INSIGHTS FROM THE CALIFORNIA ENERGY POLICY SIMULATOR

On the state's current greenhouse gas emission trajectory and six policy opportunities for deepening emission reductions

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Cover photo credit

Altus via Flickr: The image shows a scene along Highway 8 in southern California, juxtaposing the progress California has made so far in renewable electricity and the immediate challenge ahead in transportation.

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SUMMARY FOR POLICYMAKERS

California is a global leader in the clean energy transition, having met its 2020 economy-wide target of reducing greenhouse gas (GHG) emissions below 1990 levels four years ahead of schedule.[1] The state is now working toward a 2030 target of reducing emissions 40 percent below 1990 levels, meaning statewide emissions must fall below 260 million metric tons (MMT) of carbon dioxide equivalent (CO_2e).[2]

California's most recent inventory data shows emissions of 424 MMT of CO_2e in 2017, so hitting the 2030 target will require reducing emissions by an average of 13 MMT of CO_2e annually, or nearly double the annual rate of 7 MMT of CO_2e over the past decade.[3]

We developed a California version of the Energy Policy Simulator (EPS) to analyze the state's expected future emission trajectory and the likelihood it will deliver the reductions needed to meet California's 2030 emissions goal. The California EPS finds that existing climate policies reduce 2030 emissions by more than 100 MMT of CO_2e, but leave emissions about 25 MMT of CO_2e above the 2030 target.

The model also identifies and evaluates a set of six preferred policies that together hit the emissions reduction goal. Policy recommendations were crafted to reach the 2030 target based on maximizing cost-effectiveness and political feasibility while reducing technological risk.

The model finds these policy recommendations yield direct economic benefits of $7 billion, calculated as the present value of cumulative economic effects through 2030.[4] The model also estimates the monetary value of avoided costs due to climate change damage and public health improvements due to cleaner air. Health and climate effects, referred to as social impacts, are estimated at $14 billion cumulatively through 2030. Economic and social impacts total $21 billion through 2030.

The EPS evaluates economy-wide carbon pricing and dozens of sector-specific policies, enabling new visibility into the effectiveness of different combinations of climate policies. The model is transparent, open source, and freely downloadable, and it has undergone extensive peer review. Model users are able to investigate policy effects by dialing their strength up or down. We offer the option of running the full model or a web-enabled version, which runs in real time and displays about 100 pre-prepared data visualizations.[5]

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[1] Assembly Bill 32, which passed in 2006, established the 2020 target.

[2] More precisely, the target implies a limit of 258.6 MMT of CO_2e (60 percent of 431).

[3] The historical rate is calculated by comparing 2017 emissions at 424.1 MMT CO_2e with 2007 emissions at 490.9 MMT CO_2e, showing a difference of 66.7, yielding the calculation 66.7/10 = 6.67 MMT CO_2e/year. The future rate is calculated as 424.1 – 258.6 = 165.5 over 13 years, yielding 165.5/13 = 12.73 MMT CO_2e/year (CARB 2019).

[4] All monetary values are expressed as net present value in 2017 dollars with a 3 percent discount rate.

[5] Available at california.energypolicy.solutions.

POLICY RECOMMENDATIONS

The first three of the six policy recommendations strengthen existing policies:

1. **Fortify cap-and-trade design** by explicitly linking program emission permit prices to the rate of statewide emission reductions by reforming the program's price floor—the minimum price accepted at emission permit auctions. The cap-and-trade program's price floor should rise more quickly if emissions are not decreasing at a pace consistent with the 2030 target.
2. **Ratchet up clean energy standards on electricity supply**. Senate Bill 100 sets a 60 percent renewable electricity standard for 2030. The recommended enhancement increases zero emission electricity supply by 7 percent, reducing sector emissions to 38 MMT of CO_2e. This level was chosen to align with modeling performed for the state's long-run planning process, which also informs the addition of flexibility resources to the electricity system to ensure supply reliability (California Public Utilities Commission 2019).[6]
3. **Increase transportation sector ambition, increasing the state's zero emission vehicles goal to 7.5 million vehicles by 2030,** up from the current objective of 5 million. The goal is achieved in the modeling by increasing the zero emission vehicle mandate to boost the fraction of zero emission vehicles to 80 percent of new car and light truck sales in 2030.

The three remaining policy recommendations involve new initiatives:

4. **Accelerate building electrification, aiming for advanced electric heat pumps to represent at least 50 percent of new sales of water heaters and space heaters for residential buildings,** including units for new construction and replacements in existing buildings.
5. **Establish a zero emission performance standard for heat applied to the industry sector.** This policy would jump-start the use of existing cost-effective solar thermal heat, a mature and proven technology, while encouraging development of emerging zero emission options.
6. **Introduce a GHG emission performance standard for cement and concrete production.** Cement is the largest source of coal combustion in California (Global Efficiency Intelligence 2019), and is an exciting area for technological innovation (Rissman 2018).

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[6] Flexibility resources are methods that electricity system planners use to ensure electricity supply is sufficient to meet peak loads, as necessary to ensure system reliability. Our modeling uses two flexibility resources: battery storage and demand response (the ability to reduce peak demand, especially by shifting electricity loads to off-peak periods).

The three new policy initiatives merit additional explanation. Starting with building electrification, this recommendation is modeled by a policy increasing the percentage of advanced electric heat pumps in new sales of space or water heating units for home use. While success on the ground will necessitate significant action by local governments and a suite of state-level actions, recent successes in both domains are auspicious.

Industrial zero emission heat performance standards are unprecedented, to our knowledge. The policy could be initially calibrated based on the large potential for solar thermal steam to reduce natural gas use for oil extraction. Oil extraction represents a surprisingly large share of California's natural gas demand—15 to 20 percent—and more than 90 percent of energy used for petroleum extraction goes to generating steam for enhanced production (ICF 2015). Our recommended policy is calibrated to achieve half of the potential identified for solar thermal steam substitution (ICF 2015).

An advanced solar thermal plant built in Lancaster, California, has successfully reached the very high temperatures needed for many industrial processes. Photo source: Heliogen

As other technological options reach commercial viability, they can be integrated into the design of the proposed zero emission heat performance standard. Solar thermal energy has thus far been unable to cost-effectively deliver the very high temperatures needed to produce materials like cement and steel. A Pasadena company has achieved such high temperatures with solar thermal technology by leveraging the latest sensors and software, though the venture is not yet cost competitive (Temple 2019). Another promising, emerging option for zero emission heat for industrial use involves combusting hydrogen produced from electrolysis powered by renewable electricity.

The recommended GHG standard for cement and concrete production focuses on emission performance but remains technology neutral, allowing it to automatically adapt if more cost-effective options emerge. Roughly 90 percent of emission reductions in the California EPS are achieved by retrofitting existing plants for carbon capture and sequestration technology, which extracts carbon dioxide from pollutant outflows for storage in existing underground reservoirs. The remaining reductions are expected from a new method for reducing the emission-intensive inputs required to produce a unit of concrete (while increasing quality).

Alongside this GHG standard, we recommend establishing a border carbon adjustment requiring cement and concrete imports from jurisdictions with weaker climate policies to pay a fee to account for their embedded, unregulated GHG emissions. A border adjustment would level the playing field in the California market for in-state producers. Assembly Bill 398 (California Legislature 2017) recommends considering such an approach.[7] Although a border adjustment policy will carry legal uncertainty until tested in court, this instrument merits serious consideration as a potentially valuable means to manage competitiveness concerns.

CURRENT TRAJECTORY ANALYSIS

To evaluate California's current emission trajectory, we programmed the model with parameters representing existing policy commitments. In this Current Trajectory Scenario, existing policy is broadly defined to include rules backed by the force of law as well as stated commitments, such as goals set by executive order. The scenario assumes policies perform as expected based on the state's most recent long-term planning exercise, the California Air Resources Board (CARB) 2017 Scoping Plan (CARB 2017a; CARB 2017b).[8]

While the Current Trajectory Scenario generally assumes successful policy implementation, the expectation with respect to "sustainable community strategies" is an exception: Under the Current Trajectory Scenario the policy is half as effective as long-range planning had expected.

Sustainable community strategies encompass efforts to build walkable neighborhoods close to jobs and to diversify mobility choices, thus shortening commutes and reducing the need for car travel. This policy is promising given its large carbon mitigation potential and well-established co-benefits related to health, traffic congestion, and quality of life. Nonetheless, state-level efforts thus far have been hampered by lack of direct authority. Land use and transportation decisions are mostly under local control, and new data shows that motor vehicle miles traveled per capita are increasing again after a period of decline (CARB 2018c). The Newsom administration is revising its approaches under current law, and it is possible new legislation could expand state policymaker authority. Still, the setbacks in this area must be considered in charting a path to the 2030 goal. The level of effectiveness was selected in an effort to balance these factors.

We also use the California EPS to develop a range of possible future emission outcomes, testing different assumptions about policy effectiveness.

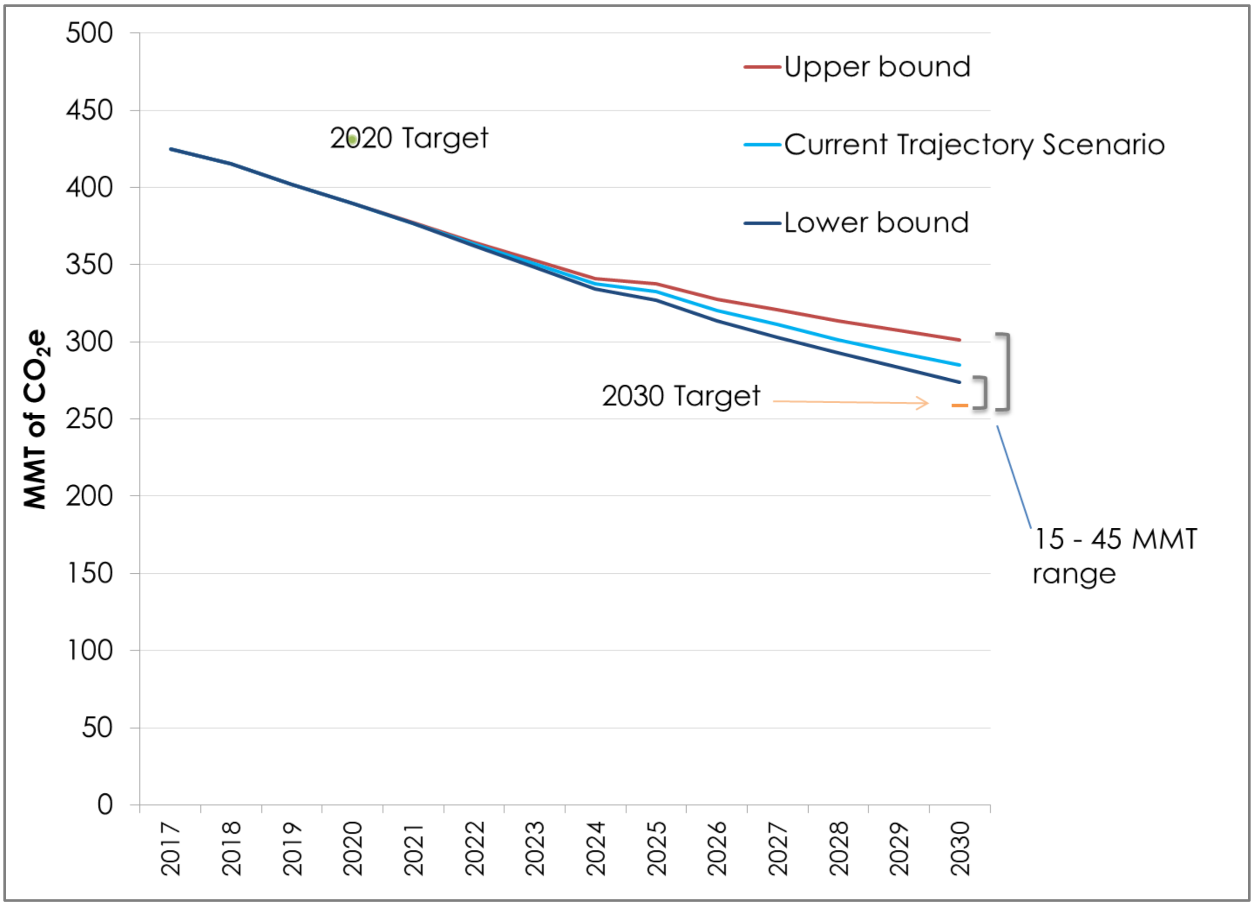
- The "lower bound" scenario models the future emission path with a higher-than-expected carbon price, reaching $63 per metric ton in 2030. By comparison, the Current Trajectory Scenario assumes the carbon price reaches $29 per metric ton in 2030.
- The "upper bound" scenario models the future emission path if motor vehicle efficiency and electrification progress are frozen at 2020 levels. The Trump administration has sought to revoke federal approval of California's existing standards, and the outcome of this dispute

[7] Section 38562.b.2.I.

[8] The Current Trajectory Scenario is calibrated to reflect policies in the 2017 Scoping Plan, California's main long-term strategy document, plus two policies taking effect later: the 60 percent renewable electricity standard and the increase of the low carbon fuel standard to 20 percent.

remains uncertain. Though not predictive, the scenario does illustrate the importance of vehicle standards to the current strategy.

Figure ES-1. Emissions under Current Trajectory Scenario and varying assumptions



Source: California EPS

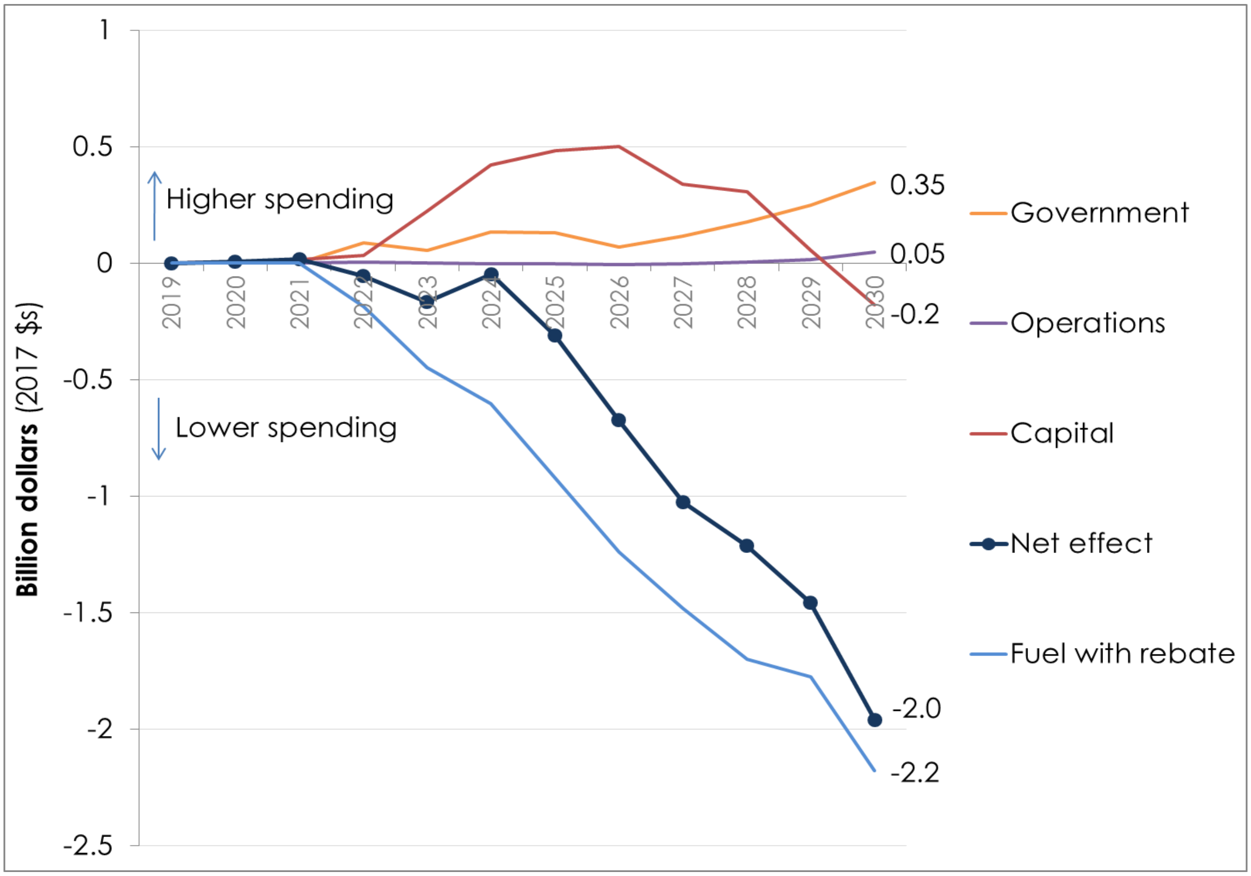
Figure ES-1 graphs these results, with existing policy driving emissions down more than 100 MMT of CO_2e by 2030. Nonetheless, the Current Trajectory Scenario finds that the current trajectory leaves emissions in 2030 roughly 25 MMT of CO_2e above the target in the central case. Sensitivity analysis finds 2030 emissions exceed the target by 15-45 MMT of CO_2e.

ECONOMIC AND SOCIAL BENEFITS

The EPS evaluates economic impacts by comparing the amount of spending demanded by the energy system under different scenarios. A policy lowers cost if energy demand can be met with lower expenditures than the system would require in the policy's absence. To evaluate the impacts of the policy recommendations in the report, results are calculated in comparison to the Current Trajectory Scenario.

Macroeconomic impacts are beyond the model's scope, but the EPS considers an array of direct economic effects. In the private sector, it accounts for capital, fuel, and other operational expenditures for businesses and households. In the public sector, it tracks government expenditures and revenue. For the three new building and industry sector policies, it estimates and includes new program development and administration costs.

Figure ES-2. Components of cost and their net effect by year



Monetary effects for each year are in 2017 dollars, calculated based on a 3 percent annual discount rate.

Source: California EPS

Figure ES-2 graphs the building blocks of overall cost and the results of their summation—the "Net effect" curve in dark blue—and provides insight into the origins of the estimated economic benefits. Reduced fuel spending after carbon price revenue rebating is the main driver. In turn, fuel savings are a function of greater conservation and more efficient capital, i.e., more energy-efficient consumer goods and business equipment.

Policies promoting electric vehicle use offer a concrete example of how energy-efficient capital saves money. Because electric vehicles are about three times more efficient than vehicles with internal combustion engines, they cost about three times less to operate. The model accounts for related rebound effects—increased driving following the adoption of efficient vehicles that cost less to drive.

Conservation effects are largely attributable to enhancing the broad carbon price signal, which increases incentives to avoid wasteful or low-value uses. These effects tend to be small; for example, a 10 percent change in transportation fuel price creates just a 1 percent change in household demand. But effects add up over the large volumes covered.

Meanwhile, as Figure ES-2 illustrates, capital costs climb in the early years but innovation reduces costs over time. For example, electric vehicles are expected to become less costly than conventional gas vehicles, even factoring in the expense of installing a home charger (Lutsey 2019), and electric heat pumps already cost less to install in many situations (Synapse Energy Economics 2018). By the late 2020s, such innovation effects cause overall capital spending to decline, making the recommended policy package even more cost effective.

Table ES-1. Impacts by policy

		Reductions (MMT of CO_2e per year)		**Cost** ($ per metric ton)	
Sector	**Policy**	Average 2022-2030	In 2030	Economic	Economic + Social
Buildings	Electric heat pumps	0.7	2.0	-$59	-$120
Transport	Zero emission vehicle policy	0.7	1.8	-$52	-$140
Industry	Zero emission heat standard	1.1	1.8	-$39	-$98
Cross-sector	Carbon pricing	6.4	9.8	-$21	-$76
Electricity	Renewable standard	3.5	8.0	$3.8	-$46
Industry	Cement emission standard	1.5	3.1	$49	$5.8

Costs per ton are calculated as the net present value of the monetized impact divided by the quantity of emission reductions (2022-2030). A 3 percent annual discount rate is applied. Costs are expressed in 2017 dollars.

Source: California EPS

The model also enables impact evaluation for individual policies, with results summarized in Table ES-1. The table depicts average annual reductions over the 2022-2030 period and reductions in 2030, including two perspectives on cost: economic effects alone and economic effects plus social costs. Social costs refer to monetary estimates of health benefits and avoided climate damage. Costs per ton are calculated as the present value of monetary effects over the sum of tons reduced through 2030.

The model finds that four of the recommended policies create net benefits from the narrower economic perspective, and only one exceeds the net benefit threshold (indicating net costs) when accounting for social impacts. In the table, net benefit results are shaded in green and net costs in red.

The cost effectiveness of these results is encouraging, yet some caution is warranted. Every effort has been made to account for added expenses, including those sometimes ignored, such as the cost to government of administering new programs. Nonetheless, suboptimal or inefficient implementation is a possibility. In evaluating impacts of the recommended package, we assume successful uptake of cost-effective opportunities to shift electricity demand from peak to off-peak times, but there is a chance the new regulatory approaches to provide the necessary incentives will be beyond reach. The results of less cost-effective peak management and several other sensitivity analyses are presented in the body of the report.

CONCLUSION

Results from the California EPS suggest the state's current framework must be strengthened to hit the 2030 target, but the findings also provide reason for optimism. The model identifies a recommended package of six policies that meet the target while also generating significant economic and health benefits.

California's climate policies are at the forefront of global efforts to battle climate change. The state's leadership and success so far have helped maintain momentum despite political headwinds. If California faltered, global efforts to reduce GHG emissions would be dealt a major setback. Meanwhile, the severe risks from runaway global warming are becoming more tangible as the state suffers from wildfires supercharged by climate change.

Today, with California's 2020 emissions milestone in the rearview mirror, it is easy to forget how challenging that goal seemed before it was set a dozen years ago. The state met that goal with time to spare, thanks in part to rapid innovation that drove down the cost of solar power, wind power, and superefficient LED lighting. Other clean technologies, including battery storage and electric vehicles, now hold the promise of similar rapid improvement.

Reasons for optimism notwithstanding, it would be unwise to underestimate the magnitude of the effort needed to transform modern energy systems. The next milestone—the 2030 target—is just a stepping stone to the even more ambitious goal of achieving carbon neutrality by 2045.[9] We hope the California EPS contributes in some small way to the state's continued success in its decarbonization journey.

[9] The carbon neutrality goal was set in a 2018 Executive Order signed by Governor Jerry Brown (Mulkern 2018).

1. INTRODUCTION

California's greenhouse gas (GHG) emissions reduction targets are among the most ambitious in the world. In 2016—four years early—the state achieved its 2020 target, requiring emissions to decrease to 1990 levels (CARB 2019). Looking ahead at the beginning of a new decade, the state's climate goals only ramp up in ambition. California Senate Bill 32 became law in 2016, setting a 2030 target of reducing emissions 40 percent below 1990 levels.

