - CZ11
        - CZ12
        - CZ13
      - New Dwellings
      - Other Fuels
        - Biodiesel
        - Diesel
        - Kerosene
        - Renewable Diesel
        - LPG
        - Wood
        - New Electricity
    - Commercial
      - College
        - SCE
          - Lighting
            - Interior Lighting
            - Exterior Lighting
          - Misc Equipment
            - Electricity Misc
            - Air Compressor
            - Motors
            - Electricity Process
            - Gas Misc
            - Gas Process
            - RNG Misc
          - Fans
            - Vent
          - Appliances

            - Refrigerator
            - Office Equipment
        - SF Appliances
            - NG Range Oven
            - Electric Range Oven
            - Electric Range Oven Replacement
            - New Electric Panels
        - Space Heating
            - Gas Boiler
            - Electric Boiler
            - Electric Boiler Replacement
            - SH NG
            - SH ER
              SH ER Replacement
            - SH HP
            - SH HP Replacement
            - SH ER Radiator
        - Water Heating
            - NG WH
            - HP WH Replacement
            - ER WH
            - ER WH Replacement
            - Gas Solar WH Replacement
            - Electric Solar WH Replacement
        - Cooling
            - Rooftop AC
            - HP Cooling
            - Gas Fired Chiller
            - Centrifugal Chiller
            - Centrifugal Chiller Replacement
    - PGE
    - SDGE
    - SMUD
    - LADWP
- Small Office
- Large Office
- Restaurant
- Retail
- Food Store
- Refrigerated Warehouse
- Unrefrigerated Warehouse
- School
- Health
- Lodging
- Misc
- Non CEUS
- Other Fuels
    - Biodiesel
    - Diesel
    - Ethanol
    - Gasoline
    - Kerosene
    - Renewable Diesel
    - LPG

        - Wood
        - New Electricity
  - Industry
    - Cement
      - Cemex
        - Biomass
        - Coal Unspecified
        - LPG
          Municipal Solid Waste
        - Natural Gas
        - Petroleum Coke
        - Tires
        - Electricity
        - RNG
      - CalPortland Mojave
      - CalPortland Oro Grande
      - Hanson Permanente
      - Lehigh Southwest Tehachapi
      - Lehigh Southwest Redding
      - Mitsubishi Cushenbury
      - National
      - Cemex CCS
        - Electricity
        - Natural Gas
        - RNG
      - CalPortland Mojave CCS
      - CalPortland Oro Grande CCS
      - Hanson Permanente CCS
      - Lehigh Southwest Tehachapi CCS
      - Lehigh Southwest Redding CCS
      - Mitsubishi Cushenbury CCS
      - National CCS
    - Food
      - Plants Greater 100k CO_2
        - General Use
          - Electricity
        - Process Heating
          - Natural Gas
          - RNG
          - Electric Resistance
          - Hydrogen Transmitted
          - Heat Pump
        - CCS
          - Electricity
          - Natural Gas
          - RNG
      - Plants 25k_100k CO_2
      - Plants Under 25k CO_2
    - Petrochemicals and Minerals
      - Plants Greater 100k CO_2
        - General Use
          - Electricity
        - Process Heating
          - Natural Gas

        - RNG
        - Electric Resistance
        - Hydrogen Transmitted
      - CCS
        - Electricity
        - Natural Gas
        - RNG
    - Plants 25k_100k CO_2
    - Plants Under 25k CO_2
  - Timber Drying
    - General Use
      - Electricity
    - Process Heat
      - Wood
      - Natural Gas
      - RNG
    - CCS
      - Electricity
      - Natural Gas
      - RNG
  - Other
    - Electricity
    - Natural Gas
    - RNG
    - Biodiesel
    - Diesel
    - Ethanol
    - Gasoline
    - Renewable Diesel
    - Refinery Gas
    - Coal Bituminous
    - LPG
    - Wood
    - Biomass
    - Lubricants
    - Replacement Electricity
    - Replacement Hydrogen
  - NG TD Leaks Not From Compressors
    - Natural Gas
  - DAC
    - HT Aqueous Solution
      - Electricity
    - LT Solid Sorbent
      - Electricity
      - Heat Pump
- Transportation
  - LDVs
    - LDA Passenger Car
      - Diesel
      - Gasoline
      - Natural Gas
      - Electricity
      - Hydrogen