California's most recent inventory data shows emissions at 424 million metric tons (MMT) of carbon dioxide equivalent (CO_2e) in 2017. So hitting the 2030 target means reducing emissions by an average of 13 MMT of CO_2e annually, or nearly double the annual rate of 7 MMT of CO_2e over the past decade.[10]

California is also battling the onset of serious climate damage. Climate change has supercharged California's fires. The lives lost, injuries suffered, homes destroyed, and businesses disrupted are the most obvious effects of worsening wildfires. Costs are also imposed on government. In addition to the immediate need to supplement firefighting budgets, a sudden and urgent suite of demands has been foisted on state policymakers, such as providing restitution to wildfire victims, making near-term regulatory adjustments to reduce the risk of massive power outages again next year; while also working to properly structure the state's electric utilities and grid in light of new climate threats.

At the same time, California is battling the Trump administration, which is attempting to revoke the state's authority to set stronger motor vehicle tailpipe emission standards, and which is also suing in federal court to sever California's cap-and-trade partnership with Quebec. These larger challenges and the importance of California's continued success in reducing GHG emissions provide the overarching motivation for our development of the California Energy Policy Simulator (EPS). Using the California EPS, this report seeks to answer three questions:

(1) What is the emission trajectory implied by current policy?
(2) If the model suggests current policy does not put the state on track to achieve the 2030 target, what additional policies should be prioritized and how should they be calibrated?
(3) What are the estimated economic and social impacts of these policy enhancements?

The model finds that current policy will achieve reductions that are deep, but not deep enough to push emissions below the 2030 goal. We estimate that current policy will result in 2030 emissions remaining roughly 25 MMT of CO_2e above the 2030 limit of 260 MMT of CO_2e. To close this gap, we recommend strengthening three established policies and adding three new policy instruments. The analysis indicates these policies will be beneficial from the narrow

[10] The historical rate is calculated by comparing 2017 emissions at 424.1 MMT CO_2e with 2007 emissions at 490.9 MMT CO_2e, showing a difference of 66.7, yielding the calculation 66.7/10 = 6.67 MMT CO_2e/year. The future rate is calculated as 424.1 – 258.6 = 165.5 over 13 years, yielding 165.5/13 = 12.73 MMT CO_2e/year. In a recent study, Next10 and Beacon Economics (2019) also concluded California will need to accelerate its rate of decarbonization to hit future targets.

perspective of direct, monetary impacts and even more beneficial when taking into account social impacts, that is, estimates of the monetary value of health and climate effects.

Initial modeling has focused on the 2030 target—the next milestone along the state's deep decarbonization journey. A 2018 Executive Order signed by Governor Jerry Brown set the goal of carbon neutrality by 2045 (Mulkern 2018), and recent work by Environmental + Economics Inc. (E3 2018) and the Energy Futures Initiative (2019) identifies promising technologies for accomplishing post-2030 goals. Though such longer-term targets are not the focus of this analysis, expanding the set of zero emission options through increased research, development, and demonstration projects will be essential to achieving the longer-term targets. In addition to the environmental imperative, targeted public research investments yield economic spillover benefits (Gruber and Johnson 2019). California has more national laboratories than any other state and is already known as a leader in innovation. This is a comparative advantage ripe for strengthening.

2. MOTIVATION

This section outlines additional motivations underlying the overarching goal of contributing to California's continued decarbonization success. First, we show how the model is responsive to requests by scholars and policymakers who convened in 2006 after adoption of the 2020 target. Second, we describe connections between this work and the most recent Scoping Plan exercise, the first to present a detailed 2030 policy strategy.

2.1. INAUGURAL CALIFORNIA CLIMATE POLICY MODELING DIALOGUE

The model fulfills specific needs identified by the California Climate Policy Modeling Dialogue, a high-level collaborative of policymakers, researchers, and industry organized by the Policy Institute for Energy, Environment and the Economy at the University of California at Davis.

Assembly Bill 32 directed the California Air Resources Board (CARB) to develop a Scoping Plan, which must be updated every five years, to set forth the state's vision and policy strategy for achieving decarbonization goals. After the first Scoping Plan was finished in 2009, the inaugural California Climate Policy Modeling Dialogue conducted a retrospective evaluation and noted: "Policymakers involved asked for more modeling of . . . individual policies (i.e., rather than generic climate policies) in order to better understand the spatial, temporal, and socio-economic effects of regulations [and] interactive effects between two or more policies" (Morrison et al. 2015, p. 555).

The EPS represents dozens of individual policies that may be adjusted by simply turning policy levers, with real-time results. The important features of each policy are embedded in the cause-effect linkages at the heart of the model; better accounting of "interactive effects" is one of the EPS's strengths as a systems dynamics model.

It is important to acknowledge the foundational groundwork laid by Energy + Environmental Economics, Inc. (E3). E3's Pathways model has added rigor and insights to the energy technology and policy landscape (Williams, J. et al. 2012). In our view, the EPS is more similar to the Pathways model than any other because both apply a systems dynamics perspective to economy-wide modeling questions. The Pathways model offers more detailed and comprehensive technological coverage—for example, including hydrogen production and hydrogen fuel cell vehicles. The EPS's strengths are its comprehensive policy coverage, which extends to carbon pricing, and its accessibility, enhanced by a user-friendly web interface.

2.2. MODELING OF CARBON PRICING IN 2017 SCOPING PLAN

E3's Pathways model achieved a breakthrough by allowing for the integrated, systemic evaluation of all of California's major policies except for carbon pricing. To evaluate the carbon pricing policy, the analysis that informed the 2017 Scoping Plan used a macroeconomic model created and maintained by Regional Economics Models, Inc.[11] A drawback to doing so is that this model does not allow for energy use as a variable input. The treatment of energy as a fixed input to production is evident in Appendix E of the Scoping Plan, Figure 2. This model schematic lists only two inputs to production—labor and capital (CARB 2017c).

The failure to represent energy as a variable input limits insights about the effect of carbon pricing. Businesses and consumers are expected to change how they use energy in response to the introduction of a carbon price through greater energy efficiency, switching to lower-carbon energy sources, and avoiding low-value energy uses. The model from Regional Economics Models, Inc. used for the Scoping Plan analysis does not allow for these adjustments.[12]

CARB's choice to use that particular model reflects the limited available options. No commercially available, regularly updated macroeconomic model allows for energy as a variable input to production. Nonetheless, the analysis underpinning the first Scoping Plan (CARB 2010a) did employ a macroeconomic model that allowed energy use to vary—the Environmental Dynamic Revenue Assessment Model, originally developed by UC Berkeley economists under CARB's direction.

The lack of a connection between the causal effects of carbon pricing represented in the Scoping Plan analysis created an opportunity. Since the California EPS allows for the integrated consideration of sector policies along with multi-sector carbon pricing, it will provide a new perspective.

The California EPS was also motivated by the growing emphasis on the importance of carbon pricing within the state's overarching strategy. In the initial Scoping Plan, which developed the policy framework to hit the 2020 target, tailpipe emission performance standards for motor vehicles were expected to drive the most reductions, and the cap-and-trade program was tasked

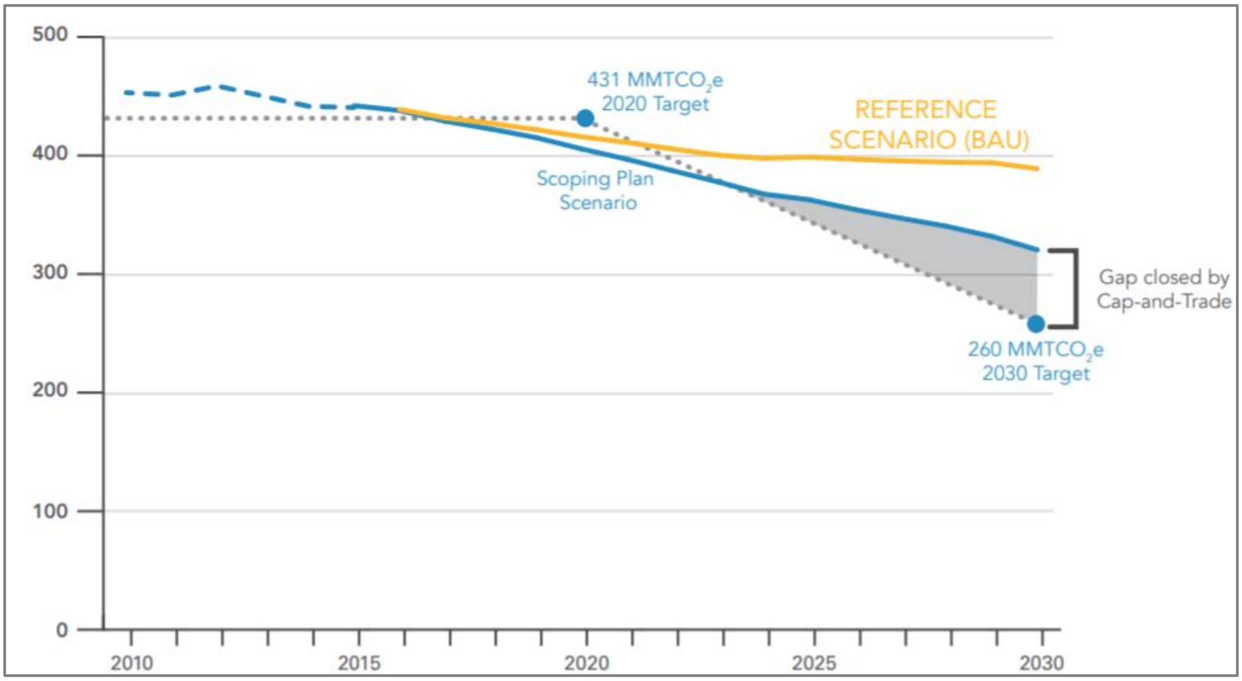
[11] REMI, Regional Economic Models, Inc. https://www.remi.com/

[12] To manage this limitation, the Scoping Plan makes assumptions about the quantity of emissions reductions expected from the cap-and-trade program: "The remaining GHG reductions are achieved through the Cap-and-Trade Program, the impact of which is calculated outside of Pathways and input into the REMI model," (CARB 2017c, p. 10).

with delivering 20 percent of overall reductions (CARB 2008, p. 17). In the most recent Scoping Plan, the cap-and-trade program is the single most important policy, expected to drive 38 percent of emission reductions from 2021 to 2030 (CARB 2017a, p. 28).

Figure 1 is a graph excerpted from the 2017 Scoping Plan, identifying with gray shading the reductions expected from the carbon price emerging from the cap-and-trade program. The level of reductions expected in 2030 is bracketed in black and labeled, “Gap closed by Cap-and-Trade.” In this scenario, the cap-and-trade program drives 47 percent of emission reductions occurring in the year 2030.

Figure 1. 2017 Scoping Plan strategy: Close the gap with cap-and-trade



Source: CARB 2017a, p. 30, Figure 9

The Scoping Plan recognizes the uncertainty inherent in analyses extending more than a decade into the future, stating that the modeled outcome “represents an expected case where current and proposed GHG reduction policies and measures begin as expected and perform as expected, and technology is readily available and deployed on schedule,” (CARB 2017a, p. 28).

The state’s long-term strategy is not static, the Scoping Plan also emphasizes: “A key element of California’s approach continues to be careful monitoring and reporting on the results of our programs and a willingness to make mid-course adjustments,” (CARB 2017a, p. ES-5). Our goal for the California EPS is to offer a new analytical tool that contributes to the success of this adaptive management model.

3. METHODS

The EPS was created by Energy Innovation, which continues to manage the model. Energy Innovation and its partners have now adapted the model to eight countries and two subnational jurisdictions. The EPS has been peer reviewed by staff at three U.S. national laboratories and several top research universities, as well as regional research partners in each modeled country. The model is regularly updated, reflecting feedback and new data availability, as detailed in the model's online documentation.

The model allows users to apply dozens of policies to a scenario reflecting business-as-usual (BAU) and to dial the strength of energy and climate policies up or down, with instant results showing direct economic impacts, changes in energy use, emissions of both GHGs and locally damaging air pollutants, and social impacts, including premature deaths and monetary estimates of avoided climate and health damage.

Different policy combinations constitute scenarios—and comparing scenarios is crucial to understanding EPS results. The calculations at the core of model results are driven by comparing energy use, emissions, and costs in the BAU Scenario with a specified policy scenario.

The model is open source, web accessible, and available free of charge. The EPS is programmed in the software Vensim, for which a free reader version is available. The source code and input data are publicly released, regularly updated, and easily downloadable from the main project website (www.energypolicy.solutions). The model structure, causal relationships, and parameters are readily comprehensible through Vensim's graphical interface. In short, the model offers unsurpassed transparency.

Additionally, input data can be adjusted by swapping in different standard comma-separated value files. For those not wishing to delve into Vensim modeling, a web-based interface provides a wealth of functionality, allowing users to develop their own policy scenarios and evaluate the impacts.

3.1. STRUCTURAL OVERVIEW

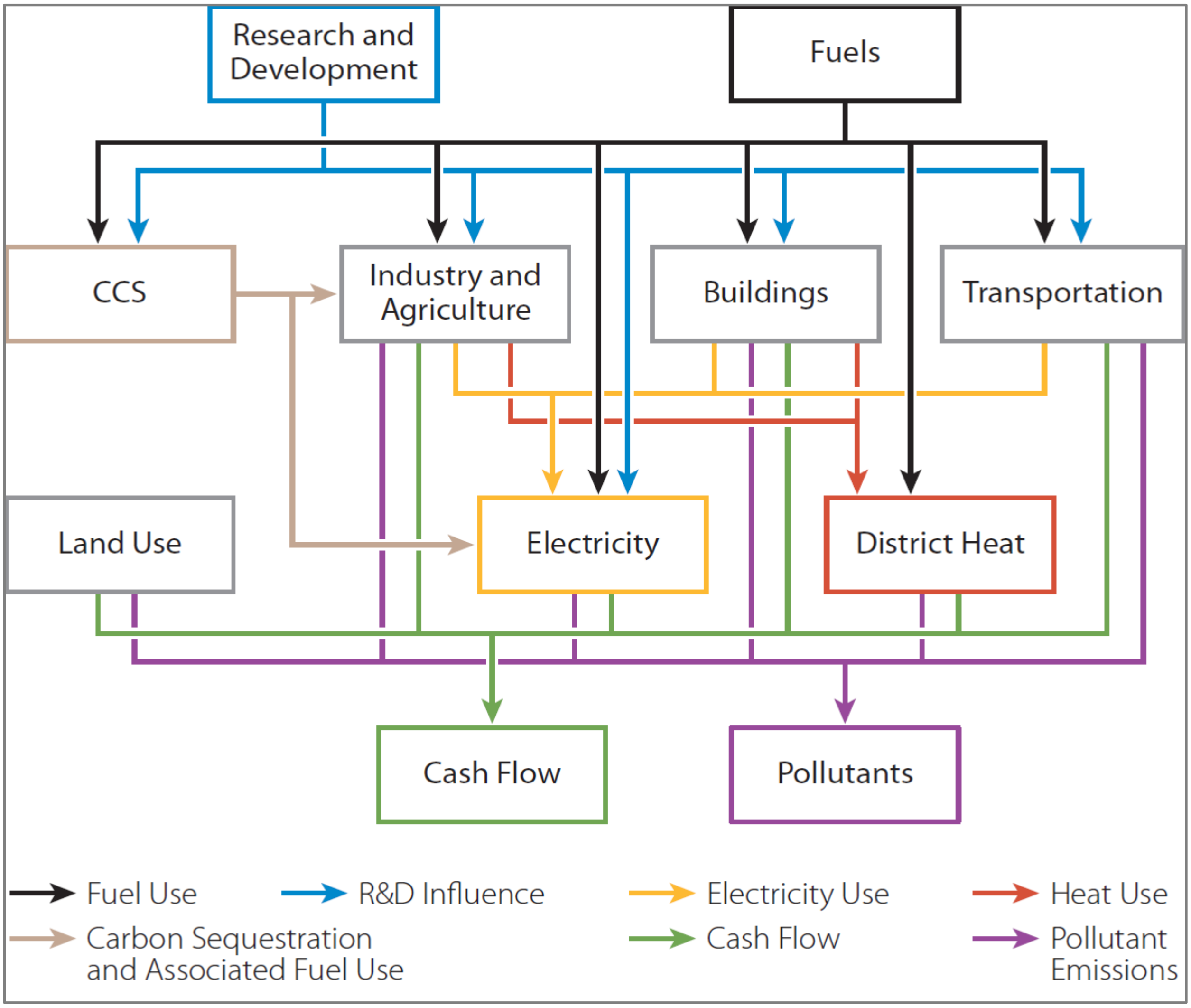
The EPS is a systems dynamics model combining elements of economic models and bottom-up accounting models with detailed technological specifications, including stock and flow dynamics. Systems dynamics models often include "stocks," or variables whose values are remembered from one time-step to the next, and which are affected by "flows" into and out of these variables. The EPS uses stocks for two purposes: tracking quantities that grow or shrink over time (such as total solar electricity generation capacity) and tracking differences from the BAU Scenario that tend to grow over the course of the model run (for instance, differences in potential fuel consumption of the light-duty vehicle fleet caused by enabled policies).

On the economic side, the EPS includes many price response functions, such as multiple endogenous choice functions (like electricity plant investment and dispatch choices, as well as vehicle choice). The model includes several rebound effects in electricity, transportation demand, and building energy demand. For example, if the cost per vehicle mile traveled changes, whether because fuel subsidies are removed or more efficient vehicles require less fuel, passenger and cargo travel demand adjust accordingly.

The model covers the entire economy, including energy demand in buildings, motor vehicles and off-road transportation modes, and industry. Agricultural energy use is included in the industry category, as are all process emissions, such as methane emissions from natural gas pipelines and livestock waste (labeled "short-lived climate pollutants" in the California dialogue). The model's geographic scope is the state of California. It does not capture geographic differentiation at smaller spatial scales, such as counties or zip codes.

Figure 2 gives an overview of the model structure, illustrating connections between each sector.

Figure 2. Overview of EPS structure



The electricity sector portion of the model considers the reliability implications of variable generation from renewable sources such as wind and solar, for example accounting for on-peak capacity factors. Capacity investments may be made either to meet new demand or to rebalance after system retirements, with the investment calculus reflecting costs, the existing policy environment (e.g., federal tax credits), and new policies. These outcomes are driven by economic factors, tempered by real-world constraints on how quickly new sources can be built and price heterogeneity.

The transportation sector portion of the model includes a choice module for motor vehicle purchases. Vehicle purchase costs, fuel costs, vehicle efficiency, policy impacts, and discount rate parameters for vehicle buyers together generate the net present value metric of total cost of ownership that drives vehicle choice. As in the electricity sector, the EPS uses a probability distribution of prices, reflecting real-world variation, overlaps, and a less-than-perfect rank-ordered choice paradigm compared to a least-cost approach based on a mean price. Energy Innovation overhauled the transportation sector of the model in preparation for the California adaptation, adding a low carbon fuel standard policy that requires a reduction in the average carbon intensity of transportation fuels over time. Hydrogen fuel cell vehicles and hydrogen use more generally as an energy source are not within the model's current technology choice set, but efforts are underway to include them in the future.

3.1.1. Carbon Pricing

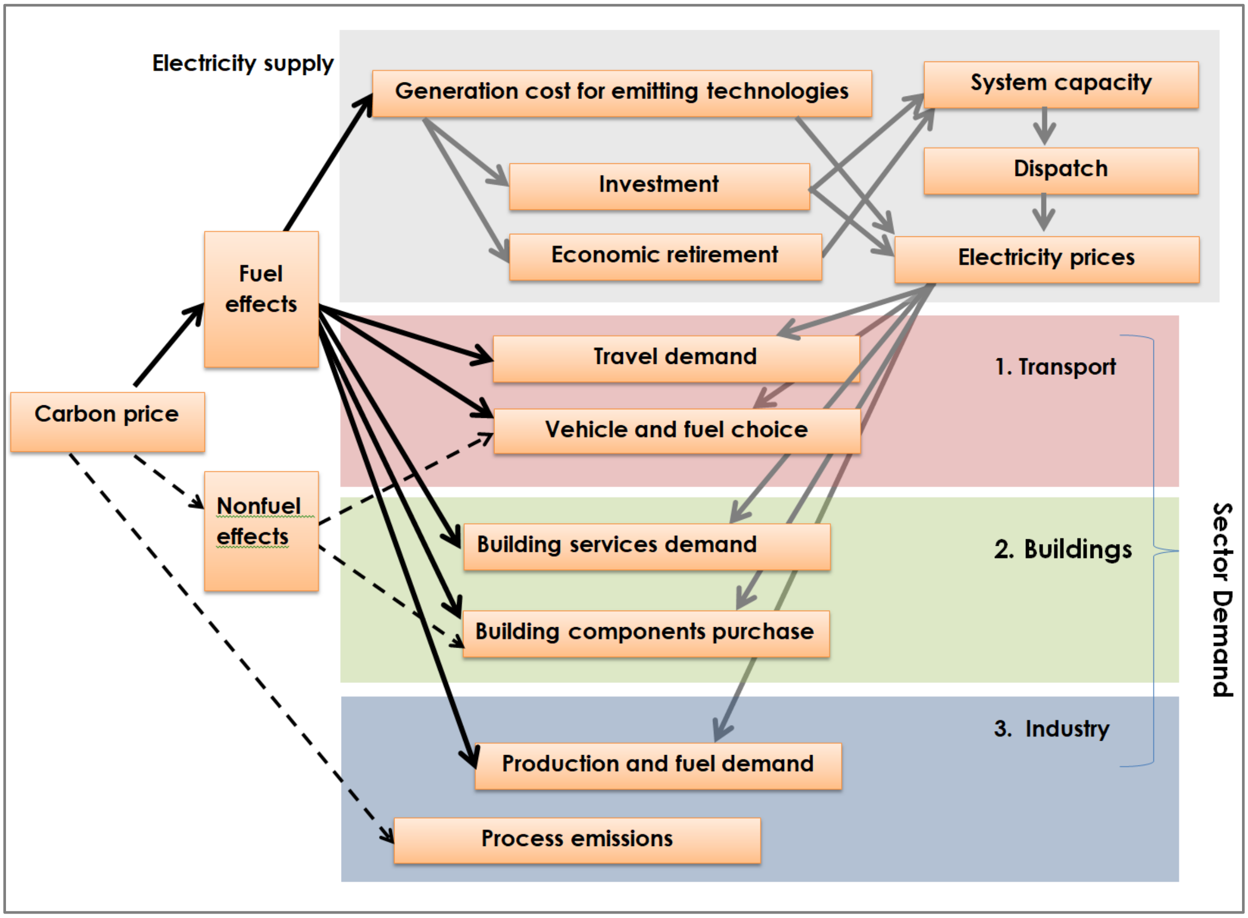
Model users may specify a carbon price level over time with the option of varying prices in different sectors. Figure 3 maps the cause-effect mechanisms by which the carbon price reduces emissions, illustrating the first-order effects caused by the carbon price and other key follow-on effects. The electricity supply sector sits atop the figure, with sector demand for transportation, buildings, and industry below (as annotated along the right-hand side).

Carbon price effects operate via three potential types of pathways: fuel effects, nonfuel effects, and process emissions mitigation. The California EPS only enables the fuel price effects pathways, identified with solid black arrows in Figure 3, which also portrays the main follow-on effects with gray arrows. Dotted lines highlight the carbon price effect pathways not initially enabled in the model.[13]

Tracing the effects in the electricity supply sector as an example, the carbon price first increases fuel costs for power generation technologies that emit carbon dioxide (CO_2). This affects dispatch decisions within the existing system as well as new investments and economic retirements. Any changes in operating and investment expenses are reflected in an adjusted electricity price, which then feeds into sector demand.

[13] The two non-activated carbon price pathways are process emissions and nonfuel price effects. Process emissions are not covered by the California carbon pricing mechanism but interesting possibilities exist for doing so, such as covering methane leakage from natural gas pipelines under the cap. Technical obstacles remain to be solved before carbon pricing can be extended to this and other non-combustion emissions. The nonfuel effects pathway allows for coverage of the embedded carbon content in materials used to make equipment such as cars or building components. The EPS does not activate the effect because insufficient life cycle data exists to populate this pathway for California. Many manufactured goods come from other states without carbon pricing, as do some material inputs to production.

Figure 3. Carbon price cause-effect pathways in the California EPS



3.1.2. *Social Impacts*

The EPS accounts for the climate and health effects of energy choices that are all too often left out of climate policy analysis. Such non-market impacts are less easily quantified because no single market price can be applied as a ready estimate of monetary value. The EPS puts a dollar estimate on the climate benefits from avoided CO_2e emissions using the social cost of carbon developed by the federal government (Interagency Working Group on Social Cost of Carbon 2013). The monetized benefits represent for each ton of CO_2e not emitted the avoided damage due to rising sea levels, extreme heat, increased wildfire risk, water shortages, and so on.

The input values we use for avoided damage is the most frequently used and authoritative source, but it is several years old. Incorporating more recent scientific findings would increase the value of avoided GHG emissions, so climate benefits identified by the California EPS may be viewed as a lower bound. As one example, a study on health impacts from increased heat extremes found “the increased global mortality burden from climate change to be 3.7 percent of global GDP by the end of the century if past emissions trends continue” (Carleton, T. et al. 2018). The EPS separately estimates climate and direct health impacts, so heat-induced effects would be classified as climate-related and separate from the direct health damage associated with increased exposure to air pollution.

Health impact evaluation in the California model follows the method developed by CARB (2010b) and used in the 2017 Scoping Plan analysis. The approach accounts for particulate pollution (primary and secondary, i.e., particulates formed from nitrous oxides and other pollutants). Yet other pollutants, notably ozone, also significantly burden human health. Further, the approach only accounts for avoided premature deaths, and not the cost of hospitalizations or other medical care, much less effects on human well-being. The indoor air quality benefits of electrified building components compared to those combusting hydrocarbons also are not included. Thus, the health benefits should be viewed as a lower bound of actual benefits, which are likely to be much higher.

3.1.3. Endogenous Innovation

Innovation may refer to improved performance or falling costs for a given level of performance. The EPS endogenous innovation module exclusively affects falling costs, in particular installed capital costs. The level of innovation responds to future deployment based on a cost-reduction factor applied with each doubling of global installed capacity, reflecting historical patterns. Results due to endogenous innovation can be viewed in the web app under the Technology Costs option.

The EPS applies the innovation function to four key emerging technologies—solar, wind, batteries, and carbon capture and sequestration. These innovation effects are often referred to as learning curves, and they occur due to both the learning that comes with experience and the economies of scale that are achieved as production scales up.

Under the endogenous innovation module, the rate of innovation over time is affected by other parts of the system, namely the level of additional deployment due to added policies. The model also anticipates and factors in global deployment, which significantly determines future price trajectories because of the large magnitude of global trends compared to trends in any single jurisdiction. Other EPS applications have addressed larger economies, such as the U.S. and China, and the effects of domestic policy are more readily observable on these scales.

3.2. IMPACT EVALUATION

The model's cost metrics track spending on fuels, capital, and other operational and maintenance costs, as well as effects on government ledgers, revenues, and incentive spending. Though the direct economic effects do reflect first-order system effects that cut across sectors, it is worth re-emphasizing that macroeconomic spillover effects are outside the model's scope.[14]

[14] Here is a transportation sector example of the EPS model's cost interactions: Travel demand is affected by the change in cost of travel, which is determined by a number of factors and can be affected by multiple policies. For example, increased fuel prices due to a carbon price, increased taxes, or decreased subsidies change the cost of travel, with demand adjusting accordingly. Similarly, the cost of travel can be affected by vehicle efficiency, with more efficient vehicles reducing travel costs. As a result, policies improving vehicle efficiency tend to increase travel demand. Changes in travel demand also influence other sectors to the extent they are affected by changes in travel inputs. For example, a policy spurring greater electric vehicle adoption would induce higher demand for electricity, which could trigger a need for new investment in power generation.

Changes in government expenditures, such as from fees or incentives, are also calculated. These changes are included in metrics with "Total Outlays" in the variable name, but not variables referring to only changes in CapEx and OpEx, which exclusively cover private-sector effects.

New policies affecting the buildings and industry sectors are assumed to require additional government expenditures. Lacking standalone studies on these costs, the budgets of some existing departments are used to approximate potential policy costs for new policy initiatives in buildings and industry.

The EPS presents cost results using two distinct treatments of carbon price impacts. The "revenue-neutral" mode returns additional spending required due to a carbon price to the economic actors from which the payment originated. The "revenue-exclusion" mode removes carbon price revenue from the benefit-cost evaluation, which has the effect of increasing the costs for the policy package and for the carbon pricing policy itself. We favor the revenue-neutral mode because excluding carbon pricing revenue would fail to account for a large impact. One advantage of the revenue-exclusion approach is that it may provide a more realistic individual cost assessment for policies other than carbon pricing in instances where carbon pricing is expected to increase the costs associated with fossil fuel combustion. These added incremental costs are invisible in the revenue-neutral approach.

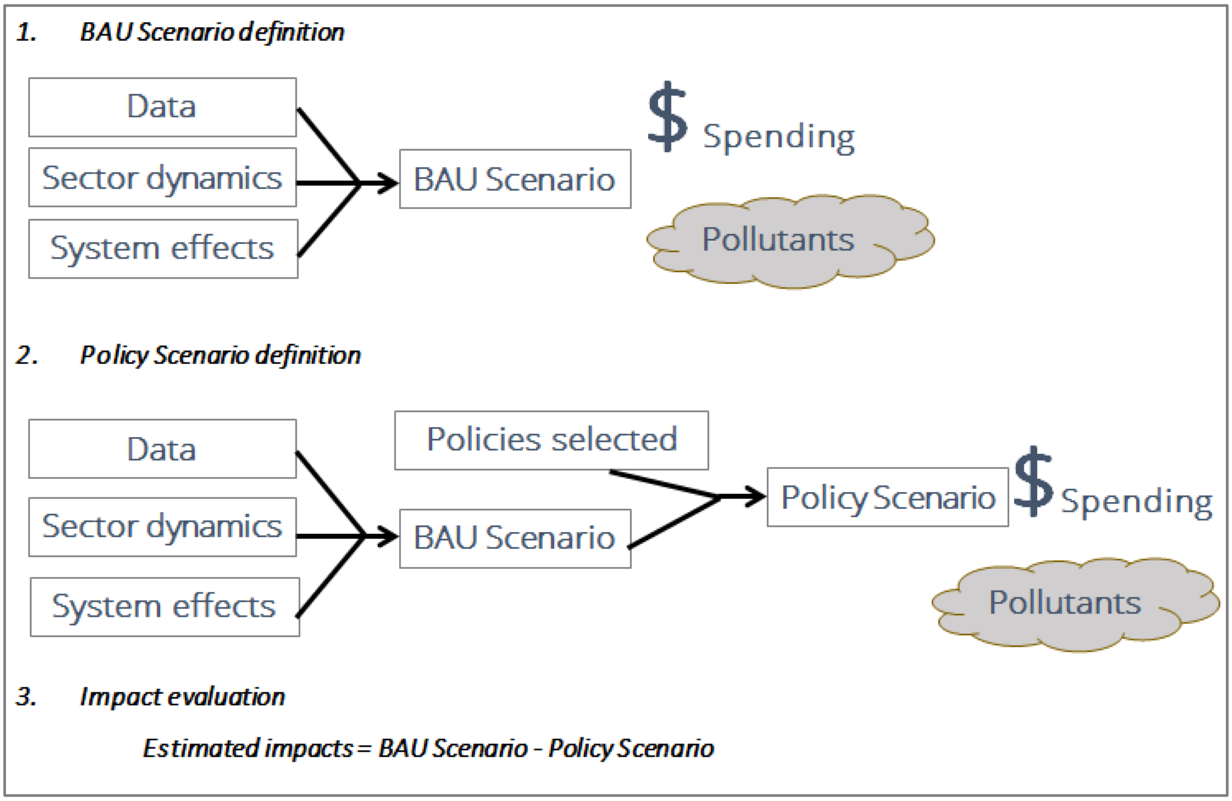
The model evaluates impacts by comparing total energy use, emissions, and a variety of other variables under different policy settings. A collection of particular policy settings define a policy scenario. Scenarios are economy-wide representations of energy use and travel demand, as well as emissions characteristics of different fuels and technologies, which together provide a complete picture of emissions and energy-related spending (covering private spending on capital, fuel, and other operational and maintenance expenses, as well as government budget impacts).

3.2.1. Impacts Calculated as the Difference Between Policy Scenarios

This section presents a schematic to illustrate how the EPS may be used for policy impact analysis. One key ingredient for impact analysis is the business-as-usual (BAU) scenario. The specifics of the BAU Scenario for the California EPS are presented in section 4.2. Generally, the BAU Scenario identifies the energy use patterns, energy-related spending, and emissions that are expected from the system under current conditions. The second key ingredient for impact analysis is a policy scenario for evaluation, increasing the strength of one or more policies above the BAU level. Finally, impacts are calculated as the difference in the variable of interest between two scenarios.

Figure 4 develops a schematic breaking down impact evaluation process into three steps. The first and second steps involve establishing the BAU Scenario and a "Policy Scenario." The dollar and pollutant symbols next to each scenario's label signifies that each scenario produces a complete (albeit simplified) representation of energy use, capital stock retirements and additions, emissions, and spending on energy, including changes in energy demand, emissions, and spending, i.e., direct economic effects. In the third step, impacts are calculated as the difference between the two scenarios. For example, economic impacts are estimated by subtracting expenditures in the BAU Scenario from those in the Policy Scenario. cenario.

Figure 4. A schematic showing how impact evaluation works in three steps



The model is designed for comparisons to the BAU Scenario, and this is the only frame of reference possible in the web application, but additional mathematical work permits comparisons between any two combinations of policies.

3.2.2. Consistent Treatment of Individual Policies within a Policy Package

A policy package's impacts on a policy-by-policy basis can be estimated in one of two ways: by measuring the effect of each policy with none of the other policies activated, or by measuring the effect of disabling a given policy on the emission reductions achieved by the remaining policies. The first method measures emission reductions that result in the absence of any of the policies, while the second method measures emission reductions lost when a single policy is disabled from the full portfolio. Since the second approach accounts for policy interaction, the California EPS uses this method.

This so-called "disabled" approach is used to create the policy wedge diagram (Figure 9. below), which shows year-by-year emission reductions, and the policy cost curve, which gives a cost per ton of average annual abatement. The emission reductions for each policy shown in the wedge diagram reflect the extra emissions that result when the policy is removed from the package. In other words, the model performs several runs to disable—or turn off—each policy and calculates the resulting emission effect. Because of policy interactions, the sum of individual policy effects is almost invariably meaningfully different from the sum found when disabling all policies together. Thus, a final step involves scaling the individual policy effects found in the first step so that, in aggregate, they equal the accurate sum of policy effects.

The abatement cost metric is also measured using the disabled approach to calculating policy effects. Costs for a given policy are calculated as a net present value of the stream of future spending effects, discounting annually at a rate of 3 percent.[15] Cumulative emission reductions attributable to the policy are calculated over the 2022-2030 period. Then, the policy's average costs per ton are calculated as the sum of spending effects divided by the cumulative emission reductions attributable to the policy are calculated over the 2022-2030 period.[16] Then, the policy's average costs per ton are calculated as the sum of spending effects divided by the cumulative emission reductions.

[15] The results presented in this report differ from the results viewable in the web application because of the different scenarios in the counterfactual (i.e., the scenario used as the frame of reference for emissions absent additional policy). The web application gives results compared to the BAU Scenario, while the results in this report give results compared to the Current Trajectory Scenario.

[16] We explain here a nuance related to calculating emission reductions due to the zero emission vehicle mandate. An understanding of the "disabled method" for calculating policy effects helps to explain why the policies requiring minimum sales of zero emission vehicles appear ineffectual in the web application, i.e., why such policies are absent from the policy wedge curve and abatement cost curve in the web application. When zero emission vehicles sales requirements are removed from the package, the low carbon fuel standard drives greater reliance on biofuels than it would otherwise. In line with state GHG accounting methods, biofuels are treated as net zero emissions. Though electric vehicles are zero emission from a tailpipe perspective, because electricity supply involves some emissions, electric vehicles entail some—albeit declining—emissions through 2030.

The structure of the model also comes into play, specifically how the system represents low carbon fuel standard compliance, which effectively happens in a two-part process. In the California model, the share of transportation energy demand provided by electricity is determined by the zero emission vehicle mandate. The low carbon fuel standard takes electricity supply as given, and fills in the remainder with biofuels and biogas, mostly biodiesel and renewable diesel.

The upshot is that ratcheting up the zero emission vehicle mandate increases electricity use for transportation, which in turn leads to lower biofuel use. Combustion of biofuels and biogas is treated as net zero in the model, following the conventions of the state emissions inventory, so substituting electricity for biofuels and biogas has the effect of increasing emissions in the model.

At present, the end uses for electricity and biofuel fueling alternatives are largely bifurcated, with biofuels mostly serving heavy-duty trucking and electricity making inroads for passenger vehicles. In our view, ratcheting up the zero emission vehicle sales performance standard permits setting the low carbon fuel standard at a higher level in practice, and the Energy Innovation Scenario is constructed to reflect this assumption. The stringency of the low carbon fuel standard increases in the Energy Innovation Scenario, but only at a level that maintains biofuel and biogas use at approximately the same level as in the Current Trajectory Scenario.

To achieve consistent results, isolating low carbon fuel standard effects and avoiding unintended interactions, the results in this report reflect an adjustment. First, the low carbon fuel standard is removed from all scenarios, including the BAU Scenario for individual policy impact evaluation. Second, individual policy impacts are scaled by a multiplier so that the sum of individual impacts in each year equals the desired difference at the package level, i.e., comparing the Energy Innovation Scenario to the Current Trajectory Scenario with the low carbon fuel standard.

4. ADAPTING THE MODEL FOR CALIFORNIA

4.1. DATA SOURCES

The downloadable version of the model includes both commonly formatted data files and notes on underlying calculations and source material. The files and notes together represent a complete, open-source accounting of model inputs. Therefore, this overview is brief.

Energy Innovation's adaption of the model for California benefitted enormously from a large body of foundational research involving experts from E3 and CARB as well as a broader community of committed researchers. E3's California Pathways model, developed in cooperation with CARB and other state energy experts, is the largest source for model inputs. We use the California Pathways model version developed and publicly released as part of the 2017 Scoping Plan process (CARB 2017b, CARB 2017c).[17] We primarily extract data from the scenario labeled "Scoping Plan Plus 60 Percent Renewable Portfolio Standard."

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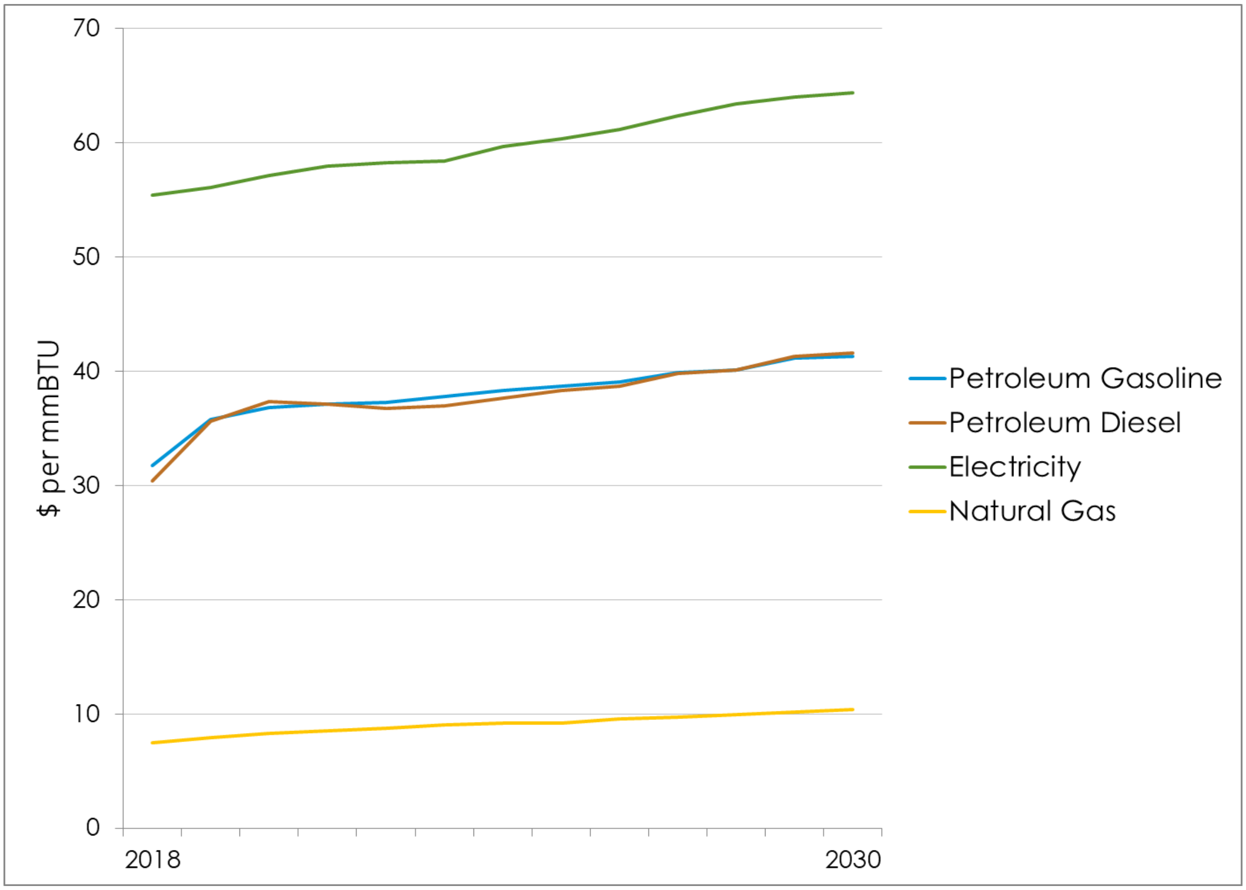
[17] The main Scoping Plan webpage has an "Appendices and Modeling Information link": https://www.arb.ca.gov/cc/scopingplan/scopingplan.htm. Scroll halfway down the linked page to see the full suite of materials: https://www.arb.ca.gov/cc/scopingplan/meetings/meetings.htm. Nine links are provided under "Modeling Information," including the main Pathways technical documentation (E3 2017).

Figure 5. BAU price forecast for natural gas, electricity, petroleum fuels



Sources: Energy Information Administration (2019) and E3 (2017)

For future fuel prices, the model uses California-specific empirical data for 2018 from the U.S. Energy Information Administration for start-year levels. From these starting values, gasoline, diesel, and coal prices grow at the same pace as nationally forecast prices from the 2019 Annual Energy Outlook produced by the Energy Information Administration (2019).

Natural gas and electricity prices vary much more across states and regions, with future prices changing over time as forecast in the California Pathways model. Further details on technology costs and their sources are provided when presenting the policy-specific benefit-cost results in section 8.2. The resulting prices for the four conventional fuel types in the BAU Scenario are shown above in Figure 5.

4.2. BAU SCENARIO DEFINITION

The BAU Scenario is the model's foundation. It represents how California's energy use and emissions are expected to shift based on policies outlined in the 2017 Scoping Plan but only insofar as the policies are reflected in existing regulations.

In the electricity sector, BAU reflects Senate Bill 100's requirements, including a minimum renewable portfolio standard for electric utilities to reach 60 percent of utility electricity supply in 2030. Given this assumption, BAU electricity sector emissions are 43 MMT of CO_2e in 2030, similar to the sector's 42 MMT cap in 2030 set in the state's most recent long-term planning work (California Public Utilities Commission 2019).

In the transportation sector, BAU assumptions include the 18 percent low carbon fuel standard, existing fuel standards, and the zero emission vehicle requirements through 2030. Vehicle electrification incentives are assumed to continue, though at declining rates. Light-duty vehicle incentives are entirely phased out in 2026, and heavy-duty incentives are phased out in 2030.

However, electric vehicles are notching impressive progress in the market, selling at levels far surpassing those required under the current zero emission vehicles sales standard. Sales of plug-in and fully electric vehicles reached 7.8 percent in 2018, a 66 percent increase from the year before. The 2018 increase partly reflected pent-up demand for the Tesla Model 3 combined with a rush to buy Tesla vehicles before federal incentives were reduced in 2019.

In the BAU Scenario, the state reaches the existing 2025 goal of 1.5 million zero emission vehicles. In 2030, the number of zero emission vehicles in the California fleet grows to approximately 2.7 million vehicles. The level could in fact be higher for several reasons, such as strong market growth in recent years, CARB's unsurpassed expertise in vehicle regulation, commitments to build out charging infrastructure, and automaker plans to invest tens of billions in electric vehicle technology development and to bring dozens of new models to market across all segments. Challenges persist, however, including counter-efforts from Washington, D.C., and the potential for trade disputes to reduce the availability of new electric vehicle models and to increase costs (Turrentine and Canepa 2018).

The BAU Scenario does not include any policies that reduce travel demand because these policies have not yet demonstrated much effect (CARB 2018a). This is not to suggest travel demand management is unimportant. "Sustainable communities strategies," as the analogous policy is called in the present California dialogue, have great potential. They can reduce emissions, encourage uptake of healthier lifestyles, and generate cost savings by making it more feasible for people to walk to goods and services. Yet such policy strategies have had limited success. Per capita vehicle miles traveled decreased after the last recession, but have begun increasing.

In the buildings sector, the BAU Scenario shows existing efficiency policies leading to an 18 percent energy demand reduction in 2030 compared to energy use in the Updated Reference Scenario of the California Pathways modeling. This 18 percent value lies between more recent California Energy Commission analysis and the reductions evident in the Scoping Plan scenario in Pathways modeling for the 2017 Scoping Plan, which lowers building sector emissions by 13 percent compared to the Updated Reference Scenario of the Pathways modeling. The California Energy Commission analysis of programs designed to meet requirements under Senate Bill 350 anticipates savings of 0.35 quads of energy, which would represent a 24 percent reduction in building energy use as measured against the Updated Reference Scenario.

The BAU Scenario does not include a carbon price for two reasons. First, the carbon pricing program was the largest single contributor in California's 2030 strategy, so assumptions about future performance are particularly important to evaluating the current policy trajectory. Since web users cannot change BAU assumptions, including a BAU carbon price would limit their options to evaluate future price trajectories. Web users could not investigate a lower-than-expected carbon price, should they wish. Evaluating carbon pricing entirely through policy layered on top of the BAU Scenario allows for more analytical flexibility.