        - Hybrid
        - Electricity Replacement
        - Hydrogen Replacement
        - Hybrid Replacement
    - T1 Light Duty Truck T1
    - T2 Light Duty Truck T2
    - T3 Medium Duty Truck
- HDVs
    - T4 Light Heavy Duty Truck 1
        - Diesel
        - Gasoline
        - Natural Gas
        - Electricity
        - Hydrogen
        - Electricity Replacement
        - Hydrogen Replacement
    - T5 Light Heavy Duty Truck 2
    - T6 Medium Heavy Duty Truck
    - T7 Heavy Heavy Duty Truck
    - Bus
    - T6 OOS Medium Heavy Duty Truck OOS
    - T7 OOS Heavy Heavy Duty Truck OOS
    - T7 Port Heavy Heavy Duty Port
    - MC Motorcoach
    - MH Motorhome
- Aviation
    - Ethanol
    - Gasoline
    - Jet Kerosene
    - Avgas
    - Renewable Jet Fuel
    - Hydrogen Transmitted
    - Electricity
- Rail
    - Biodiesel
    - Diesel
    - Renewable Diesel
    - Hydrogen Transmitted
    - Electricity
- Water Borne
    - Biodiesel
    - Diesel
    - Ethanol
    - Gasoline
    - Renewable Diesel
    - Hydrogen Transmitted
- Other
    - Biodiesel
    - Diesel
    - Renewable Diesel
    - LPG
    - Lubricants

- Electricity
  - Agriculture
    - Natural Gas
    - RNG
    - Biodiesel
    - Diesel
    - Ethanol
    - Gasoline
    - Kerosene
    - Renewable Diesel
    - Electricity
  - Remaining Electricity
    - Remaining Electricity Flat
    - Remaining Electricity Shape
- Transformation
  - Ethanol Production
    - Fermentation
  - Biodiesel Production
    - Transesterification
  - Refinery FCCU and CHP
    - LA Refinery Marathon
    - El Segundo Refinery Chevron
    - Richmond Refinery Chevron
    - Golden Eagle Refinery Marathon
    - Benecia Refinery Valero
    - LA Refinery Phillips66
    - Torrance Refinery PBF
    - Martinez Refinery PBF
    - Rodeo Refinery Phillips66
    - Wilmington Refinery Ultramar
    - Kern Oil And Refining
    - Greka Refining
    - Lunday Thafard South Gate
    - San Joaquin Refining
    - Valero Wilmington Refinery
  - Renewable Diesel Refining
    - New Plants
    - Converted Plants
  - Crude Oil Extraction
    - Crude Oil Extraction
  - Steam Generators
    - Steam Generators
    - Steam Generators With CCS
  - Crude Oil CHP
    - Elk Hills
    - Midway Sunset
    - Kern River
    - Sycamore
    - South Belridge
    - Salinas River
    - Berry
    - Berry Placerita
    - Kern River Eastridge
    - Western Pwr and Steam
    - Berry Tanne Hills 18

        - Southeast Kern River
        - Taft 26C
        - Cymric 36W
        - Dome Project
        - Coalinga 25D
        - McKittrick
        - Lost Hills
        - Coalinga
        - Aera San Ardo
        - Cymric 6Z
        - Cymric 31X
        - Welport Lease
    - Distributed PV
        - Solar Distributed
    - Electricity TD
        - Electricity
    - Electricity Production Exogenous
        - NW Coal
        - NW Natural Gas
        - NW Nuclear
        - NW Large Hydro
        - NW Small Hydro
        - NW Unspecified
        - NW Biomass
        - NW Geothermal
        - NW Solar
        - NW Wind
        - SW Coal
        - SW Natural Gas
        - SW Nuclear
        - SW Large Hydro
        - SW Small Hydro
        - SW Unspecified
        - SW Biomass
        - SW Geothermal
        - SW Solar
        - SW Wind
        - Natural Gas CCS
        - Hydrogen Fuel Cell
        - Landfill Gas
        - AD Manure
        - AD WWTP
        - AD Food Green Waste
    - Hydrogen TDS
        - Hydrogen TDS
    - Hydrogen Production
        - SMR Chevron Richmond
        - SMR PBF Martinez
        - SMR Air Products Wilmington
        - SMR Torrance Refining
        - SMR Valero Benicia
        - SMR Air Liquide Rodeo
        - SMR Marathon Carson
        - SMR Phillips66 Wilmington
        - SMR Air Products Carson