Second, this approach allows for consistent treatment of carbon pricing effects because the response induced by a given carbon price depends on the starting price level. A carbon price of a particular level will have a larger impact if the starting price is lower.[18]

4.3. CARBON PRICING

California's approach to carbon pricing is a hybrid of the two differing approaches to pricing carbon. By default, the program is initially set up to operate as a cap-and-trade model. The program requires large emitters of CO_2 to obtain permits to cover their emissions. Pollution is limited—capped—by the supply of permits circulated by the state. A price for carbon emission permits then emerges from market forces, whether through permit auctions or carbon market trading.

But if carbon price under the program reaches the upper or lower extreme of a pre-determined price range, known as the price ceiling and price floor, the program morphs into a carbon tax policy. In practice, the policy achieves price containment through auctions, either withholding permits at low prices or offering additional permits for sale at the ceiling price. Effects are translated to secondary prices, providing effective guardrails that contain prices between the floor and the ceiling.

Turning to the modeling, the Current Trajectory Scenario assumes the price of carbon stays close to the floor price, reaching $29 per metric ton in 2030 (in 2017 dollars, the base currency for model outputs). Section 5.3, the "Carbon Price" section under the "Current Trajectory Analysis," further explains the underlying reasoning and different carbon price scenarios developed for sensitivity analysis.

Next we describe key input variables affecting the carbon price responsiveness of emissions across sectors.

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[18] This footnote drives the point home mathematically. The given equation defines a generic elasticity of quantity of a given energy type demanded as a function of price for that type of energy. The equation shows that the price of energy before carbon pricing is introduced (the variable P_0) directly enters the lower term of the equation. Therefore, it directly affects the final results.

$$\varepsilon = \frac{\%\Delta Q}{\%\Delta P} = \frac{\frac{Q_0 - Q_1}{Q_0}}{\frac{P_0 - P_1}{P_0}}$$

Where $\mathcal{E}$ = elasticity.

Q_0 and Q_1 are the quantity of energy demand before and after carbon pricing.

P_0 and P_1 are the price of energy before and after carbon pricing.

In the industry sector, the key input parameter is -0.5 price elasticity of demand for natural gas, meaning that for a given percentage change in fuel price, fuel use changes by half as much. This is the mid-point of the range used in the Borenstein et al. (2017) study of expected carbon prices through 2030. The selected price elasticity value reflects a mid-term perspective, appropriate over a 2030 timeframe.[19] The structure of the model for the industry sector does not allow for varying price elasticities over time. There is a single time-invariant input value for each fuel. The selected value would produce inappropriately large short-run effects in the early years of policy implementation if not addressed. Whereas the short-run response is dominated by behavioral adjustments, as more time passes broader changes to capital stock are possible, expanding the scope for the response to a carbon price and increasing its potential effect. This means price elasticities are lower in the short run.

To avoid overestimating the response to carbon price, we adjust the policy implementation schedule. We apply a scaling function to the schedule to lower the emission reductions caused by the carbon price in the early years. The reductions attributable to carbon pricing increase to full strength in 2026.

The EPS explicitly accounts for differences between short-run and long-run elasticities for other sectors. For example, the transportation sector travel demand variable (i.e., passenger miles traveled or freight ton miles traveled) responds to one elasticity parameter, while the carbon price separately enters the vehicle purchase choice function.

In the building sector, carbon price affects energy use and emissions via two pathways, related to equipment efficiency and demand effects. The elasticity of demand for building services with respect to price ranges from -0.15 to -0.3, drawing on the Annual Energy Outlook (Energy Information Administration 2019). The lower value determines the carbon price effect on natural gas combustion in residential buildings, the largest source of building emissions. The inducement a carbon price offers to purchase more-efficient building components (i.e., heating and cooling) is also included. The elasticity of building equipment energy demand with respect to energy cost ranges from -0.26 to -0.45. The size of this effect on average device efficiency across all buildings is limited in the near term by the rate of capital stock turnover. While not as durable as buildings themselves, components can last 15-20 years, with the average space heating lifetime estimated at 19 years.

In the transportation sector, the carbon price affects emissions through the elasticity of travel demand for transportation, estimated at -0.1 for light-duty passenger vehicles and -0.15 for commercial trucks, reflecting well-researched short-run responses. Carbon price also factors into vehicle choice, affecting the net present value ownership costs for different vehicle technologies (i.e., fueled by gasoline vs. plug-in hybrid electric vs. full battery electric). Yet other factors, such as vehicle cost or even the energy cost savings per mile driven for electric vehicles in the BAU

[19] The research uses a range of -0.4 to -0.6 for the price elasticity of demand for natural gas. See page 17-18 of Borenstein et al. (2017) for a discussion of the authors' elasticity choices and why they view elasticities in between the short- and long-runs as most appropriate for a 2030 timeframe.

Scenario, are more important determinants of relative cost effectiveness than the carbon price effects at levels considered politically feasible.[20]

4.4. LEAKAGE

Leakage refers to the shifting of emissions to areas outside of California when economic activity relocates. Most GHG emissions in California are from economic activities rooted locally and resistant to locational change. Consider passenger vehicle emissions, which represent roughly a quarter of the state's overall emissions. The fraction of drivers located close enough to state boundaries that they would regularly drive out of state to purchase transportation fuel is miniscule. Household electricity demand is similarly not subject to leakage. Shifting from a household to a commercial perspective, research has shown that climate policies do not put most small businesses at a competitive disadvantage because their competitors operate on the same playing field (Brattle Group 2009).

Leakage risks have been the subject of greater concern in relation to industrial firms producing energy-intensive, tradable products. Our results implicitly assume that net effects on industrial economic performance cancel each other out—that clean technology growth takes the place of carbon-intensive economic activity. We point to four factors mitigating leakage concerns for the industry sector and supporting our approach.

First, CARB has distributed millions of free emissions permits and significant free allocation of emission permits will continue. For the express purpose of preventing leakage, Assembly Bill 398 increased future levels of free permit allocation above levels expected under prior plans leakage. The method CARB has used to determine free allocation—output-based allocation, which provides free allowances contingent on the level of continued domestic production—is at the forefront of global best practice.[21]

Second, economic evidence raises doubts that manufacturing output will be negatively affected. For instance, an empirical study commissioned by CARB found that California's manufacturing output will increase 0.15 percent on average over the long run under a carbon pricing regime, as shown in "Table 6. Long-Run Impacts of Energy Price Increases" (Gray et al. 2016, p. 38). Although the report notes that "for a variety of technical reasons the authors offer caution when

[20] The vehicle choice function in the initial California EPS release (version 1.4.3) is determined entirely by variables related to the economic cost of vehicle ownership. EPS version 2.0 (the current version of the federal US EPS) adds variables related to vehicle performance and convenience. Without these other factors, the model was predicting higher levels of electric vehicle deployment than was deemed appropriate according to feedback received from transportation sector specialists. As a corrective measure, a variable determining the maximum annual percentage sales growth was set according to a composite forecast of eight future scenarios, ranging from pessimistic to optimistic. (See the input spreadsheet for the variable "Max Percent New Vehicles by Technology" for details on generating the composite forecast.) The maximum growth constraint results in the stock of electric vehicles growing to about 2.7 million vehicles in 2030 in the BAU Scenario. The only policy in the EPS that is able to override the maximum growth constraint is the electric vehicle sales requirement. A zero emission hydrogen fuel sales requirement is an option in the EPS version 2.0.

[21] We hope that policymakers will push forward the idea of boundary adjustments as an alternative, but so far, no jurisdiction has pioneered this method.

interpreting the industry-specific long-run results," (ibid. p. 21), the overall finding that climate policy positively affects manufacturing does not fall under that caveat. The authors offer no warning regarding the overall average result. And in fact, long-run effects are generally summarized as being "for the most part clustered closer to zero," (ibid. p. 18).

Third, optimism that any negative leakage effects would be moderate to negligible is bolstered by the historical record. As California has intensified its climate policy, the state's economy has generated very strong growth rates and levels of wealth creation, outperforming other large states like Texas by many macroeconomic measures (Busch 2018). An ideal analysis would compare actual outcomes to economic performance in the absence of any climate policy. Without such research, this much is clear: intensifying climate policy thus far has co-existed with solid economic growth in California.

Fourth, the potential for leakage relates to the strength of climate policies in other jurisdictions, including carbon pricing programs in China and Canada. Leakage is caused by unequal climate policies. As other major economies intensify their climate policy efforts, the potential for leakage diminishes.

4.5. LAND USE

The effects of land-use change on emissions are included in neither the 1990 emissions inventory that has been used to define long-range targets nor the state's annual GHG inventory.[22] However, state policymakers have been actively working to incorporate land-based strategies into planning. California aims to expand carbon sequestration in natural and working lands, defined as including forests, rangelands, farms, wetlands, and soils. A concept paper put forward a "preliminary goal for sequestering and avoiding emissions by at least 15-20 MMT CO_2e by 2030 through existing pathways and new incentives" (CARB et al. 2018).

To calibrate the BAU Scenario, we refer to Sleeter et al. (2019), which estimates that changes in land cover and land use will lead to net emissions of 8.4 MMT of CO_2e in 2030. Policy potential and cost have also been estimated, but these require further vetting. We consider land-change inputs and results as preliminary and subject to refinement. Model users are asked to refrain from citing results or input from the land-use sector.

5. CURRENT TRAJECTORY ANALYSIS

5.1. THE CURRENT TRAJECTORY SCENARIO

The Current Trajectory Scenario seeks to represent the policies in the 2017 Scoping Plan (CARB 2017a), California's main long-term strategy document, along with two major policy changes after the plan's release: the 60 percent renewable electricity standard for 2030 established by

[22] California state agencies refer to managing emissions or sequestration from changes in land cover and land use as managing natural and working lands.

Senate Bill 100 and the increase in the low carbon fuel standard from 18 to 20 percent instituted by CARB.

The Current Trajectory Scenario seeks to test a relatively optimistic interpretation of the emission implications of existing policy. It assumes successful implementation of not only existing laws and regulations, but also stated commitments and executive orders, which future administrations could ignore or reverse.

For example, the Current Trajectory Scenario reaches the 2030 goal of 5 million zero emission vehicles established by executive order, accomplished with a zero emission vehicle sales standard that requires manufacturers to sell increasing numbers of electric vehicles. When combined with the BAU requirement, zero emission vehicles sales reach nearly 50 percent of new light-duty passenger vehicle sales in 2030.

The scenario also adds a carbon price and several other transportation policies, including an increase in the low carbon fuel standard from 18 percent to 20 percent, reflecting regulations revised after the Scoping Plan was finalized. Additional transportation policies include targeting emissions from conventional motor vehicles and increasing vehicle electrification.

Strengthening vehicle standards in this scenario covers conventional passenger vehicles as well as light- and heavy-duty trucks. Such policies require approval from the U.S. Environmental Protection Agency under the federal Clean Air Act, which gives the federal government exclusive authority to regulate the environmental performance of motor vehicles, with an exception for California. The Act allows California to set stronger standards (which other states may follow). This is currently a hotly contested area of federal-state environmental relations. The federal administration has sought to revoke California's existing authority for light-duty vehicle standards through 2025 as part of a larger effort to weaken national standards. Revocation of a previously approved waiver would be unprecedented and unlikely to succeed, but the potential effects are explored via sensitivity analysis.

The Current Trend Scenario also advances electrification of passenger buses and light- and medium-duty freight trucks, with zero emission mandates in 2030 reaching 50 percent for buses (approximating the requirement for 100 percent of urban transit buses to be electric by that time) and 10 percent for medium-duty trucks, reflecting Scoping Plan strategies targeting these vehicle types.[23]

5.2. SUSTAINABLE COMMUNITY STRATEGIES

The Current Trajectory analysis assumes sustainable community strategies are half as effective as had been expected when the last Scoping Plan analysis was completed in 2017.[24]

Sustainable community strategies, analogous to the policy called transportation demand management in the model, are a collection of methods for lowering the need for motor vehicle travel, thereby reducing CO_2e emissions from conventionally fueled vehicles. These strategies encompass a range of measures: encouraging the development of transit-oriented and walkable neighborhoods close to jobs, upgrading infrastructure for pedestrians and bicyclists, and improving public transit quality and convenience.

The Current Trajectory assumption about the expected effectiveness of the policy should not be taken as opposition. Five years ago, we co-authored a research report, Moving California Forward, which found that sustainable community strategies offer significant emission reduction potential while delivering clear economic benefits that grow even stronger when considering broader social impacts. Current results from the California EPS also show sustainable community strategies to be attractive. Emission reductions are negative cost, saving many hundreds of dollars per ton—more than any other policy considered. And these results do not even consider the economic benefits from consumers wasting less time in traffic (a productivity drag) or the public health benefits associated with more active lifestyles. Further, walkable communities with good transit service are in high demand yet are undersupplied. Myriad market failures stop new development of this sort, so another unpriced benefit of sustainable community strategies is giving people the ability to choose these communities.

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[23] Excerpts from page 25 of the 2017 Scoping Plan:

Light-Medium Duty Truck related strategies:

- Deploy over 100,000 freight vehicles and equipment capable of zero emission operation and maximize both zero and near-zero emission freight vehicles and equipment powered by renewable energy by 2030.
- Put in place a new regulation targeting Last Mile Delivery, resulting in the use of low NO_X or cleaner engines and the deployment of increasing numbers of zero emission trucks primarily for class 3-7 last mile delivery trucks in California. This measure assumes [zero emission vehicles] comprise 2.5 percent of new Class 3–7 truck sales in local fleets starting in 2020, increasing to 10 percent in 2025.

Passenger Bus-related strategies:

- Innovative Clean Transit: Transition to a suite of innovative clean transit options. Assumed 20 percent of new urban buses purchased beginning in 2018 will be zero emission buses with the penetration of zero emission technology ramped up to 100 percent of new bus sales in 2030.

[24] The 2017 Scoping Plan aimed to reduce per capita vehicle miles traveled 25 percent below the 2005 level by 2035. Adjusted to 2030, this amounts to an 18 percent reduction below the 2017 level, our California model's start year. Therefore, the assumption of policy effectiveness at half the Scoping Plan level implies a reduction in per capita vehicle miles traveled of roughly 9 percent below the 2017 start year.

Thus, we support continued efforts to find new strategies that will deliver better urban design and mobility. The lower expectation in the model regarding future emission reductions from sustainable community strategies simply reflects the institutional and political challenges, as well as empirical evidence showing the difficulty of lowering vehicle miles traveled.

Success on this front has remained elusive under Senate Bill 375, which became law in 2008, and related efforts. Senate Bill 375 did not give new authority to the state to force land-use change. In 2017, the state adopted Senate Bill 150, calling for retrospective analysis every four years thereafter. CARB did not mince words in its recent assessment: "A key finding of this report is that California is not on track to meet the GHG reductions expected under Senate Bill 375 for 2020, with emissions from statewide passenger vehicle travel per capita increasing and going in the wrong direction" (CARB 2018a).

Compounding the challenge are mega trends driving increased demand for both freight and passenger travel. E-commerce is already pushing freight transportation miles upward. New food and other delivery services are also growing in popularity, placing continued upward commercial pressure on travel demand.

In passenger transportation, innovations such as shared mobility and self-driving cars are very likely to increase vehicle miles traveled. Ride sharing is currently recognized as raising vehicle miles traveled due to "deadheading," i.e., driving around looking for a passenger. Self-driving vehicles are almost certain to boost travel demand. A recent empirical study found that overall vehicle miles traveled increased by 83 percent with self-driving vehicles (Harb et al. 2018). This was just one study with a small sample size, but it provides real-world evidence that the spread of self-driving cars is likely to lead to more vehicle miles traveled.

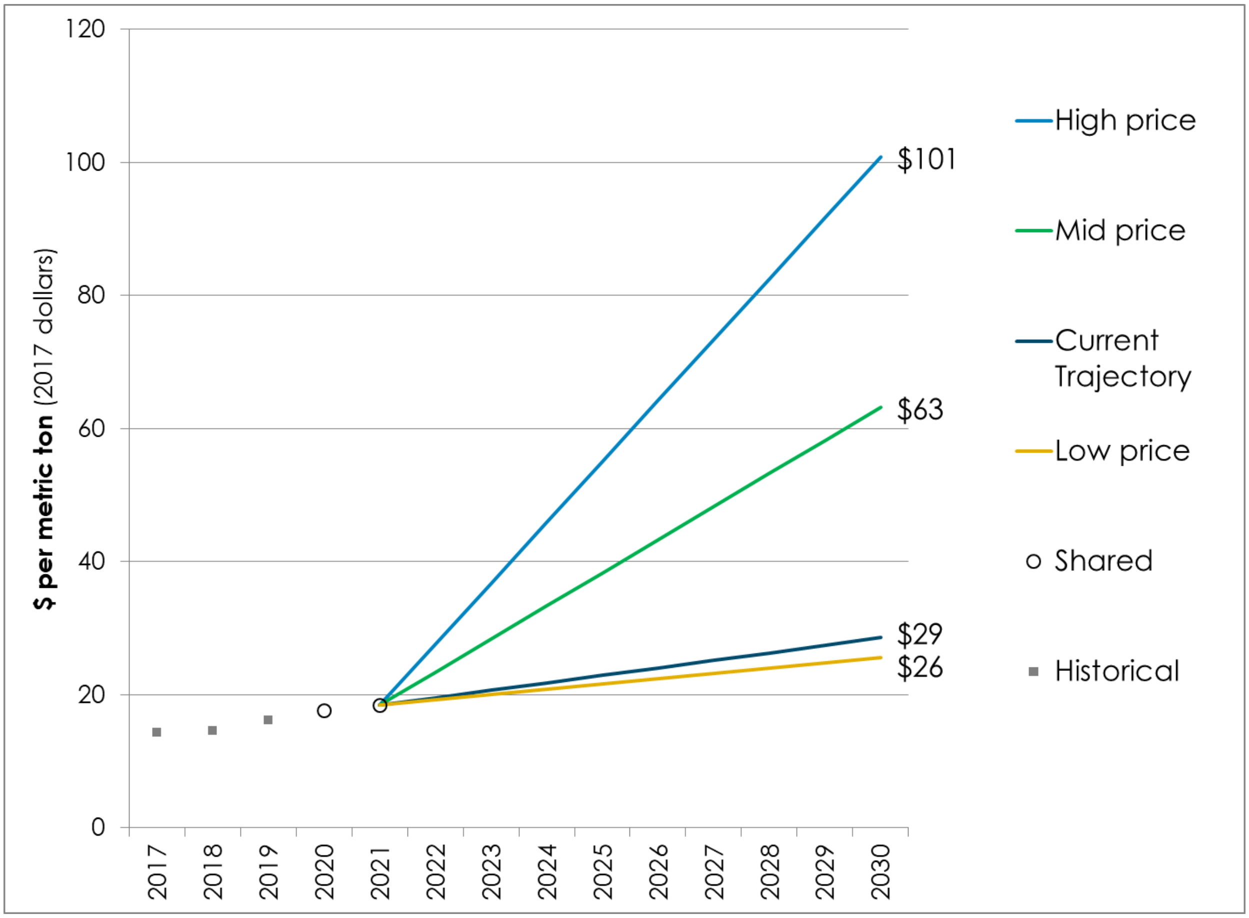
For these reasons, a lower level of effectiveness reflects more realistic expectations of future trends for vehicle miles traveled.

Notably, some progress has been made in the realms of transit and transit-oriented development. And it is possible that the legislature could pass a transformative law, fundamentally shifting the state-local balance of power regarding land-use decisions. Legislative efforts appear to be gaining steam, though prospects for success are uncertain. We explore the possibility that sustainable community strategies will become more effective as part of the sensitivity analysis conducted for this report.

5.3. CARBON PRICING

In the Current Trajectory Scenario, the carbon price is expected to reach $29 per ton in 2030. In 2030, the Low Price and High Price scenarios reach $26 per metric ton (2017 $s) and $101 per metric ton (2017 $s), respectively, approximating the floor and ceiling in the current design. A Mid Price Scenario splits the difference between these two. Figure 6 graphs the future carbon price scenarios considered.

Figure 6. Carbon price expected in Current Trajectory and other scenarios



The "Shared" label identifies two values—for 2020 and 2021—that are not appropriately labeled "Historical" and that are included in all the scenarios' modeling of changes to carbon pricing. Because of the overlap, the graphical presentation uses a different label for these future values. Historical values are calculated as an average of quarterly auction settlement prices.

Source: CARB auction results for historical data 2017-2019

The Appendix discusses in more detail the inputs considered in forming price scenarios, delving into the history, political-economy, and leading studies from academicians and carbon market consultants. Briefly, we note that privately-held banked allowances, i.e., those in the hands of regulated businesses or speculative investors beyond the amount needed to cover current and past emissions, now total roughly 200 million surplus allowances, more than half a year's worth of covered emissions (Inman et al. 2019; Lithgow 2019b). Surplus allowances can be held indefinitely and used in future years.

In May 2018, the "Yellow Vest" unrest set off in part by a carbon tax increase in France drew headlines (Rubin and Somini 2018). The crowds have dwindled in size, but the protests appear to have reminded many policymakers of the political target presented by carbon pricing.

The carbon price in the Current Trajectory Scenario, reaching $29 per metric ton in 2030, is the result of a constant projection method, based on the price that resulted in the May 2019 allowance auction, which was 12 percent above the price floor. The level of the price floor is calculable for future years, based on the formulae by which it changes from year-to-year, increasing above the prior year's value at a rate of five percent plus annual inflation. Using constant 2017 dollars as this analysis does means the inflationary component can be ignored. Therefore, in the Current Trajectory Scenario, the carbon prices in future years are estimated as 12 percent above the price floor.

5.4. UPPER AND LOWER BOUNDS ON CURRENT POLICY EFFECTIVENESS

The future emission pathway resulting from the Current Trend Scenario represents an expected outcome, but different plausible future scenarios are possible. Sensitivity analysis evaluated a range of alternative values considered reasonably likely.

The Lower Bound Scenario defines the fastest emission reductions developed as a result of varying assumptions underlying the Current Trajectory Scenario. The Lower Bound Scenario includes one variation from the policy settings in the Current Trajectory Scenario: a higher-than-expected carbon price, reaching $63 per metric ton in 2030. By comparison, the Current Trajectory Scenario assumes the price of carbon reaches $29 per metric ton in 2030.

The Upper Bound Scenario defines the slowest emission reductions developed as a result of varying assumptions underlying the Current Trajectory Scenario. In this scenario, vehicle standards—both fleet average tailpipe emissions standards and zero emission vehicle standards—are frozen at 2020 levels. This scenario explores the possible effects of an action proposed by the US Environmental Protection Agency that would weaken existing federal rules for increasing vehicle fuel economy, requiring "no vehicle fuel economy or [GHG] emissions improvements for a period of at least six years" (CARB 2018b). The action also directly targets California's vehicle emission policies, proposing a "California waiver withdrawal" (U.S. Environmental Protection Agency and U.S. Department of Transportation 2018).

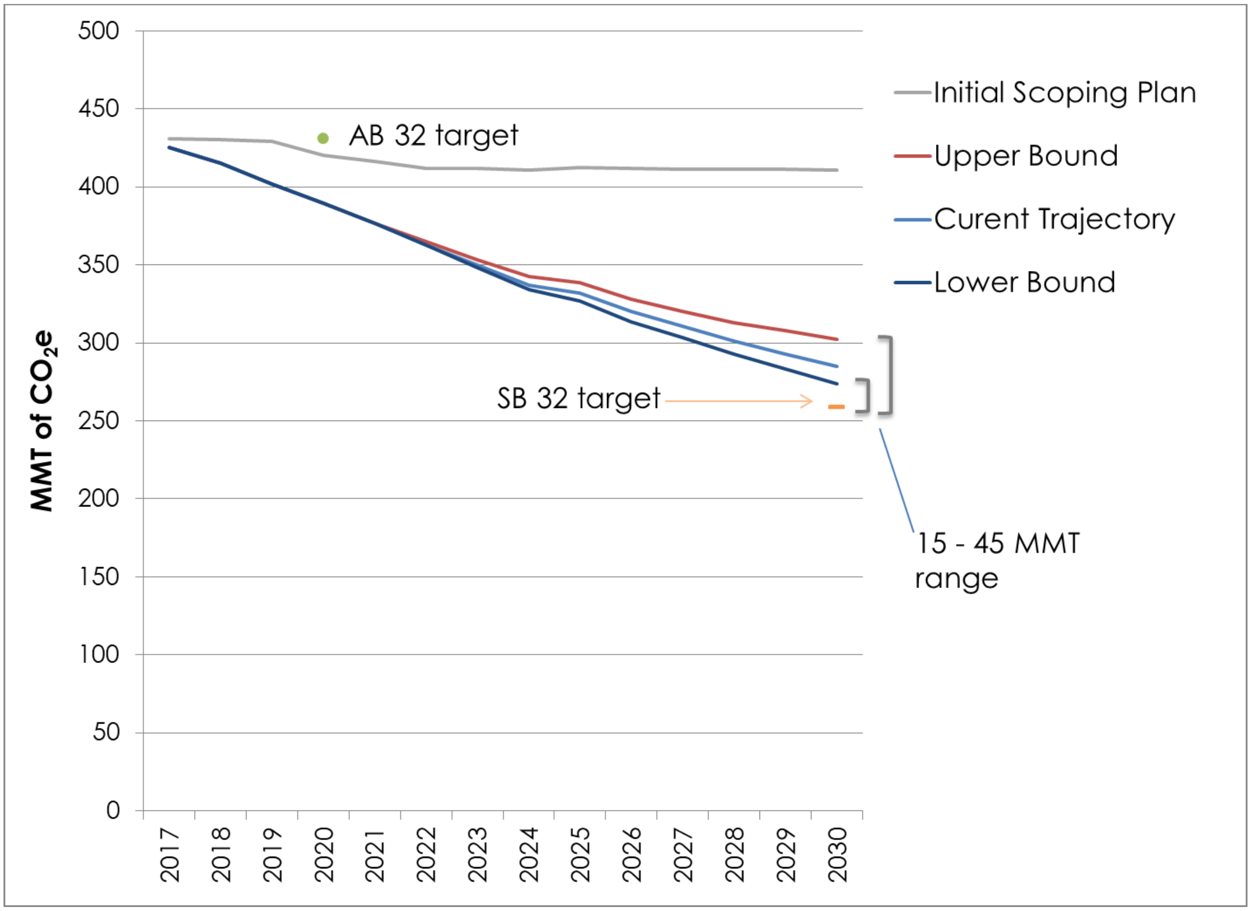
The federal Clean Air Act explicitly permits California to set vehicle emission standards under certain conditions, as validated through a waiver of the rules otherwise giving the federal government exclusive authority to regulate motor vehicle emissions. The state has used this authority to set "clean car standards"—tailpipe emission standards that govern all vehicles sold—and also to support the emergence of zero emission vehicle technologies through minimum sales requirements.

The revocation of an existing waiver has never been attempted and CARB has a track record of winning in court, but expert legal opinion is divided on the likelihood of success. Given these complexities, the Upper Bound Scenario should not be read as a prediction of the likely effects of a Trump administration victory in its battle with California over vehicle standards. What the Upper Bound Scenario does is illustrate the importance of the carbon intensity of motor vehicles in California.

5.5. CURRENT TRAJECTORY RESULTS

Using the Current Trajectory Scenario as a representation of existing policy, the EPS finds that the current framework causes emissions in 2030 to fall to 284 MMT of CO_2e, roughly 25 MMT above the target, as illustrated below. This quantity of emissions remaining above the target is defined as the "policy gap."

Figure 7. California EPS finds a policy gap of approximately 25 MMT of CO_2e



Source: California EPS

Figure 7 graphs the results of the current trajectory analysis, showing that the Current Trajectory Scenario leaves emissions approximately 25 MMT of CO_2e above the 2030 target. The figure also shows the emissions paths found for the upper and lower bound scenarios and the resulting 2030 emission gap, which ranges from 15-45 MMT of CO_2e. Finally, Figure 7 also shows emission levels estimated for an Initial Scoping Plan Scenario, referring to the first economy-wide policy planning process CARB undertook in service of meeting the 2020 target.[25] This comparison offers some context on the strength of current policies, which reduce emissions by roughly 130 MMT of CO_2e over the original Assembly Bill 32 package reflected in the Initial Scoping Plan Scenario.

In other recent work, Next10 and Beacon Economics (2019) take a different approach to analyzing current trends. They project recent emission reduction trends into the future without

[25] The emission projection to 2030 for the Initial Scoping Plan Scenario is drawn from a pre-release version of the California EPS that was developed during participation in the third California Climate Policy Modeling Dialogue (Fulton et al. 2019).

attempting to account for changing policy parameters. Next10 and Beacon Economics (2019) also conclude California will need to strengthen its policies in order to hit the 2030 target.

6. CRITERIA FOR POLICY STRENGTHENING

This section describes the criteria used to recommend policies to meet California's 2030 emissions target. Four criteria were used: (1) meeting the 2030 goal, (2) cost effectiveness, (3) technology risk, and (4) policy effectiveness and political risk.

The first two criteria interact directly with model outputs—effect on emissions and economic and monetized social impacts. The overarching goal was inducing emission reductions sufficient to achieve the 2030 target. Within the constraint of 2030 emissions falling below 258.6 MMT of CO_2e, significant attention also went to cost effectiveness. Optimization of the type common in economics and operations research is not built into the structure of the EPS, but such cost minimization can be approximated using the model.[26]

Minimizing technology risk was a third consideration. In practice, with the target just one decade away, this means relying on currently available and substantiated technology. Ultimately, these options proved largely sufficient to hit the goal. The carbon capture and sequestration technology used as a lynchpin of the compliance strategy for the proposed cement and concrete standard is the most novel technology deployed. Demonstration carbon capture and sequestration projects exist—some of them quite large in scale. But despite promising indicators of falling cost, significant market deployment has yet to occur.

Fourth, recommendation development took into account the possibility of policy underperformance and political risk. Institutional and behavioral barriers are among the factors that may inhibit policy effectiveness. For example, the sustainable community strategies that the state is pursuing under Senate Bill 375 appear highly cost effective in California EPS results, saving on the order of $1,000 per metric ton.[27] Nonetheless, it was deemed unwise to count too significantly on reductions from passenger travel demand management. Local government control of land-use decisions is one clear factor limiting the effectiveness of such state policies.

Carbon pricing presents an example of political risks. The carbon price included in the Energy Innovation Scenario—reaching the mid-point between the current price floor and ceiling in 2030, i.e., roughly $63 per metric ton (2017 dollars)—reflects a judgment that higher levels may be politically infeasible.

[26] The EPS model download provides Python code to enable batch runs and to enable searching for expenditure savings across a range of policy combinations, allowing identification of cost-minimizing combinations.

[27] As mentioned, the state policy is represented using the passenger travel demand management in the model. The units presented for this metric are the same as for the policy benefit-cost curve. Direct monetary impacts are calculated as the net present value of spending effects through 2030, discounted at 3 percent annually.

7. RECOMMENDED POLICY STRENGTHENING

This section introduces the six recommended policy enhancements in the Energy Innovation Scenario, explaining how they function and their calibration in the modeling.

Some of the recommendations are readily connected to existing policy instruments; they are ready to implement off the shelf, so to speak. The carbon pricing concept and ratcheting up of the electricity sector and zero emission vehicle standards fall into this category. The three other recommended policies are more novel. The discussion that follows will explain how these policies are represented in the model and suggest practical next steps for policymakers.

How strong policy is—in EPS terminology, the policy setting—is the key factor determining the effect of a policy for a given set of input assumptions. How a policy changes over time—known as the policy implementation schedule—is also crucial. Model users running either the Vensim software or the web application can adjust both parameters.

Policies in the recommended package begin ramping up in 2022, starting with carbon pricing and electricity sector policies. New initiatives are expected to take more time to launch, but we recommend prioritizing a fast start on the policy targeting emissions from cement and concrete production. Quick action will leverage current federal tax credits for carbon capture and sequestration, which require projects to be installed by January 1, 2024. Other policies on building electrification, vehicles, and industry heat are implemented beginning in 2024.

Table 1, below, provides an overview.

Table 1. Recommendations in brief – key features and quantitative calibration in the model

Policy (sector)	Description	Calibration
Strengthening of existing policies		
Cap-and-trade program (Multiple sectors)	Link the program's carbon price floor to whether or not overall emissions are on track for the 2030 goal.	As augmented, the carbon price reaches the mid-point between floor and ceiling prices, $63 per metric ton, in 2030.
Clean energy standard (Electricity supply)	Ratchet up standards. Modeling also represents additional storage and demand response needed for electricity reliability.	Electricity sector emissions fall to 38 MMT of CO_2e in 2030, compared to 46 MMT under current plans. Zero emission generation grows by roughly 7 percent. Modeling accounts for system reliability needs through additional battery storage and measures to shift demand to off-peak times.
Zero emission vehicles (Transportation)	Increase requirements under the zero emission vehicle mandate for passenger cars and trucks.	Zero emission vehicles reach 80 percent of passenger car and truck sales in 2030, by which time California's electric vehicles number 7.5 million.
New initiatives		
Building electrification	Continue to recalibrate state building and appliance policies to promote faster substitution of electrified technologies for natural gas.	Policy effects are modeled as a shift to increasing shares of advanced electric heat pumps in new unit sales for residential space heating and water heating, reaching 50 percent of new sales in 2030.
Zero emission heat standard policy	Implement steadily increasing performance standard requiring a minimum amount of zero emission steam.	Reductions peak at half the technical potential for solar thermal steam to substitute for natural gas as identified by ICF (2015). In 2030, this is roughly equal to a 6 percent fuel switch from natural gas to solar thermal.[28]
Cleaner cement and concrete production	Implement performance standard requiring steady reductions in GHG emissions.	Carbon capture and sequestration plus material input techniques reduce emissions to approximately 50 percent below current levels in 2030.

7.1. CARBON PRICING

The Energy Innovation Scenario models a higher carbon price ($63 per metric ton in 2030) than does the Current Trajectory Scenario ($29 per metric ton in 2030). The EPS finds that the carbon price generates favorable economic and social impacts, but policymakers have expressed concerns over a political backlash if prices rise too much or too fast. Absent political constraints, our recommendations would have included an even more robust contribution from higher expected carbon prices.

The political challenges associated with carbon pricing, which policymakers ignore at their peril, can partly be traced to problems of perception. A carbon price works to counter the market failure that exists if atmospheric dumping is free. The added cost is needed for efficient market functioning, but it also is subject to being labeled as a "tax," a politically challenging frame.

The problem is not just one of perception. The carbon pricing narrative from economic theory emphasizes smooth, rational adjustments. In this narrative, the carbon price avoids suboptimal energy use. The driver turns off the car instead of letting it idle while waiting. The homeowner remembers to turn off the air conditioning as she leaves the house.

In reality, some households could face higher costs with little opportunity to adjust. For example, in the context of California's car-dependent transportation systems and housing scarcity, some people of modest means cannot afford to buy a more efficient vehicle and have limited prospects for moving closer to their place of work. For Californians facing already-thin household margins for survival—especially those with long commutes—any new costs tied to higher carbon prices may trigger feelings of injustice. More broadly speaking, changing the economic playing field without addressing underlying structural constraints that limit individuals' or firms' opportunities to adjust can generate political opposition.

Carbon market supply and demand trends and other factors shaping price expectations and the carbon pricing recommendation are further discussed in the Appendix.

7.2. CLEAN ELECTRICITY STANDARD

The state's renewable portfolio standard has served as the most important driver of decarbonization in utility-level electricity supply. The renewable portfolio standard requires electric utilities to deliver an increasing percentage of renewable electricity over time, calculated as a fraction of retail sales.[29] Renewable power sources include wind, utility-scale solar thermal and photovoltaic, biomass, geothermal, and small hydroelectric.

[28] "Fuel switching" refers to the substitution of a zero- or low-carbon source of energy for a higher-emitting source.

[29] Typically, up to 10 percent of electricity consumed in California may fall outside of the scope of retail sales. Water pumping, a large source of electricity demand, is an example. Also, note that electricity imports are static as represented in the BAU Scenario, unless directly modified by policy levers that allow model users to directly increase or decrease imports and exports. Turning up the strength of the clean energy standard policy in the EPS only affects capacity and generation within California. The reason for the lack of more nuanced treatment of imports is that

Senate Bill 100's requirement for 60 percent renewables was introduced in the BAU Scenario discussion in section 4.2. The requirement is maintained in the Current Trajectory Scenario. The bill marks a transition to an emphasis on "clean" or "zero emission" generation sources. Also known as "The 100 Percent Clean Energy Act of 2018," the bill establishes a 2045 target of 100 percent clean energy. The legislation does not specifically define the term "clean," delegating this decision to the California Energy Commission. Though the Commission has issued no ruling yet, conventional wisdom would suggest that the broader standard may also allow nuclear, large hydroelectric and natural gas with carbon capture and sequestration.

Senate Bill 100 has launched a debate about whether and how fast to transition from current renewable electricity standards to a broader clean energy standard. Renewable technologies have been prioritized in California based on an understanding they have a lower collateral environmental impact than other low-emission sources. At very high levels of decarbonization, it makes sense to allow for a broader set of zero emission sources.

Our work is guided by the most recent assumptions used in state's long-term planning process, which considered three scenarios (California Public Utilities Commission 2019). These three scenarios are referred to according to the level of sector-wide emissions achieved in 2030: 46, 38, and 30 MMT of CO_2e, respectively. The 46 MMT Scenario, currently driving system planning, is the basis for the BAU and Current Trajectory scenarios in this report. The Energy Innovation Scenario's electricity sector policy is calibrated to the 38 MMT Scenario.

We note that even in the 30 MMT Scenario, modeling for the state's long-run planning uses a mix of new solar and wind power as new sources of electricity generation. This reflects an assumption that only renewables, natural gas, and storage and demand response are available as new resources (E3 2019). California has banned new nuclear power plants and has not added meaningful large hydroelectric capacity in many years. Nuclear and hydroelectric are two of the main candidates added to the list of qualifying technologies by the expansion of qualifying technologies under a clean energy standard as compared to a renewable energy standard. An oft-mentioned third candidate is carbon capture and sequestration for natural gas, but this technology is still quite costly compared to other zero-carbon alternatives. Yet at levels substantially below 90 percent decarbonization, as contemplated in the state's long-run planning and in this report, the distinction between "renewable" and "clean" electricity requirements is less important than when the system approaches 90 percent or 100 percent carbon free.

The Energy Innovation Scenario increases the amount of electricity sourced from solar and wind power by 7 percent in 2030, which reduces electricity supply emissions by approximately 8 MMT of CO_2e in 2030. The strength of the policy was calibrated by ratcheting up the clean energy standard's requirements until sector emissions declined to 38 MMT to align with modeling done for the state's electricity sector long-run planning process, as mentioned (California Public

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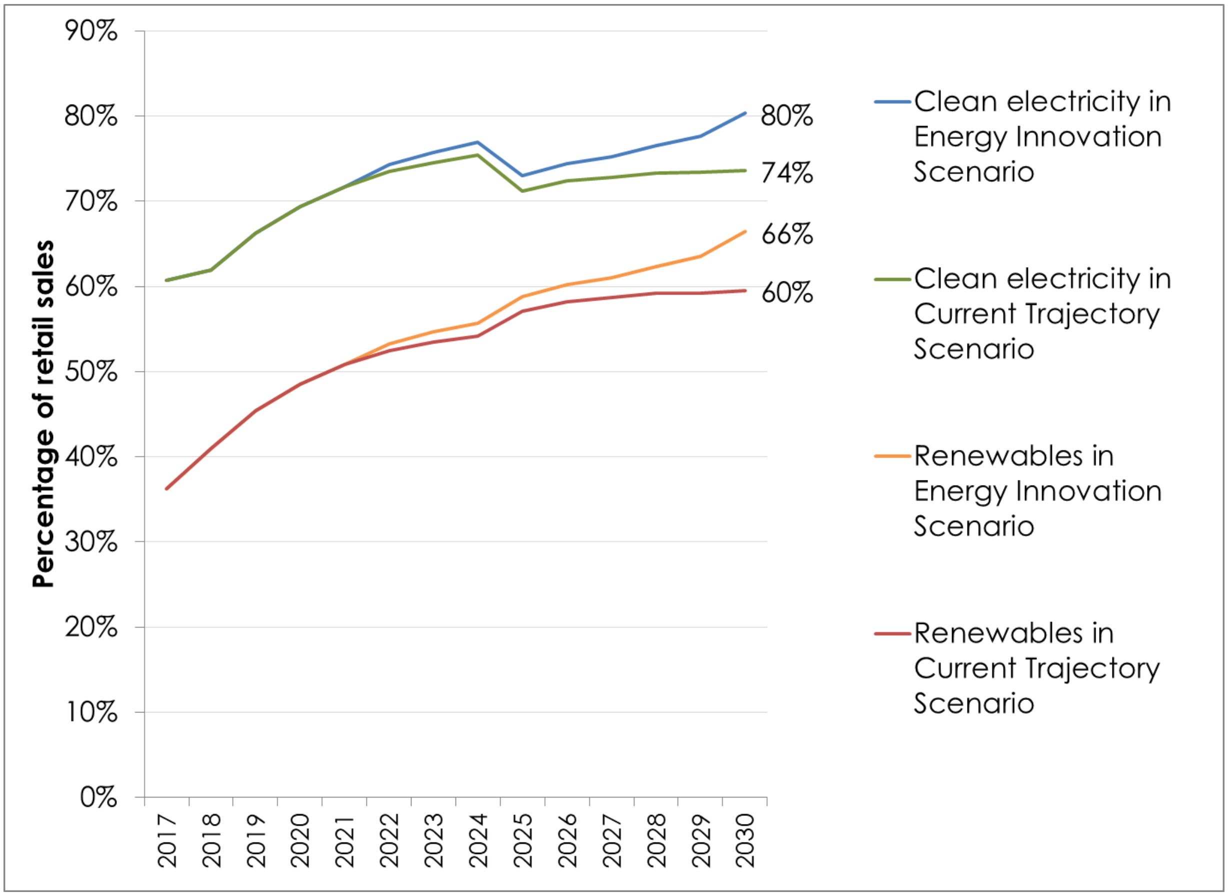
Energy Innovation has typically applied the EPS to large countries where imported electricity is relatively insignificant. The large share of imported electricity in California's generation mix is unusual even among U.S. states.

Utilities Commission 2019).[30] Modeling of the policy also draws on the state's long-run planning process to inform assumptions made regarding the parallel investments in flexibility resources associated with higher levels of zero solar and wind power, for the purpose of system reliability.[31]

Figure 8. Electricity supply metrics in BAU and Energy Innovation scenarios



Percentages are based on the share in retail sales.

Source: California EPS

Figure 8 shows renewable and clean energy generation achieved as percentages of retail sales, illustrating that the planned Diablo Canyon nuclear power plant closure causes the share of clean generation to decrease between 2025 and 2026.

[30] The relevant proceeding at the utilities commission is technically known as the Integrated Resource Plan and Long Term Procurement Plan.

[31] Flexibility resources are a way for electricity system planners to analyze whether different hypothetical system configurations will ensure electricity supply is sufficient to meet peak loads, as necessary for system reliability. Electricity sector modeling with the California EPS for this report makes use of two flexibility resources: battery storage and demand response (the ability to reduce peak demand, especially by shifting electricity loads to off-peak periods).

7.3. ZERO EMISSION HEAT STANDARD

The recommended zero emission heat standard for industry is calibrated in the modeling based on the potential to displace natural gas with solar thermal energy in oil extraction. Though initially calibrated to reflect the potential available with current technologies, the policy should be refined—requirements upped—as other technological options reach commercial scale and cost competitiveness. Several emerging options show promise to reach commercial viability.

In 2017, natural gas combustion for oil extraction accounted for more than 20 percent of California's total natural gas use, almost entirely for the purpose of creating steam for enhanced oil extraction.[32] The recommended calibration of this policy equals approximately half of the fuel switching potential in California, as identified by the consultancy ICF International (2015), which estimates cost-effective displacement for up 30 percent of steam from natural gas for oil extraction.

Several companies are now offering to provide solar thermal steam at a price competitive with conventionally generated steam. Yet the price signals from the state's cap-and-trade program and the low carbon fuel standard have not provided sufficient incentives for investment. While emission reduction credits under the low carbon fuel standard have recently approached the price ceiling, future prices are still too uncertain to unlock the large up-front financing required.

Natural gas combustion for enhanced oil and gas extraction presents a singularly large emission reduction opportunity based on a relatively simple technological substitute that already exists and is commercialized, but is not seeing fast-enough uptake. In the end, it is the most cost-effective policy.

Turning from the near-term opportunity for more use of currently commercialized solar thermal technology, several emerging technologies for providing zero emission heat are showing promise. In laboratory and demonstration projects, solar thermal energy has been able to reach the very high temperatures needed to produce materials like cement and steel, but no company has managed to deliver such high temperatures at commercial or industrial scale, at competitive prices. A Pasadena company is trying to do so with a new approach leveraging the latest advances in sensors and software (Temple 2019). Another emerging option for zero emission heat for industrial use involves combusting hydrogen produced from electrolysis powered by renewable electricity. Carbon capture and sequestration methods could provide another pathway.

The zero emission steam performance standard for industry is new, but it is rooted in the concept of the flexible performance standard that California policymakers have done so much to advance. While motivated by the large emission reduction potential and cost effectiveness that

[32] Of all energy used in California oil production, 90 percent is in the form of steam (ICF 2015 p. 2). This is equivalent to approximately 96 percent of energy from natural gas, based on the oil extraction subsector data on energy demand in the 2017 Scoping Plan analysis (CARB 2017b).

solar thermal itself appears to present, the policy should be open to other zero emission technologies.

A zero emission steam performance standard would very likely require new legal authority. Such a policy appears to be excluded from CARB's current authority under Assembly Bill 398's provision that the cap-and-trade program alone shall be "the rule for petroleum refineries and oil and gas production facilities to achieve their [GHG] emissions reductions" (Assembly Bill 398 at Section 38592.5(a)(1)).