        - SMR Air Products Martinez Waterfront Rd
        - SMR Marathon Martinez
        - SMR Air Liquide El Segundo
        - SMR Chevron El Segundo
        - SMR Air Products Martinez
        - SMR Phillips66 Rodeo
        - SMR Praxair Ontario
        - SMR San Joaquin Refining
        - SMR Air Products Sacramento
        - New SMR
        - New SMR RNG
        - New SMR CCS
        - New SMR RNG CCS
        - New ATR
        - New ATR RNG
        - New ATR CCS
        - New ATR RNG CCS
        - New Gasification
        - New Gasification CCS
        - New Electrolysis
    - Electricity Production Optimal
        - Solar Current
        - Solar SPGE
        - Solar Kramer
        - Solar Northern California
        - Solar Sacramento River
        - Solar SCADSNV
        - Solar SW
        - Solar Tehachapi
        - Solar Westlands
        - Wind Current
        - Wind SPGE
        - Wind NW
        - Wind Sacramento River
        - Wind SCADSNV
        - Wind SW
        - Wind WY
        - Offshore Wind Cape Mendocino
        - Offshore Wind Diablo Canyon
        - Offshore Wind Humboldt Bay
        - Offshore Wind Morro Bay
        - Large Hydro
        - Small Hydro
        - Old Natural Gas
        - New Natural Gas
        - Natural Gas CCS Retrofit
        - New Natural Gas CCS
        - Geothermal
        - Biomass
        - Nuclear
        - Hydrogen Fuel Cell
        - BTM Li Ion
        - Li Ion
        - Pumped Hydro
        - New Pumped Hydro

- CNG Production
  - Compression
- CRNG Production
  - Compression
- RNG Compressors
  - RNG Compressor
  - RNG Compressor Upgraded
- RNG Production
  - Current Landfill Gas
  - Current AD Manure
  - Current AD WWTP
  - Current AD Food Green Waste
  - New AD Manure
  - New AD WWTP
  - New AD Food Green Waste
- NG Compressors
  - NG Compressor
  - NG Compressor Upgraded

- Non-Energy
  - Residential
    - Methane Leaks
      - Methane
    - Aerosols
      - HFC134a
      - HFC152a
      - HFC227ea
      - HFC4310mee
    - Foams
      - HFC134a
      - HFC245fa
    - Fertilizer
      - Nitrous Oxide
    - Refrigerants
      - Annual_Emissions
        - First Refrigerator
        - Second Refrigerator
        - Freezer
        - Central AC
        - SH HP
        - Room AC
        - HP WH
        - Dehumidifier
        - HP Clothes Dryer
        - Portable AC
      - EOL_Emissions
  - Commercial
    - Fertilizer
      - Nitrous Oxide
    - Aerosols
      - HFC134a
      - HFC152a
      - HFC4310mee
    - Fire Protection
      - PFC14

- HFC125
- HFC227ea
- HFC236fa

- Foams
  - HFC134a
  - HFC245fa
- Refrigerants
  - Annual_Emissions
    - HP WH
    - SH HP
    - Rooftop AC
    - Centrifugal Chiller
    - Cold Storage Large
    - Cold Storage Medium
    - Cold Storage Small
    - Non Retail Refrigerator Large
    - Non Retail Refrigerator Medium
    - Non Retail Refrigerator Small
    - Non Retail Refrigerator Sub Small
    - Food Processing and Dispensing Equipment
    - Ice Maker
    - Retail Refrigerator Large
    - Retail Refrigerator Medium
    - Retail Refrigerator Small
    - Retail Refrigerator Sub Small
    - Stand Alone Refrigerator
    - Vending Machine
    - Water Cooled Drinking Fountain
  - EOL_Emissions

- Industry
  - Cement Process CO_2
    - Cemex
    - CalPortland Mojave
    - CalPortland Oro Grande
    - Hanson Permanente
    - Lehigh Southwest Tehachapi
    - Lehigh Southwest Redding
    - Mitsubishi Cushenbury
    - National
  - Refrigerants
    - Annual_Emissions
      - Industrial Cooling Large
      - Industrial Cooling Medium
      - Industrial Cooling Small
    - EOL_Emissions
  - Semiconductor Manufacturing
    - C2F6
    - C3F8
    - C4F8
    - CF4
    - HFC23
    - NF3
    - SF6