7.4. BUILDING ELECTRIFICATION

Strengthening the building electrification policy lever directly ratchets up new sales of advanced electric heat pumps in residential buildings for water and space heating and cooling. Put differently, building electrification is accomplished in the model by dialing up new equipment sales. This policy is calibrated in the model such that 50 percent of new sales of residential space heating and water heating equipment in 2030 are shifted to electricity from units otherwise fueled by natural gas in the BAU and Current Trajectory scenarios. Those scenarios include some purchase of electric heat appliances, but not of the highly efficient advanced heat pump type.

The building electrification policy targets new equipment, which affects both newly constructed buildings and replacement of equipment in existing buildings. Every building sees turnover of water and space heating equipment. These new purchases to replace units reaching end of life in existing buildings are also up for grabs in the marketplace, and are affected by the EPS building electrification policy.

Theoretically, renewable natural gas use presents an alternative approach to addressing the emissions targeted with building electrification. Our modeling assumes that renewable natural gas displaces all conventional gas use in the transportation sector. But the limits on sustainable supply of renewable natural gas appear to be a barrier to much more widespread use. "Assuming California could access up to its population-weighted share of the U.S. supply of sustainable waste-product biomass, excluding purpose-grown biomass crops, there appears to be insufficient biomethane[33] to displace the necessary amount of building and industry fossil natural gas consumption to meet the state's long-term climate goals," (E3 2018, p. 33). Such research, in the context of the California EPS's use of renewable natural gas for transportation, suggests the sustainable supply of renewable natural gas is not large enough to also support large-scale decarbonization in buildings.

Initial modeling with the California EPS has targeted residential sector buildings because our interviews with experts in the field suggested residences are understood to be the largest source of cost-effective emission reductions. GHG emissions from the residential sector are roughly

[33] Biomethane is natural gas from sources understood to be carbon neutral. Biomethane, sometimes called biogas, is naturally occurring gas produced by the so-called anaerobic digestion of organic matter. Chemically, it is identical to natural gas stored deep in the ground. Biomethane is considered to be a carbon-neutral source of energy under California's GHG accounting methods, as is typical of inventory methods.

double the level of those in the commercial building sector. Moreover, the research literature on residential buildings offers a recent, detailed economic analysis using empirical data on actual California heat pump installations (Synapse 2018).

Though the California EPS identifies a pathway to reaching the 2030 target with a building electrification policy only affecting residential buildings and reaching 50 percent of sales in 2030, policy should aim higher. In light of the fifteen- to twenty-year lifetime of such building components and post-2030 goals, the state should direct that advanced heat pumps account for 100 percent of new water heater and space heater sales for residential buildings, or as close as possible to that goal.

The level of building electrification was selected in part to recognize potential hurdles. For example, installation in some existing buildings may be costly or deemed impractical. Moreover, electric heat pumps are less effective in very cold climates, though these conditions are likely to affect only a small fraction of California buildings.

The policymaking environment is also challenging. If the federal government already has appliance energy efficiency standards, such as exist for space and water heating, states are "pre-empted"—barred—from setting their own, separate efficiency standards. Federal preemption is a barrier to using appliance efficiency standards, which could otherwise transform this market segment.

It seems clear a portfolio of policies will be needed to help advanced heat pump technology move from niche to mainstream. At the state level, building and appliance policy must be aligned with the goal of electrification. In the past, before rapid progress in decarbonizing electricity, more efficient use of natural gas was the priority. Changes are already underway to recalibrate appliance incentive programs to encourage switching from natural gas to electric appliances. For example, in 2019, the California Public Utilities Commission revised rules for utility efficiency programs to support uptake of advanced electric heat pumps. The California Energy Commission (2019) has adopted an "Energy Efficiency Action Plan," developing a 2030 strategy for building electrification.

Local government action is another pathway for transforming the market for water heating and space heating equipment, and the California Energy Commission (2019) recently approved applications from six cities for code changes that encourage building electrification. In July 2019, Berkeley prohibit the connection of new homes to natural gas infrastructure, effectively banned natural gas in new construction within city limits (Myers 2019), and a flurry of local government action has followed. Dozens of cities, from Carlsbad in the south, to San Luis Obispo in the central coast, to Windsor and Davis in the north, have taken steps ranging from prohibiting natural gas use in new building construction to creating monetary incentives that encourage consumers to purchase electric heat pump appliances.

7.5. ZERO EMISSION VEHICLE POLICY

To spur additional light-duty passenger vehicle deployment, the Energy Innovation Scenario uses the model's electric vehicle sales performance standard, analogous to an existing California policy known as the zero emission vehicle mandate. Leaving aside current policy details, which include complications such as partial credits for hybrid vehicles, the policy in the model requires automakers to steadily ramp up electric vehicle sales. As specified in the recommended package, the policy ratchets up in strength to reach 80 percent of new sales in 2030, leading to roughly 7.5 million zero emission light-duty passenger vehicles in the California fleet overall, compared to 5 million under the Current Trajectory Scenario.

In the past, federal approvals under the Clean Air Act were requested and received in advance of implementing the state's zero emission vehicle mandate. Therefore, the ongoing dispute between the Trump administration and California regarding the state's unique authority to set vehicle emission standards under the federal Clean Air Act affects this recommendation. A performance standard, as used in the modeling, may be unavailable in practice, requiring the use of other tools.

Even if the state has a free hand to craft vehicle policies as it chooses, a broader array of measures and policies must be involved. This is because, as with building electrification, the end goal for policy ultimately involves consumer choice. An example in the area of transportation policy is the issue of electric vehicle charging. The cost of charging infrastructure is included in the modeling, but the model is not able to answer questions about the optimal mix of charger types: How to regulate public charging, for instance, or how as a practical matter to ensure access by renters living in multi-family buildings, where the option to install a dedicated vehicle charger may not exist.

7.6. PERFORMANCE STANDARD FOR CEMENT AND CONCRETE

Cement is an exciting area for innovation in decarbonization technology. In fact, the potential for net negative cement emissions exists because of the natural process of carbonization, whereby the cement within concrete reabsorbs some of the CO_2 emitted during production in the decades after its manufacture (Rissman 2018). We recommend establishing a GHG emission performance standard for cement and concrete production.

The combined effect of other policies in the Energy Innovation Scenario, not counting the proposed performance standard for cement and concrete production, reduces the cement and concrete subsector's emissions from 7.9 MMT of CO_2e in 2017 to 6.4 in 2030, 22 percent below the 2017 level. The proposed standard leads to further reduction of 60 percent, lowering the subsector's 2030 total to 3.8 MMT of CO_2e under the Energy Innovation Scenario.

In parallel, we also recommend establishing a border carbon adjustment for imported cement, whereby cement imported from jurisdictions with weaker climate policies would be required to pay a fee—the border adjustment—to account for unregulated GHG emissions, leveling the playing field in the California market for in-state producers. Assembly Bill 398 (California

Legislature 2017) specifically recommends considering such an approach: “The state board shall include recommendations to the Legislature on necessary statutory changes to the program to reduce leakage, including the potential for a border carbon adjustment, while maintaining the state’s ability to reach its targets” (Section 38562.b.2.I.).

Border carbon price adjustments have long been seen as an elegant solution to competitiveness concerns, but the lack of notable real-world examples evidences the challenges, which are in large part analytical. Recent work by Hasanbeigi and Springer (2019) develops new insights about California industry and provides emission benchmarks for California production as compared to that of other countries. This work provides a head start to taking on these issues. The initial focus on a single industry subsector will also help manage required international supply chain analyses.

Expert opinion is divided about the legal vulnerabilities of such a policy. Until the courts weigh in, a border adjustment policy necessarily involves legal uncertainty. Nonetheless, border adjustments hold great potential as a tool for managing competitiveness concerns.

Hewing to best practice in policy design and encouraging innovation, we recommend a technology-neutral GHG emission performance standard allowing plants to use their preferred mitigation approach. We use the model to select a cost-effective combination of mitigation options, principally using carbon capture and sequestration technology. Injection of CO_2 during the cement-making process accounts for a smaller portion of the reductions. This reduces the need for carbon-intensive material inputs, as reviewed by Rissman (2018), who also profiles other cutting-edge material input advances under development. Fuel-switching from coal to natural gas was considered for inclusion among recommended policies, but was found to be a higher-cost option.

Turning to the details relevant to carbon capture and sequestration, CO_2 concentrations in flue gas waste streams flowing out of cement kilns (the main energy-using stage) are higher than for typical coal or natural gas power plants or other industrial factories. Therefore, these emissions are particularly amenable to carbon capture technologies.

According to the most recent data, 63 percent of the targeted sector’s emissions come from process emissions, due not to combustion but to a chemical process needed to prepare limestone as an input to cement production. The quantified carbon capture and sequestration potential includes these process emissions as well as combustion-related CO_2 emissions. This approach is supported by Leeson et al., who observe that “both sources are amenable to CO_2 capture” (2017, p. 75).[34] A CO_2 capture efficiency rate of 60 percent, which is the lower bound of

[34] The model’s structure does not currently allow the carbon capture and sequestration policy lever to affect process emissions. To overcome this, CO_2 emissions from petroleum refineries in an amount equivalent to the process emissions from coal are included under available potential and accessed in the Energy Innovation Scenario. This approach helps ensure the calculations correctly account for the energy penalty associated with carbon capture and sequestration technology. Results presented in this report are processed to re-allocate these emission reductions to the cement subsector, but web application results will not automatically carry out this adjustment.

capture efficiency estimates among cement capture studies surveyed, is assumed for this policy (Leeson et al. 2017, p. 76, see Table 4).

Because this policy requires new infrastructure development, its effectiveness will depend on gaining community acceptance for projects and the required infrastructure. “The absence of sufficient CO_2 pipeline infrastructure in California is another impediment to [carbon capture] project development . . . there are an estimated 4,513 miles of dedicated CO_2 pipelines in the United States, none of which are in California,” notes the Energy Futures Initiative (2017, p. 51).

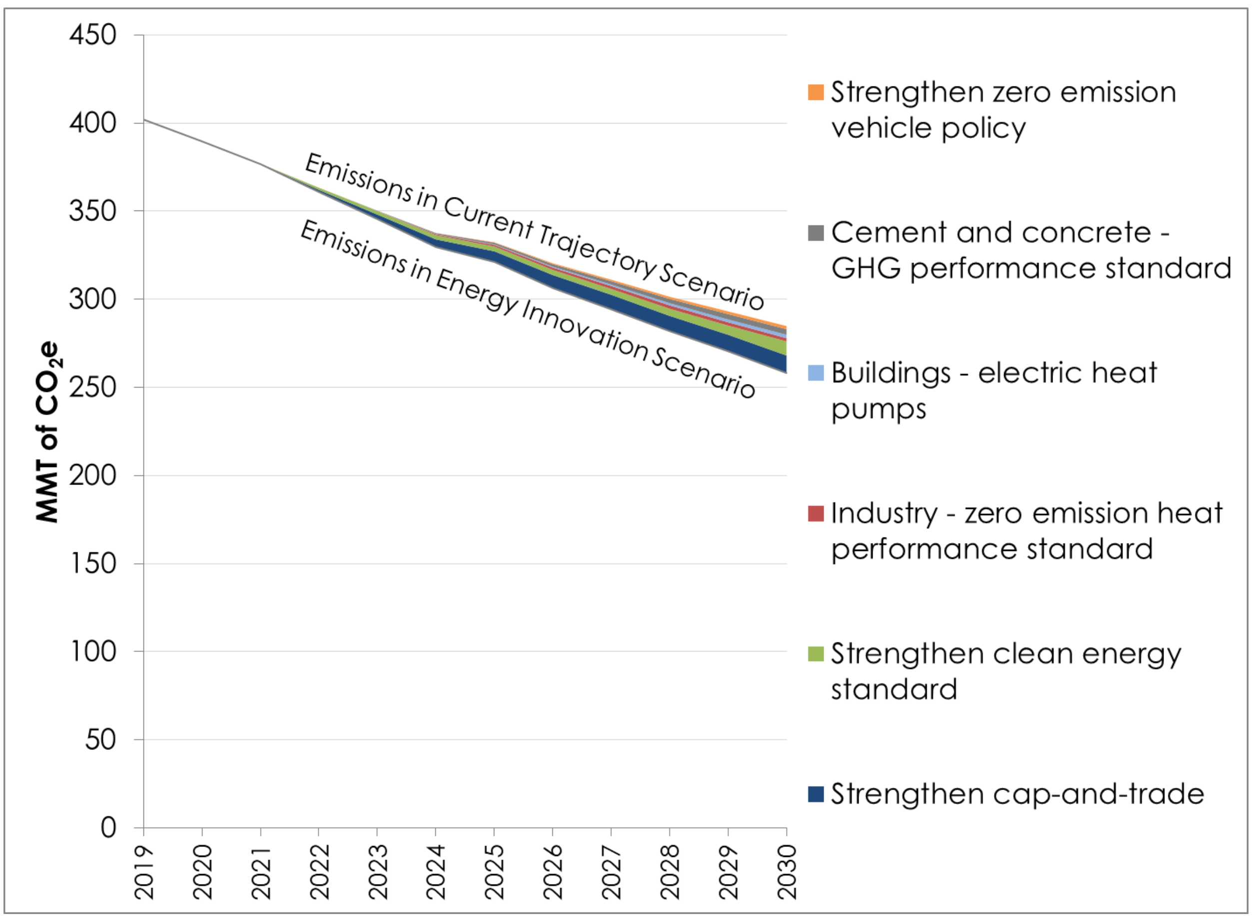
8. RESULTS

This section reviews estimated impacts from the recommended policies, starting with individual emission impacts and costs by policy, then turning to impacts for the package as a whole.

8.1. EMISSION REDUCTIONS BY POLICY

Emission reductions induced by the recommended policies are depicted in two ways. Figure 9 provides a broad view, showing emission reductions for each policy over time—called policy wedges—with the vertical axis showing the full emissions range over time.

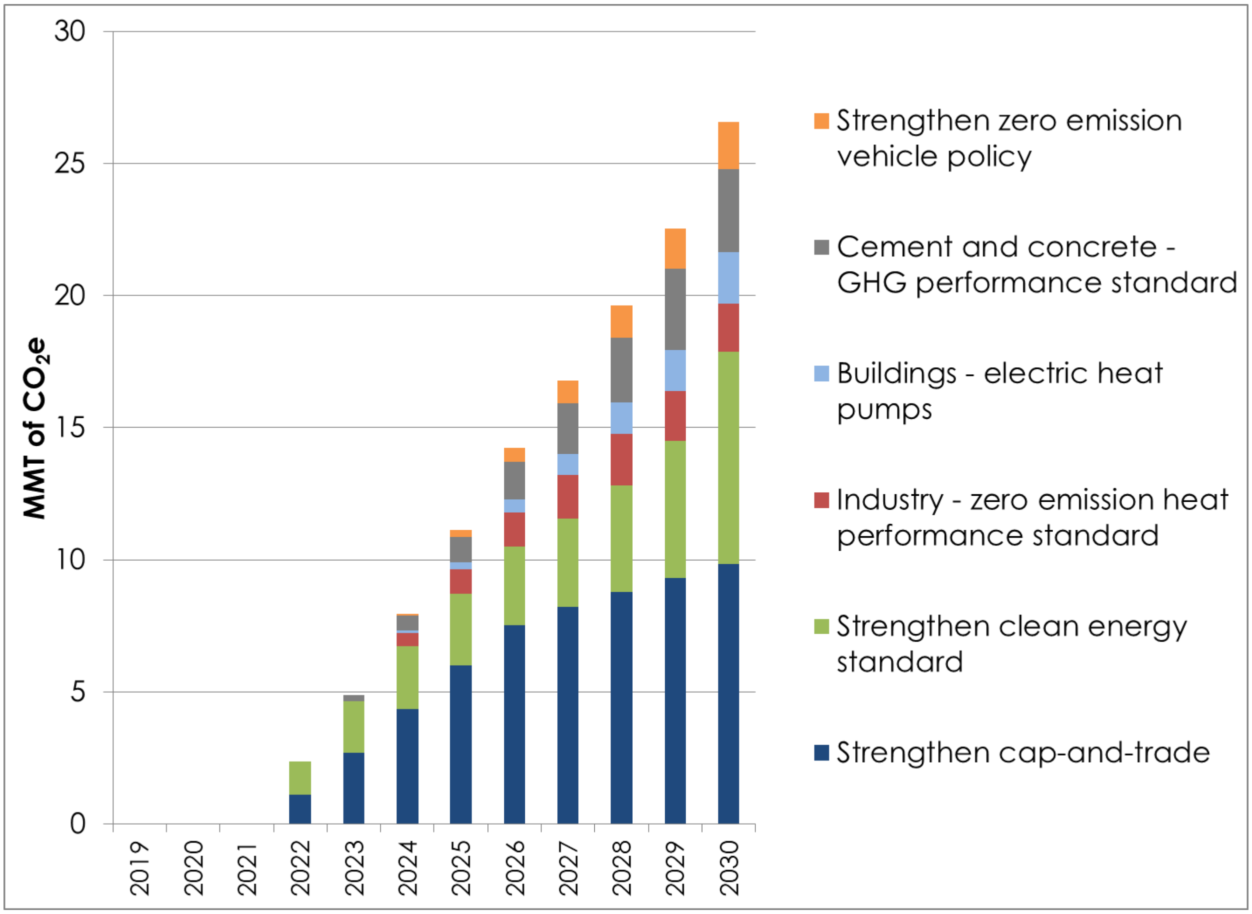
Figure 9. Policy wedges – effects on emissions by policy



Source: California EPS

The second perspective, shown in Figure 10, focuses on emission reductions in isolation from emission levels. Shrinking the axes makes it easier to see how individual policy effects change over time.

Figure 10. Policy wedges – close-up perspective on emission reductions



Source: California EPS

The increasing impact of the electricity sector policy in later years is much more readily observable in Figure 10. Increased building electrification and greater use of electricity as a transportation fuel over time magnify emission reductions attributable to the electricity sector policy. In 2030, strengthening of the clean energy standard produces an impact estimated at 80 percent of the impact due to carbon price strengthening. In comparison, in earlier years, strengthening the clean energy standard induces emission reductions that are less than half as large as those due to carbon price strengthening. [35] This result illustrates how system interactions can play an important role in determining policy effects.

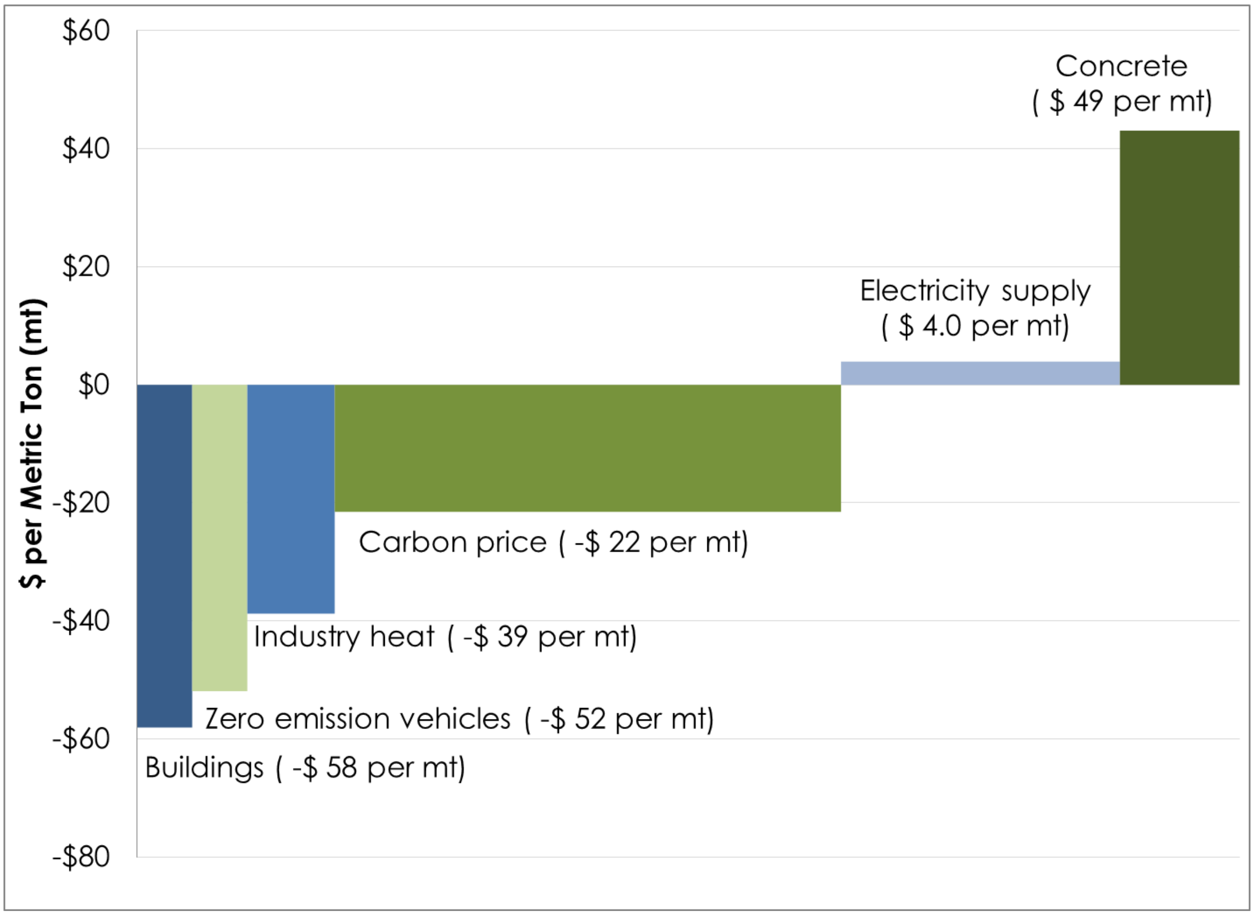
[35] Policy-by-policy results are determined by the magnitude of the effect when a single policy is disabled (and other policies in the package remain in force). In other words, these results show how much emissions increase when the policy is eliminated (or reduced to the level in the Current Trajectory Scenario) but all other Energy Innovation Scenario policies remain enabled. Readers may consult subsection 3.2.2., Consistent Treatment of Individual Policy in a Package, for additional explanation.

8.2. ECONOMIC AND SOCIAL IMPACTS BY POLICY

This section analyzes cost effectiveness on a policy-by-policy basis. We measure a policy's cost effectiveness as the net present value of monetized impacts divided by average emission reductions.

We define monetized impacts as expenditure effects for direct economic impacts, extended to include economic valuation estimates for climate and health effects for economic plus social impacts. Monetized impacts are calculated as the cumulative net present value through 2030 discounting at a 3 percent annual rate. Average emission reductions are estimated as the sum of emission reductions divided by nine years (reflecting the 2022-2030 period for which the Energy Innovation Scenario yields emission reductions). As is the case for calculating policy wedges, impacts are measured as the difference between the Energy Innovation Scenario and the Current Trajectory Scenario. The first graphic shows the policy benefit-cost curve for direct economic impacts.