- Aerosols
  - HFC134a
  - HFC152
  - HFC4310mee
- Fire Protection
  - CF4
  - HFC125
  - HFC227ea
  - HFC236fa
- Foams
  - HFC134a
  - HFC245fa
- Solvents
  - CF4
  - HFC245fa
  - HFC365mfc
  - HFC4310mee
  - Other PFC and PFE
- Waste
  - CH4
  - N2O
- Landfill
  - Landfill CH4
  - Landfill N2O
- Fugitives
  - Not Specified
  - Solvents and Chemicals
  - Oil and Gas

- Transportation
  - Refrigerants
    - Annual_Emissions
      - Transport Refrigerated Units
      - Refrigerated Shipping Containers
      - Ships
      - Mobile Vehicle AC LDVs
      - Mobile Vehicle AC HDVs
      - Mobile Vehicle AC Buses
    - EOL_Emissions
  - Aerosols
    - HFC134a
  - Infrastructure Buildout
    - LDV BEV Home Chargers
    - LDV BEV Commercial Chargers
    - HDV BEV Chargers
    - FCEV Infrastructure
- Agriculture
  - Residue Burning
    - Methane
    - Nitrous Oxide
  - Crop Residue
    - Nitrous Oxide
  - Fertilizer
    - Nitrous Oxide

            - Liming
                - Carbon Dioxide
            - Manure
                - Nitrous Oxide
            - Enteric Fermentation
                - Cattle
                - Other Livestock
            - Histosol Cultivation
                - Nitrous Oxide
            - Manure Management
                - Methane
                - Nitrous Oxide
            - Rice Cultivation
                - Methane
            - RNG Averted Methane
                - Manure
                - WWTP
                - Food Green Waste
        - Electricity Production
            - SF6
            - TD Cost
        - Carbon Removal
            - Electricity Production
                - NGCCS
            - Hydrogen Production
                - New SMR CCS
                - New SMR RNG CCS
                - New ATR CCS
                - New ATR RNG CCS
                - New Gasification CCS
                - SMR Chevron Richmond
                - SMR PBF Martinez
                - SMR Air Products Wilmington
                - SMR Torrance Refining
                - SMR Valero Benicia
                - SMR Air Liquide Rodeo
                - SMR Marathon Carson
                - SMR Phillips66 Wilmington
                - SMR Air Products Carson
                - SMR Air Products Martinez Waterfront Rd
                - SMR Marathon Martinez
                - SMR Air Liquide El Segundo
                - SMR Chevron El Segundo
                - SMR Air Products Martinez
                - SMR Phillips66 Rodeo
                - SMR Praxair Ontario
                - SMR San Joaquin Refining
                - SMR Air Products Sacramento
            - Industry
                - Steam Generators
                    - Steam Generators With CCS
                - CHPs

- Elk Hills
    - Midway Sunset
    - Kern River
    - Sycamore
    - South Belridge
    - Salinas River
    - Berry
    - Berry Placerita
    - Kern River Eastridge
    - Western Pwr and Steam
    - Berry Tanne Hills 18
    - Southeast Kern River
    - Taft 26C
    - Cymric 36W
    - Dome Project
    - Coalinga 25D
    - McKittrick
    - Lost Hills
    - Coalinga
    - Aera San Ardo
    - Cymric 6Z
    - Cymric 31X
    - Welport Lease
- Refining
    - LA Refinery Marathon
    - El Segundo Refinery Chevron
    - Richmond Refinery Chevron
    - Golden Eagle Refinery Marathon
    - Benecia Refinery Valero
    - LA Refinery Phillips66
    - Torrance Refinery PBF
    - Martinez Refinery PBF
    - Rodeo Refinery Phillips66
    - Wilmington Refinery Ultramar
    - Kern Oil And Refining
    - Greka Refining
    - Lunday Thafard South Gate
    - San Joaquin Refining
    - Valero Wilmington Refinery
- Timber Drying
    - Timber Drying
- Petrochemicals and Minerals
    - Plants Greater 100k CO_2
    - Plants 25k_100k CO_2
    - Plants Under 25k CO_2
    - Plants Greater 100k CO_2
    - Plants 25k_100k CO_2
    - Plants Under 25k CO_2
- Cement
    - Cemex
    - CalPortland Oro Grande
    - CalPortland Mojave
    - Mitsubishi Cushenbury
    - National
    - Hanson Permanente

            - Lehigh Southwest Tehachapi
            - Lehigh Southwest Redding
        - DAC
            - DAC
- In State Incentives
    - LCFS Fuel Production Pathway
        - Electricity Emissionless
        - Electricity Hydrogen Fuel Cell
        - Electricity Municipal Solid Waste
        - Electricity AD Manure
        - Electricity AD WWTP
        - Electricity Food Green Waste
        - Electricity Natural Gas
        - Electricity RNG
          Electricity Biomass
        - Hydrogen SMR
        - Hydrogen SMR CCS
        - Hydrogen SMR RNG CCS
        - Hydrogen ATR
        - Hydrogen ATR CCS
        - Hydrogen ATR RNG
        - Hydrogen ATR RNG CCS
        - Hydrogen Gasification
        - Hydrogen Gasification CCS
        - Hydrogen Electrolysis
        - Ethanol
        - Biodiesel
        - Renewable Diesel
        - CNG
        - CRNG
    - LCFS Carbon Removal Pathway
        - NGCCS
        - Old Hydrogen
        - Steam Generators
        - CHPs
        - Refining
        - DAC
    - Cap and Trade
        - Credits
    - RPS
        - Credits

Table 17: DECAL's Tree Structure.

Appendix F: Levers

Most levers available in DECAL are summarized in Table 18.

Sector	Lever Type	Levers
Residential	Cost Levers	• Cost over time of appliances • Cost over time of top-down residential electrification • Cost over time of refrigerant mitigation
	Bottom-up Levers	• Sales rate of electric space heaters, water heaters, ovens, and clothes dryers • Space heater technology choice: heat pump, electric resistance • Water heater technology choice: heat pump, electric resistance, thermal solar water heater (electric backup), thermal solar water heater (gas backup) • RNG blend fraction • Refrigerant GWPs • Refrigerant EOL Leak Rate • Water heater load shape: standard, solar focused
	Top-down Levers	• Adoption rate of Residential Other electrification
Commercial	Cost Levers	• Cost over time of appliances • Cost over time of top-down commercial electrification • Cost over time of refrigerant mitigation
	Bottom-up Levers	• Sales rate of electric space heaters, water heaters, ovens, and gas fired chillers • Space heater technology choice: heat pump, electric resistance • Water heater technology choice: heat pump, electric resistance, thermal solar water heater (electric backup), thermal solar water heater (gas backup) • RNG blend fraction • Refrigerant GWPs • Refrigerant EOL Leak Rate
	Top-down Levers	• Adoption rate of Commercial Other electrification • Commercial Other renewable diesel blend conversion
Industry and Fossil Fuel Production	Cost Levers	• Cost over time of CCS • Cost over time of manufacturing fuel switch (food, petrochemicals and minerals) • Cost over time of NG compression • Cost over time of DAC • Cost over time of top-down industry fuel switch
	Bottom-up Levers	• CCS capture rate (by default 90%) • CCS adoption rate (separately for each subsector – cement, food, petrochemicals and minerals, timber drying, crude oil CHPs, crude oil SGs, refineries) • Fuel switching adoptions rate (separately for each subsector – food, petrochemicals and minerals) • Fuel switching technology choice (separately for each subsector – food, petrochemicals and minerals): heat pump, electric resistance, hydrogen • Direct air capture adoption rate • Direct air capture technology choice (low temperature solid sorbent, high temperature aqueous solution) • DAC load shape: fraction solar focused