Figure 11. Policy benefit-cost curve: economic impacts

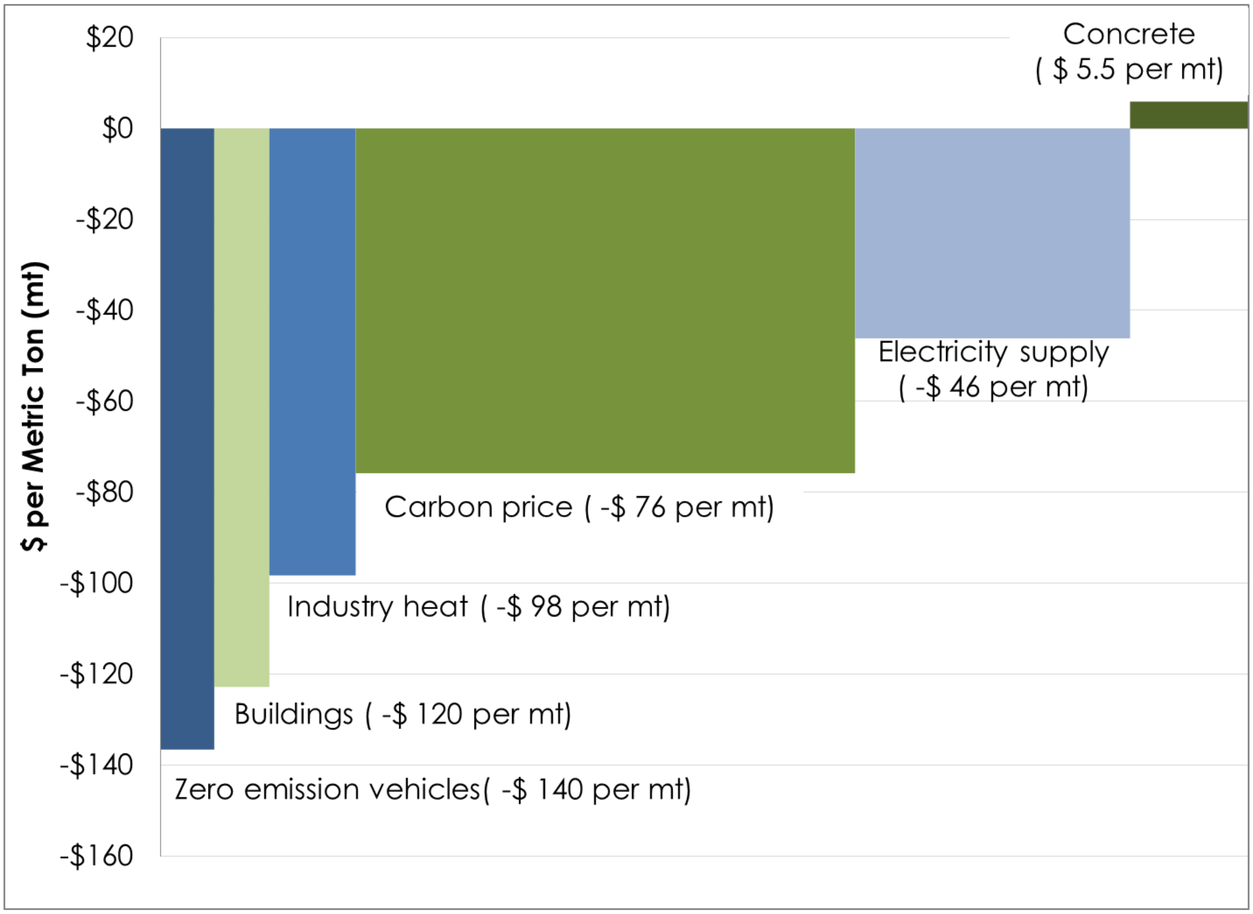


The width of each bar equals the annual average reductions induced by the policy from 2022 to 2030. The height of a bar indicates a policy's cost per ton, calculated as the net present value of economic effects to 2030, with values expressed in 2017 dollars. Values below the horizontal axis, i.e., negative numbers, indicate economic benefits.

Source: California EPS

The model finds negative cost effects, i.e., economic benefits, for four of the policies. When monetized social impacts are added to the direct economic effects, as in Figure 12, all recommended policies except for the cement standard yield net benefits.

Figure 12. Policy benefit-cost curve: economic + social impacts



This figure adds social impacts—monetized estimates of health benefits and avoided climate damage—to evaluation of the effects of individual policies.

Source: California EPS

Figure 12 also shows a slight reordering of relative advantage. When social impacts are accounted for, the zero emission vehicle policy swaps places with building electrification, emerging as the most beneficial of all policy enhancements. This result follows from the somewhat greater health benefits of reduced gasoline and diesel combustion compared to the avoided natural gas combustion from building electrification.[36]

[36] A caveat is that the present estimate of social impacts for building electrification does not account for avoided carbon monoxide poisonings. It seems clear building electrification will have some benefit in this regard, but we were unable to locate a sufficient research basis to estimate and integrate the effect.

Table 2 brings together the policy-by-policy results for the two measures of emission reductions and the two cost metrics, giving reductions induced in the year 2030 as well as the average annual reductions through 2030.

Table 2. Emissions, economic effects, and social effects by policy

		Reductions[37] (MMT of CO_2e per year)		**Cost**[38] ($ per metric ton)	
Sector	**Policy**	Average 2022-2030	In 2030	Economic	Economic + Social
Buildings	Electric heat pumps	0.7	2.0	-$59	-$120
Transport	Zero emission vehicle policy	0.7	1.8	-$52	-$140
Industry	Zero emission heat standard	1.1	1.8	-$39	-$98
Cross-sector	Carbon pricing	6.4	9.8	-$21	-$76
Electricity	Renewable standard	3.5	8.0	$3.9	-$46
Industry	Cement emission standard	1.5	3.1	$49	$5.8

Source: California EPS

8.2.1. Carbon Price

The results for the carbon price policy are net positive. The economic metric returns a value of -$21 per metric ton, and adding social impacts yields an estimate of -$76 per metric ton, indicating lower expenditures.

Economic benefits due to carbon pricing are caused by the incentive to avoid low-value energy use, which translates to reduced energy consumption. Lower energy consumption, in turn, requires less spending. Savings by households and in commercial buildings due to the carbon price are included in evaluation of both individual policy cost and aggregate costs for the package, but lower energy spending in industry is excluded. The industry sector is subject to competitiveness concerns, which make it a special case.

[37] To calculate average annual reductions, cumulative reductions through 2030 are divided by a factor of nine, the number of years in the 2022-2030 period over which policy impacts accrue. The start year of the model is 2017, but 2022 is the first year for which effects due to additional policies are expected.

[38] Costs per ton are calculated as the net present value of the monetized impact divided by the quantity of emission reductions (2022-2030). A 3 percent annual discount rate is applied. Costs are expressed in 2017 dollars.

Carbon pricing benefits stem in part from the assumption that carbon pricing revenue is returned to energy consumers, i.e., the revenue-neutral model. The model also provides an alternative perspective, in which carbon pricing revenue is effectively treated as a pure cost, with carbon pricing revenue excluded. In this revenue-exclusion mode, the policy forces extra spending due to fuel price effects, but the revenue does not add to government cash flow.

Note that the Canadian government also found net economic benefits when evaluating its carbon pricing plan. The Ministry of Finance concluded that the federal carbon pricing backstop option, to be implemented in provinces that develop their own approach to carbon pricing, will increase average household incomes by C$50-150 (Finance Canada 2018).[39]

Table 3. Emission reductions due to carbon price by sector[40]

Sector	Emission reductions in MMT per year	Percentage of total
Industry	5.1	80%
Electricity supply	0.2	2.7%
Transportation	0.5	7.7%
Buildings	0.6	9.5%

Source: California EPS

Table 3 shows that a large share—almost 80 percent—of overall carbon price effects occur in the industry sector. The industry sector effect is sourced from Borenstein et al. (2017), recently published in the prestigious *American Economic Review* (2019). Key carbon price elasticity assumptions for industry and other sectors are outlined in section 4.3., and sensitivity analysis in section 9.3. explains how alternative assumptions about industry sector price responsiveness affect results.

Meanwhile, in the building and transportation sectors, emission reductions due to carbon pricing are about an order of magnitude smaller than the industry effect. These sectors are generally recognized as less responsive to carbon price. The importance of consumer behavior in determining the economic choices that lead to energy and emission outcomes is one key reason. Consumers are understood to be less sensitive to price changes because they tend to devote less attention to cost minimization than a corporation or business. Even if households behave as rational utility maximizers, they are less likely to possess effective optimization skills.

Turning to electricity supply, electricity includes more cause-effect pathways for carbon price than any other sector. Carbon price affects fuel prices, particularly the cost to produce electricity

[39] The results from Finance Canada 2018 do not directly give the cited numbers, but they do provide the two elements needed for calculation: the average household cost impact and the average climate action incentive payment per household.

[40] Section 3.2.2. explains the procedure used to obtain consistency in emission reduction effects between package-level and individual policy effects. An analogous approach is used to calculate carbon price-related emission reductions by sector. Raw results found in a first step must be scaled to equal the total emission reductions for the policy as found under the Energy Innovation Scenario.

from generators running on coal and natural gas. In turn, changes in fuel prices affect the levelized cost of electricity from new investments. Because economic choices of both new investment and dispatch are represented in the EPS electricity sector structure, the model has the potential to show significant carbon price responsiveness.[41]

Yet results from the California model show the electricity sector to be the least responsive of any sector. A key factor lowering responsiveness in this sector is that California has been working toward a coal-free future. As a result, the system is already expected to rapidly shed remaining coal power in the BAU Scenario.[42]

Other factors are the fundamentals of the California electricity system and market, namely limited electricity demand growth and ample existing capacity (Penn and Menezes 2017). Most significantly, overall electricity demand has been relatively flat in the past, and grows only moderately in the BAU Scenario. Economic power plant retirement is also modest at the modeled carbon price levels. The upshot of these demand and supply side market fundamentals is that little new generation investment is required in the model. Furthermore, absent a policy driver such as the clean electricity standard used in the Energy Innovation Scenario, little new electricity generating capacity is required as a result of new investment.

New investment is not, however, the only pathway for carbon price to affect electricity supply-related emissions. Another pathway is lower carbon use by existing resources through the model's dispatch mechanism, which determines which existing electricity generators are called upon to meet demand.

A carbon price does meaningfully tip the economics away from coal-fired plants and in favor of natural gas. Yet this effect is of little import in California, which has largely transitioned away from coal already. A carbon price has little practical benefit for renewables and other zero emission generators through the dispatch pathways. The reason is that no fuel costs are associated with wind, solar, and hydro. These resources are approximately zero cost to operate from a marginal cost perspective. Even without a carbon price, zero emission generators are the lowest-cost type of generation to dispatch, so adding a carbon price has little effect.

8.2.2. Clean Electricity Standard

Results for ratcheting up the clean energy standard yield an estimated net positive cost of $3.9 per metric ton. Adding social impacts pushes costs into the negative category, estimated at -$46 per metric ton, meaning the model finds net benefits for the policy under the broader socioeconomic measure.

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[41] Dispatch refers to grid operators' decisions regarding which electricity generators to call upon from available capacity in order to satisfy current demand.

[42] In 2006, under Senate Bill 1368, California applied new minimum threshold performance requirements to in-state capacity and long-term contracts for power imports. These standards effectively prohibit building new coal plants or signing long-term power purchase agreements unless the generator is outfitted with carbon capture and sequestration. As a result, there is scant coal-based power capacity within the state. Imported coal has also been on the decline. Consistent with the 2017 Scoping Plan, the BAU Scenario anticipates that California's coal imports drop to zero in 2025.

These estimated effects include system integration measures, such as expenses for added battery storage and the capacity to shift peak energy demand to off-peak times. To represent the costs of parallel investments in flexibility resources, we build on the technical work done for the state's long-run planning process (California Public Utilities Commission 2019).

In the Current Trajectory Scenario, California EPS modeling adds two types of flexibility resources: battery storage and demand response (the ability to reduce peak demand, especially by shifting electricity loads to off-peak periods).

As a sensitivity analysis, we report results for a scenario that adds approximately 4 gigawatts of battery electric storage capacity. This sensitivity case assumes the same reliance on battery storage as does the state planning process modeling.

The amount of demand possible to cost-effectively shift to off-peak times is subject to debate. Extensive technical work suggests that a very large potential exists. A study by Lawrence Berkeley National Laboratory, E3, and Nextant finds that 10-20 gigawatt hours per day—an amount almost equal to the increment added by peak demand—is available at around $100 per kilowatt hour (Alston et al. 2017). At the capacity level required to buttress the more intensive clean energy standard, the cost is less than $50 per kilowatt hour. The nonprofit Gridworks find reasons for optimism, pointing to potential for "more aggressive [time-of-use pricing], predictable dynamic prices, and other means combined with enabling technology" (Gerke et al. 2018, p. 13).

While the technological and economic potential is evident, the policies and institutions needed to capture it are still under development. Murtishaw (2019) details a range of barriers to more effectively integrating demand response. In light of the challenges—energy agency officials' responsibility for power reliability, the central role of electricity in modern life, and the recent public safety power shutoffs in California—it is easy to understand why authorities might not want to be cautious in evaluation the topic of resource adequacy, preferring to minimize dependence on solutions involving meaningful uncertainty.

Seasonal storage has been a topic of debate, principally concerning decarbonization at a level even deeper than the 83 percent zero emission supply under the recommended policy. We also note recent work by E3 (Ming et al. 2019) demonstrating the potential to use existing natural gas capacity to ensure resource adequacy, at least as a temporary contingency measure, until zero emission technology can cover the infrequent, periodic capacity shortfalls that could arise if seasonal storage needs go unconsidered.

Most input parameters were taken from the E3 Pathways modeling done for the 2017 Scoping Plan analysis (CARB 2017b). The key cost variables of solar photovoltaic and battery storage derive from updated values in the Resolve model, one of two official tools used in the state's long-run planning (E3 2019).

A final note is that results would be more favorable under a longer time horizon, such as to 2040 or 2050. Because renewable energy production entails no fuel costs, almost all incurred costs are upfront capital investments. Such projects invariably include a debt financing component, which is why levelized cost of electricity is a common cost metric used to compare power generation technologies.

8.2.3. Zero Emission Heat Standard

Modeling the industry sector standard returns an economic benefit of -\$39 per metric ton for the narrower economic measure, and -\$98 per metric ton when social impacts are added. A California-specific analysis by ICF International (2015) provides key technical potential and economic cost inputs. We add a rough estimate of new government implementation costs, approximated at \$40 million annually.

On the industry revenue side, the price solar thermal steam is expected to yield for producers is assumed equal to the cost of steam generation from natural gas combustion, only accounting for natural gas fuel costs, not capital or operations and maintenance. A customized natural gas price is estimated in recognition of the low prices paid by steam-enhanced oil recovery projects. The U.S. Energy Information Administration's modeled industry sector price, which is nearly twice the price for electricity sector consumers, is far too high to use for such projects. By our estimate, the average price for natural gas for steam-enhanced oil recovery is 11 percent above the electricity sector price.

Projects of this type are highly capital intensive, involving loans and long payback periods. Accordingly, we calculate costs on a levelized cost-of-steam basis. Our accounting model follows the method shown in Lazard (2018), which breaks down the elements involved in financing an "illustrative" power plant. Lazard's illustrative model involves a 60/40 split of debt to equity (meaning loans taken versus the portion of the investment paid in cash), and each part of the split requires a rate of return. In Lazard's model, loans are paid back at an 8 percent rate of interest, and equity investors receive a 12 percent rate of return. Higher margins were assumed when calculating rates for a solar thermal steam project because lenders and investors would very likely perceive higher than normal risks. Though producing solar thermal steam is a well-established technology, it has not yet been widely deployed in California or globally. Therefore, our analysis assumes loans at a 10 percent interest rate and an internal rate of return of 15 percent for investors. A twelve-year time horizon for financing is used to calculate levelized cost, shorter than the twenty-year duration of project finance in the Lazard analysis, which was deemed more appropriate in light of the state's decarbonization ambitions and the uncertainty those ambitions introduce regarding the long-run survival of oil extraction in California.

The proposed approach of a performance standard steadily ratcheting up over time would spawn the type of long-run power purchase agreements that supported the emergence of solar and wind power as major sources. With multi-year zero emission steam purchase agreements in hand, it would be much easier to arrange financing, a crucial factor in light of high upfront capital investment costs.

This technological solution is already incentivized by two existing policies, but the price signals from the state's cap-and-trade program and the low carbon fuel standard appear to be failing to unlock this option's potential. The incentives these policies offer are insufficient or too uncertain to help secure the low-cost financing essential to these projects, which require large upfront investments. The lack of a floor on the price of compliance credits under the low carbon fuel standard program increases uncertainty about their value.

Our view that under-investment in solar thermal steam is likely under the current policy framework. Interviews with those working in the industry indicated there is only one solar thermal steam project under development, the Belridge project in Kern County. A review of applications seeking to generate low carbon fuel standard credits confirms that just one application is pending under the relevant "innovative crude oil" project type and no projects have yet been approved.[43]

8.2.4. Building Electrification

The building electrification policy is calibrated to target the most cost-effective abatement opportunity in residential buildings: faster adoption of electric heat pumps for space heating and water heating. The policy yields estimated net economic benefits of -$59 per metric ton, growing to -$120 per metric ton with social impacts added.

Equipment costs vary based on whether the installation is in a new or existing home, whether it is in a single- or multi-family building, and whether space heating overlaps with replacement of space cooling needs. Electric heat pumps cost less when both space heating and space cooling services are desired, and they cost more for heat alone (Synapse 2018). The efficiency advantage of advanced heat pumps helps counterbalance the higher cost of electricity as a heat source.

The cost of building electrification accounts for a range of impacts beyond narrow equipment and fuel costs. On the cost side, the modeling incorporates the expense of electric panel upgrades at $5,000. On the benefit side, savings on new natural gas infrastructure in new homes are included, as are savings from time-of-use policies providing stronger incentives than those currently in force.

Historically, the cost of electricity generation at different times has not affected electricity prices. Time-of-use pricing programs have been instituted, but not at the level needed to fully capture the benefits of shifting demand for water and space heating to off-peak times, when slack capacity in the electricity system can provide the required energy at low cost: "The default [time-of-use electricity] rate has too small a price differential (at most, peak pricing is 19 percent greater than off-peak pricing) to encourage significant load shifting or to capture significant

[43] The CARB website for the low carbon fuel standard program lists projects approved and applications pending. Information we cite was gathered in January 2020. Two projects have been approved, but they create emissions by substituting electricity from new solar photovoltaic electricity generation. CARB's analysis has not sought to predict a likely future compliance path. We do observe that the "illustrative compliance scenario calculator" for the low carbon fuel standard regulation released by CARB (2018e) presents a range of possibilities, but most fall far short of the nearly 2 MMT in annual CO_2 reductions reached in the Energy Innovation Scenario. At the high end of the range for annual emission reductions modeled with the illustrative compliance scenario calculator, the innovative crude project type induces annual reductions of 2 MMT. This compares to 0.35 MMT at the low end of the range. The average of the annual emission reductions induced by the innovative crude project type in 2030, the year when emission reductions peak, is 1.05 MMT across the 10 "illustrative" scenarios (CARB 2018e).

savings and it may not recoup the added cost of equipping the devices with extra control capability to operate flexibly" (Billimoria et al. 2018, p. 18). Professor Severin Borenstein has observed that substituting electricity for natural gas to provide the energy needed for water heating could be a low-cost option—if the state's prices for electricity were set "at a rate that reflects its true cost," adding that space heating is also approaching cost effectiveness (Morris 2019).

8.2.5. Zero Emission Vehicle Policy

The zero emission vehicle policy will generate an estimated economic impact benefit of -$52 per metric ton. Adding social impacts increases the benefit to -$140 per metric ton.

The large efficiency advantage of electric vehicles compared to internal combustion engines vehicles primarily explains these economic benefits. Lower fuel expenditures are enough to overcome the initially higher cost of electric vehicles as well as vehicle charging infrastructure. In the California EPS, fully electric light-duty passenger vehicles are about $15,000 more expensive than conventional gasoline vehicles in the start year of the model, 2017, falling below the price of a new gasoline-powered car in 2029 as the result of expected innovation. Electric vehicle infrastructure charging costs add a total of $1.4 billion[44] in spending to the economic accounting.[45]

Vehicle cost parameters are developed mainly based on research from the International Council on Clean Transportation (Lutsey 2019), which provides detailed production cost information for both electric and gasoline-fueled vehicles.

Regarding purchase price, Lutsey (2017) finds that a 150-mile range electric car's purchase price falls below that of a gasoline-fueled car in 2024, and by 2028 all electric vehicles cost less upfront than their conventionally fueled counterparts.

We note that Lutsey (2019) does not cover pickup trucks, but we estimate these cost values for better accuracy regarding weighted average costs associated with battery electric light-duty passenger vehicles.[46] Vehicle electrification has been most economic for small vehicles so far, but to reach the high levels of electrification recommended, meaningful numbers of pickup

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[44] This value is calculated using this report's standard convention, the net present value through 2030 discounting at 3 percent annually and using constant 2017 dollars.

[45] The structure of model version 2.0 includes a policy option to build more charging infrastructure to encourage electric vehicle adoption and directly accounts for this infrastructure cost. Results in this report add infrastructure costs in an ex-post adjustment to model results.

[46] To calculate powertrain and battery specifications for electric pickup trucks we scale up the powertrain and battery specification for large SUVs. The multiplier used for scaling up is calculated as the ratio of engine size for pickups over large SUVs using data from the 2019 Transportation Energy Data Book. Table 4.16 provides the 2018 engine size data for pickups and large SUVs ("t. Calculations produce a multiplier of 1.45, and a battery with a capacity of 186 kilowatt hours for a 250-mile range pickup. We also account for the expectation of higher automaker profitability in the pickup market segment. The analysis sets a 25 percent profit margin for pickups (this compares to 15 percent for large SUVs and 5 percent for cars in Lutsey (2019).

trucks will have to be part of the mix. Several new electric pickup trucks have entered mass production or will soon.

Battery costs are the largest driver of the difference in purchase price between electric vehicles and conventional-fuel vehicles. Battery prices have been falling, however: “When the first mass-market [electric vehicles] were introduced in 2010, their battery packs cost an estimated $1,000 per kilowatt-hour. Today, Tesla’s Model 3 battery pack costs $190 per kilowatt-hour, and General Motors’ 2017 Chevrolet Bolt battery pack is estimated to cost about $205 per kilowatt-hour” (Reichmuth and Goldman 2017). Beyond batteries, UBS (2017) identifies significant potential for cost reductions in other aspects of the powertrain, which transfers power from the battery to the kinetic energy needed to turn the wheels.

We estimate infrastructure needs using research by the California Energy Commission with support from the National Renewable Energy Laboratory. The work, by Bedir et al. (2018), evaluated the infrastructure needed to support 1.5 million electric vehicles by 2025, suggesting 254,000 chargers should be built and recommending types: curbside, workplace, multifamily, parking lot, and direct-current superfast chargers. We apply cost estimates for the different types of chargers (Rocky Mountain Institute 2014) and then sum for an aggregate cost. We divide this total cost by the 1.5 million vehicles supported, yielding an estimated public infrastructure cost of $1,480 per vehicle.