		• NG compressor upgrade adoption rate • RNG blend fraction • Refrigerant GWPs • Refrigerant EOL Leak Rate • Refinery dispatch rule: proportional to capacity (refinery operations ramp down with less demand) vs full capacity (refinery operations are maintained with less demand and fuels are exported)
	Top-down Levers	• Adoption rate of Industry Other fuel switch • Industry Other fuel switch technology choice: electricity, hydrogen • Industry Other renewable diesel blend conversion
Transportation	Cost Levers	• Cost over time of automobiles (separately for each vehicle type and ZEV option) • Cost over time of transportation infrastructure (BEV chargers, hydrogen refueling stations) • Cost over time of top-down transportation fuel switch • Cost over time of refrigerant mitigation
	Bottom-up Levers	• Sales rate of LDV ZEVs and HDV ZEVs • LDV ZEV technology choice: BEVs, FCEVs, hybrids • HDV ZEV technology choice: BEVs, FCEVs • VMT multiplier over time • Fuel economy multiplier over time • Bioenergy blend fractions: Ethanol, Biodiesel, Renewable Diesel, CRNG • Refrigerant GWPs • Refrigerant EOL Leak Rate • LDV load shape: residential focused, commercial focused • HDV load shape: fraction solar focused
	Top-down Levers	• Aviation adoption rate • Aviation technology choice: electricity, hydrogen, renewable jet fuel • Rail adoption rate • Rail technology choice: electricity, hydrogen • Rail renewable diesel blend conversion • Boat adoption rate • Boats renewable diesel blend conversion • Adoption rate of Transportation Other fuel switch • Transportation Other renewable diesel blend conversion
Agriculture	Cost Levers	• Seaweed feed additive mitigation cost over time
	Top-down Levers	• Agriculture Other technology rate • RNG blend conversion • Agriculture Other renewable diesel blend conversion • Seaweed feed additive adoption rate • Seaweed feed additive fraction of cattle applicable • Seaweed feed additive burp reduction rate
Electricity Production	Cost Levers	• Cost of generators/storage over time (separately for each generator type – e.g., solar, wind, offshore wind, geothermal, hydrogen fuel cell, biomass, NGCCS, battery storage, pumped storage, etc.). • Cost of transmission & distribution over time
	Bottom-up Levers	• Clean generation constraint

		• Imports multiplier: nuclear, coal, and natural gas • Renewable qualified NGCCS, Hydro, & Nuclear: separately control how clean the optimization model considers NGCCS (default 90%), hydro (default 100%), and nuclear (default 100%) • RNG blend fraction
Hydrogen Production	Cost Levers	• Cost of new hydrogen generation over time (separately for SMR, SMR CCS, ATR, ATR CCS, Gasification, Gasification CCS, Electrolysis) • Cost of distribution & storage over time
	Bottom-up Levers	• CCS adoption rate on refinery SMR plants • RNG blend fraction for refinery SMR plants • New hydrogen technology choice: SMR, SMR RNG, SMR RNG CCS, ATR, ATR RNG, ATR RNG CCS, Gasification, Gasification CCS, Electrolysis
Bioenergy Production	Cost Levers	• Cost over time for RNG production, separately for landfill gas, wastewater, food/green waste, manure • Cost over time for Ethanol production • Cost over time for Biodiesel production
	Bottom-up Levers	• RNG Production adoption rate: separately for landfill gas, wastewater, food/green waste, manure • Fraction of biogas used for electricity production (balance of biogas is upgraded to RNG) • In-state Biodiesel production multiplier • In-state Ethanol production multiplier • In-state Renewable Diesel production adoption rate • In-state Renewable Diesel production: fraction coming from existing plant retrofit vs new plants
Commodities and Incentives	Cost Levers	• Credit prices for incentives listed in Chapter 2 • End-dates (where applicable) for incentives listed in Chapter 2 • Durations (where applicable) for incentives listed in Chapter 2 • Fuel prices for fuels listed in Chapter 2

Table 18: DECAL's Levers.

Appendix G: Additional Resources

The following resources can be found at this link: https://sccs.stanford.edu/california-projects/pathways-carbon-neutrality-california

- A full excel export of the DECAL model – including the entire tree structure, raw data inputs, and expressions.
- The DECAL LEAP file as well as installation instructions. The model can be explored and even run for free, but results cannot be saved without subscribing to LEAP for an annual fee.
- In order to run DECAL systematically and efficiently, a VBA program was created; said program can input large batches of levers from an excel file into DECAL, and then output results back into excel. At the link, you can view the excel files that were used to create the scenarios shown in this report. There is one master excel file that contains all the scenario definitions, and then several others that contain results. At the webpage, you will also find the VBA script itself. Note however it is only possible to run the script as a LEAP subscriber.
- Finally, in order to interpret results quickly and effectively, a python program was created to take graphing instructions populated in excel, as well as result files created using the aforementioned VBA script, and produce legible graphs.

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