This approach implicitly assumes that the same number of chargers will be required regardless of the point in market transformation. This may bias the cost estimate upwards, as it is possible that fewer chargers per vehicle will be needed as electric vehicle deployment moves beyond the early stages to the middle stages.

Incentive levels start at $10,000 in 2017 for a full battery electric vehicle, representing the sum of California and federal incentives. The BAU incentive level anticipated lower federal incentives due to current rules stepping down support as automakers reach sales of 200,000 vehicles. Tesla and General Motors have already crossed this threshold. Looking forward, BAU incentives follow a linear trajectory to zero in 2026. No federal incentives exist for freight trucks, so these BAU incentives exclusively reflect support from the state. Freight electrification incentives in future years are set to decline from current levels to zero in 2030.

The Energy Innovation Scenario does not increase consumer incentives for electric vehicle purchases. Because of BAU incentives, however, the stronger zero emission vehicle policy in the Energy Innovation Scenario induces more sales, which leads to more incentive payments. BAU incentive levels applied to sales in the Energy Innovation Scenario generate an additional $1.3 billion in net present value. The effects of this dynamic are evident in results disaggregated by government or consumer cash flows. For metrics on both individual policy and package impacts, however, the spending is treated as a transfer and hence is cost neutral.

8.2.6. Performance Standard for Cement and Concrete

The cement and concrete policy returns an economic cost of $49 per metric ton, or $5.8 per metric ton when social impacts are added. Costs for the policy are based on the use of carbon capture and sequestration technology, which removes CO_2 from pollutant outflows. Once captured, CO_2 may be used as an input to production. These applications are currently limited, so the expectation is that most captured CO_2 will be transported to natural underground reservoirs for storage.

Carbon capture and sequestration delivers more than 90 percent of the emission reductions in cement and concrete in modeling compliance with the GHG standard. The remaining portion comes from a straightforward material input technique, the timely injection of a small quantity of CO_2 gas, which reduces the need for other inputs by 5 percent. The reduction in required inputs translates directly to lower "process emissions," i.e., lower emissions due to clinker production, the main cement input (Rissman 2018).

Leeson et al. (2017) is the primary source for carbon capture and sequestration input data. The modeling incorporates new federal tax credits for carbon sequestration, based on the projects completed in time to be eligible and the capacity additions in the Energy Innovation Scenario. Although the cost to install and run carbon capture machinery is the main factor, cost estimates also include transportation and storage infrastructure, the additional electricity demand required for carbon capture and sequestration, and program administration costs to implement a new government policy.

Though the cement standard comes in as the most costly in the package, we note three reasons why future costs could be lower and could even represent an economic opportunity. First, the sector is rife with innovation, mostly not currently modeled. Rissman (2018) identifies many emerging technologies for lowering emissions in the sector, some already commercialized and others emerging from research laboratories.

Second, the selected value for the transport and storage costs draws on the upper end of the cost range provided by Rubin et al. (2015). These higher costs are associated with the lower end of the capacity range considered in that research—3 MMT of CO_2e transported and stored per year—because this range most closely matches the amount of carbon annually captured and stored under the concrete and cement standard in the Energy Innovation Scenario.

Third, given the industry's global significance, domestic innovation could pay off in the future through increased exports—perhaps not finished cement itself but rather the underlying technology and expertise. We observe that climate policy has already played a role in supporting the emergence of a clean tech product among California's top exports: In 2017, electric vehicles broke into the ranks of the state's top ten exports by monetary value (Census Bureau 2019).

As a closing note, our modeling considered fuel switching from coal to natural gas but found it to be less economically beneficial. We have no reason to believe cement plants have access to the much lower-priced natural gas that steam-enhanced oil recovery projects do. Gaining such access, however, could be enough to tip the balance of cost effectiveness within the cement and concrete subsector. It is also worth highlighting an ancillary benefit from fuel switching to natural gas in cement and concrete production. From a system perspective, it would be helpful to contribute a stabilizing force to the natural gas system. New sources of natural gas would help make up for lower demand elsewhere as electrification captures larger and larger shares of energy in buildings and electric power supply.

8.3. PACKAGE BENEFITS – ECONOMIC AND SOCIAL IMPACTS

This section presents impact analysis for the package of Energy Innovation Scenario policy enhancements. Below, a series of graphs break down the components of economic and social impacts to uncover the key drivers.

Beginning with the economic breakdown, the model differentiates private-sector economic impacts for three categories of spending: capital, fuel, and operations and maintenance. Capital costs reflect changes in equipment purchases for businesses and vehicles, buildings, and household appliance-related spending. The economic graphs develop two perspectives on crucial fuel spending effects, one combining and one separating fuel spending and carbon price revenue rebates. Carbon pricing revenue is a significant economic factor. Presentation of both approaches—in the one case separating and in the other combining fuel expenditures and carbon price revenue effects—illuminates this important dynamic.

Figure 13 presents two different perspectives on direct economic effects to reveal interactions between fuel spending and carbon pricing, with the top panel separating fuel spending from carbon price-related effects and the lower panel combining them.

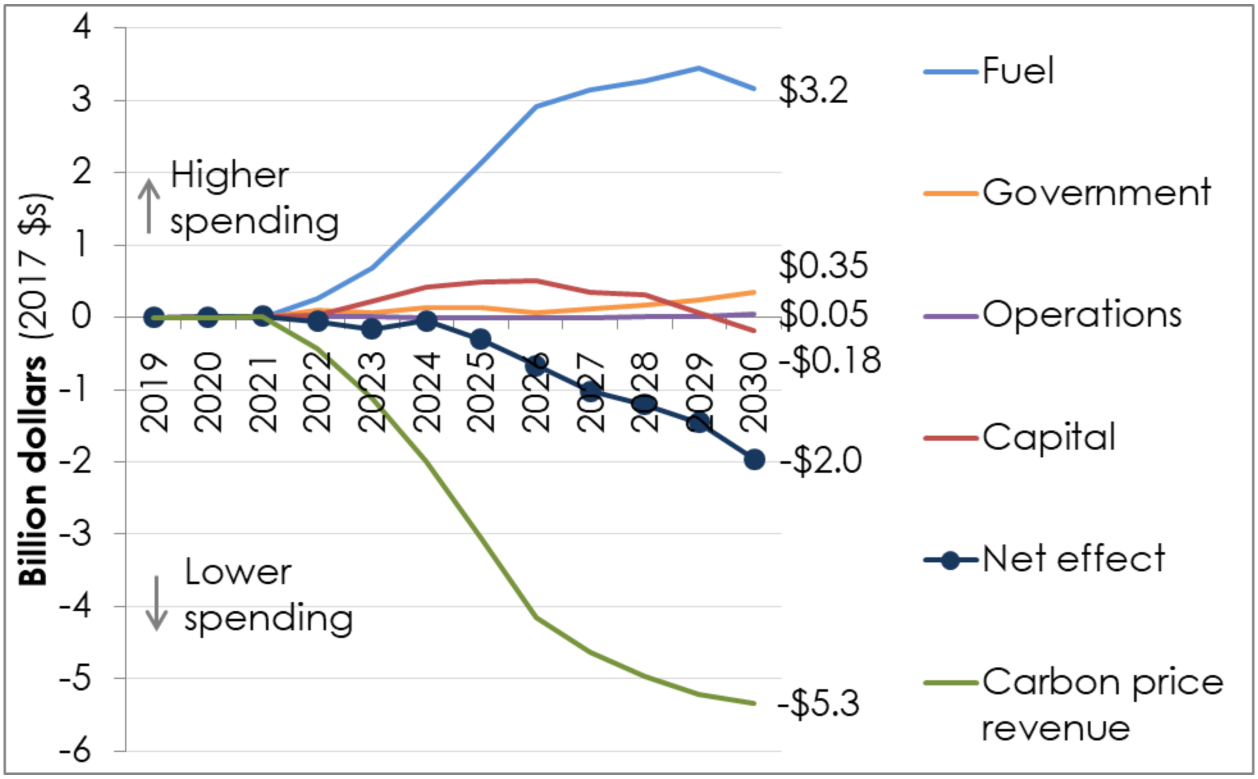
The top panel in Figure 13 separates carbon revenue and fuel spending effects, treating revenue raised through carbon pricing as part of fuel cost, splitting off and separately tracking carbon price revenue raised as a result. This perspective highlights the importance of carbon price revenue within the set of components feeding into direct economic effects. The lower panel in Figure 13 shows how carbon pricing revenue has the potential to completely nullify the policy's budgetary effects on fuel users.

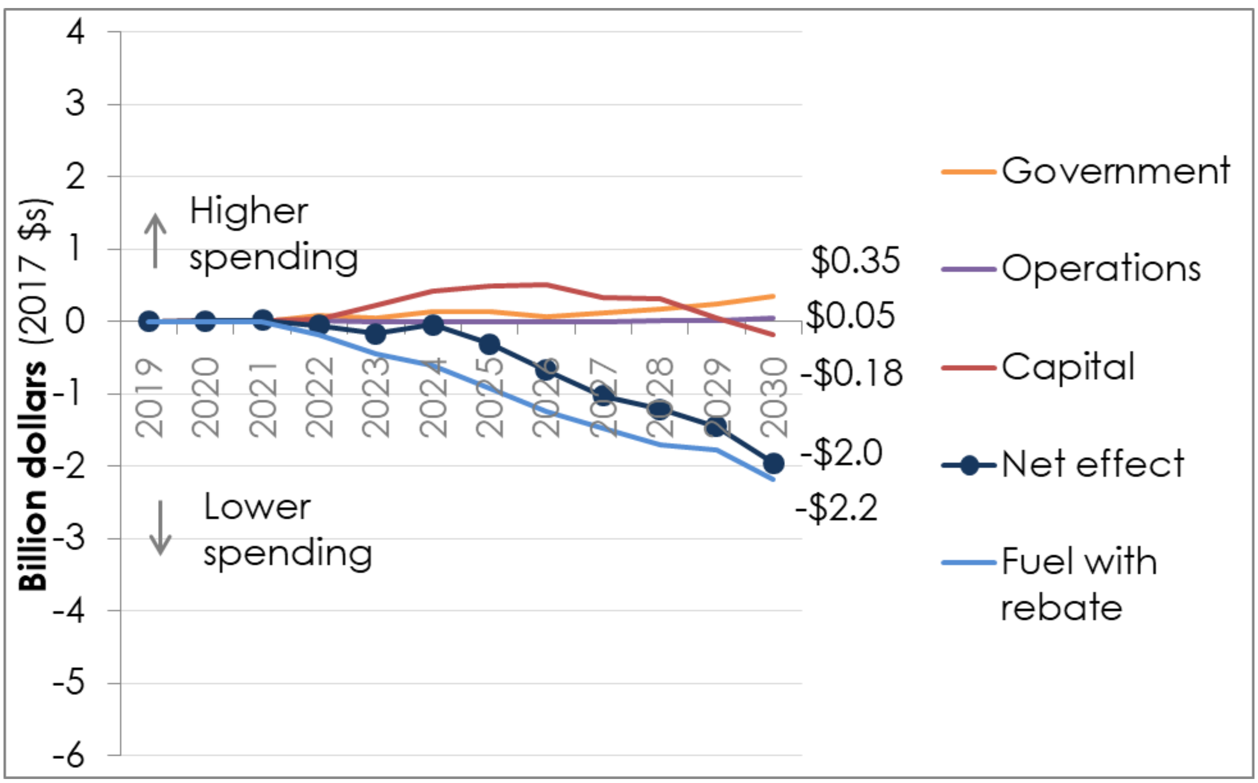
After carbon price revenue, fuel expenditure changes are the largest driver of net economic effects. Savings accrue from substituting solar thermal steam for natural gas, as steam requires no inputs. Electric vehicles also have lower operational costs due to their efficiency edge, even though electricity costs more on a per-unit energy basis. Carbon pricing likewise contributes, as closing the GHG pollution loophole increases the incentive for conservation and energy efficiency.

In buildings, switching to electricity puts upward pressure on fuel costs, even after factoring in the efficiency of advanced heat pumps. But in some cases the switch can offer equipment savings over costs associated with conventional units, such when both heating and cooling services are demanded.[47]

[47] As contrasted to a unit that offers heating only, not both heating and cooling.

Figure 13. Breakdown of economic impacts by year





The top panel separates carbon price revenue from other fuel expenditure changes, while the bottom panel combines the two variables. Results given in present value, 2017 dollars, using a 3 percent annual discount rate.

Source: California EPS

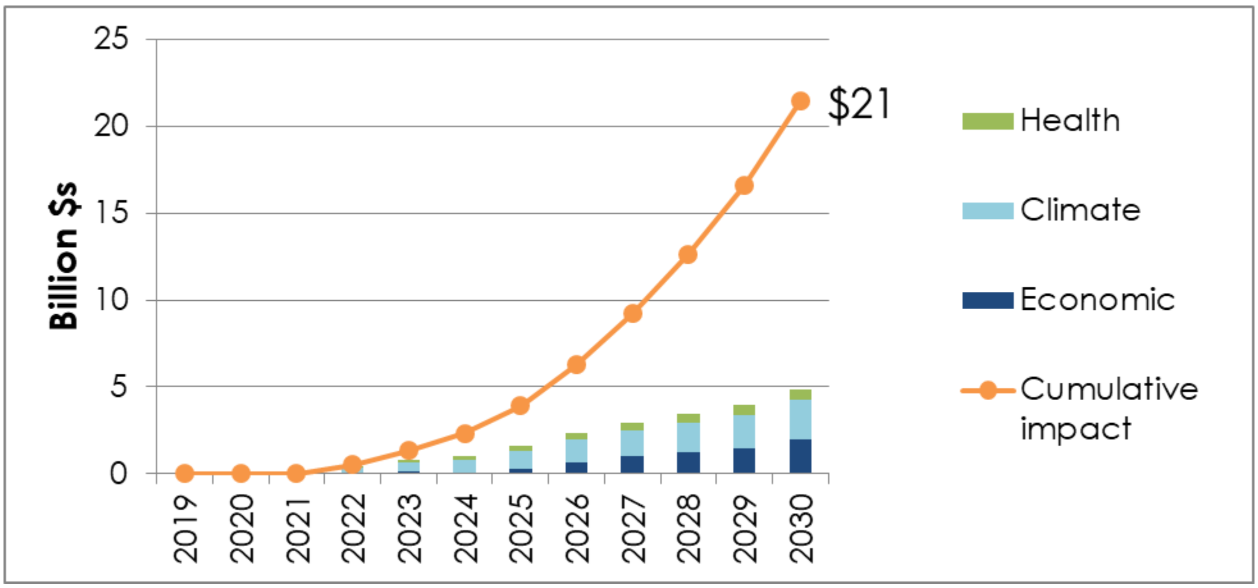
Fuel savings underpinning results in Figure 13 are a function of greater conservation and more efficient capital, i.e., more energy-efficient consumer goods and business equipment. Fuel expenditure savings grow over time as capital stock turnover occurs, creating cost-effective opportunities for new investments in zero- or lower-emitting equipment.

Policies promoting electric vehicle use offer a concrete example of how more energy-efficient capital saves money. Because electric vehicles are about three times more efficient than internal combustion engines, electric vehicles cost about three times less to operate. The model accounts for what are referred to as rebound effects—the increase in driving that follows from the adoption of efficient vehicles that cost less to drive.

Conservation effects are largely attributable to enhancing the broad carbon price signal, which increases the incentive to avoid wasteful or low-value uses. These effects tend to be small; for example, a 10 percent change in transportation fuel price leads to just a 1 percent change in household demand. But effects add up over the large volumes covered.

Turning to a broader perspective, we also consider social impacts and the cumulative effects of annual impacts through 2030. The model approximates the monetary value of avoided climate change damage and improvements to public health due to cleaner air. Health and climate benefits, referred to as social impacts, are estimated at $14 billion cumulatively through 2030. [48]

Figure 14. Annual economic and social (climate and health) impacts and their cumulative effect



Annual impacts are represented with stacked bars. Together, the net present value of the combined economic and social effects is estimated to reach $21 billion in 2030.

Source: California EPS

[48] As is the convention herein, all monetary values are expressed as net present value in 2017 dollars calculated using a 3 percent discount rate.

Figure 14, above, shows annual economic, health, and climate impacts. For simplicity, only the cumulative sum of economic and social impacts is graphed, reaching an estimated net present value of $21 billion in 2030.

9. SENSITIVITY ANALYSIS

We conducted sensitivity analysis by investigating model results under different possible input assumptions. The emphasis is on uncertainties surrounding policy effectiveness and cost. Other important uncertainties exist as well, such as macroeconomic fluctuations, highlighted in the 2017 Scoping Plan analysis and in work by Borenstein et al. (2019).

The first subsection tests varied assumptions regarding "current policy," analyzing the effects of higher carbon prices or more effective sustainable community strategies. The second subsection investigates changes in the cost of building sector and electricity supply policies if cost-effective opportunities are not captured to shift energy use away from costly periods of peak demand. A third subsection tests the effect of different levels of carbon price responsiveness in the industry sector. The last subsection evaluates the cost implications of different assumptions about the rates of innovation for emerging technologies.

9.1. CURRENT POLICY EFFECTIVENESS

The Current Trajectory Analysis represents the future emissions scenario considered to be the most likely outcome if current policies remain in force. The analysis also explores a range of possible deviations from that outcome by varying several key assumptions affecting the expected effectiveness of current policies. This section tests the implications of even more optimistic assumptions for carbon pricing and the effect of sustainable cities strategies, which have already been discussed at some length. This section also tests a policy related to off-road freight efficiency, i.e., efficiency of freight transportation by train, plane, or ship.

Increasingly, reliance on high-frequency delivery of goods, whether for business or household use, is putting upward pressure on freight transportation emissions. This trend, which is difficult to counteract through policy, suggests existing projections may underestimate travel demand attributable to freight transportation. Freight efficiency policy was excluded from the Energy Innovation Scenario for these reasons, but this section considers this policy in evaluating what might be considered maximum feasible bounds.

The specific policy variations tested are listed in Table 4. The third column, labeled "2030 calibration," details the maximum strength reached by each variation in the sensitivity. The fourth column lists the strength of the policy in the lower bound—the edge of the current range.

Table 4. Additional sensitivity analysis with respect to current policy efficacy

Policy	Label	2030 calibration	Policy calibration in lower bound[49]
Carbon price	High price	$101 per metric ton	$63 per metric ton
Sustainable cities strategies	Stronger city	18 percent reduction in passenger vehicle miles traveled per person, the goal in the 2017 Scoping Plan analysis[50]	9% reduction in passenger vehicle miles traveled per person
Freight efficiency	Freight	25 percent improvement in efficiency of off-road freight transportation[51]	Not applicable

Figure 15 graphs emission pathway results, with labels identifying the combinations of the additional sensitivities added to the policies in the Lower Bound Scenario, at the lower edge of the range previously defined around the Current Trajectory Scenario. Below the lower bound, Figure 15 shows emissions resulting from the additional sensitivities developed in this section. Reaching 259.2 MMT of CO_2e, the scenario labeled "High price + stronger city" falls 0.6 MMT of CO_2e short of the 2030 goal. It is only when all three of these additional sensitivity cases are considered together that additional reductions are sufficient to bring emissions approximately in line with the 2030 target.[52]

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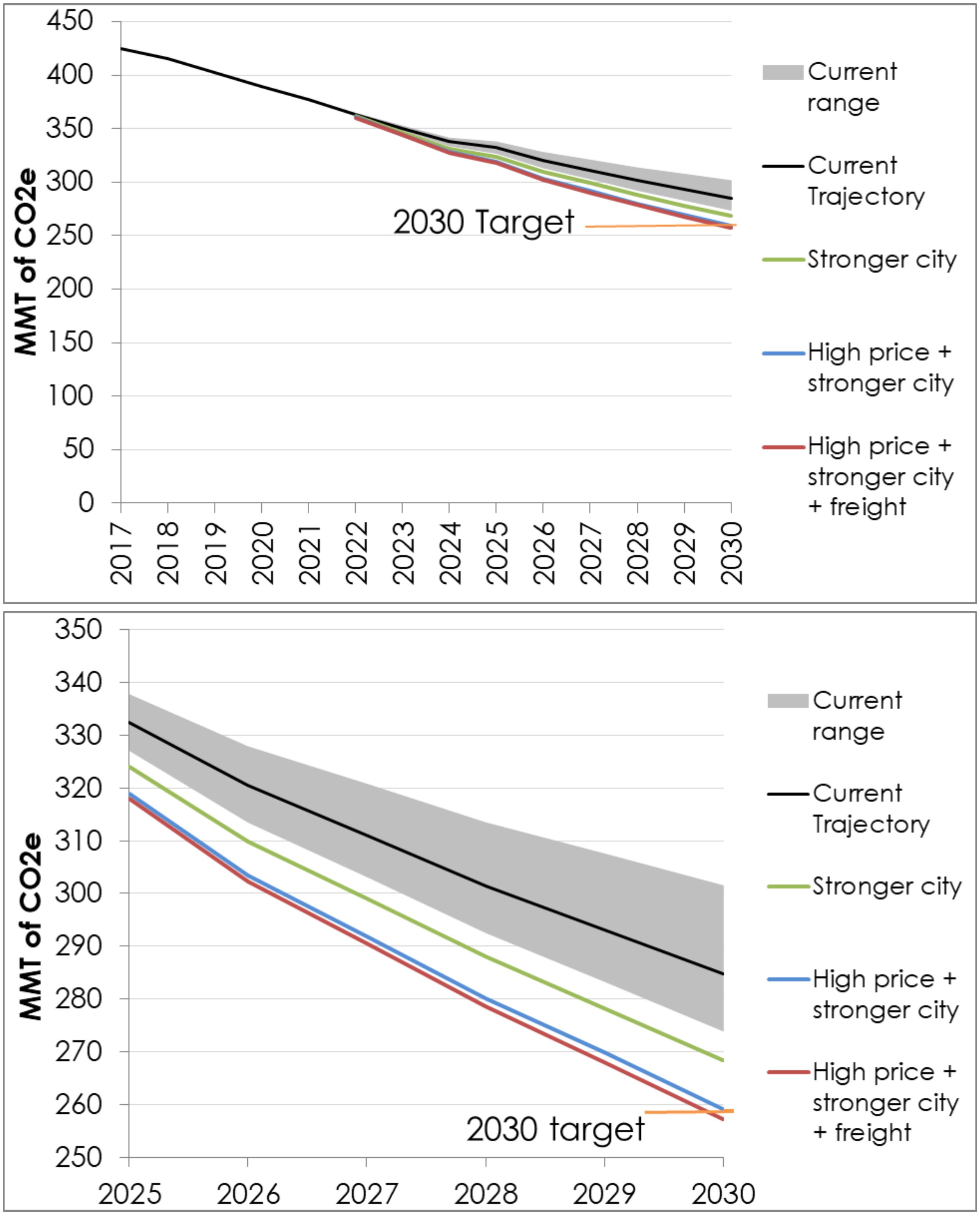
[49] This is the maximum strength of policy setting previously considered in the Current Trajectory Analysis. The increase portrayed in the additional sensitivities defined in this section, as specified in the third column, is measured relative to this lower-bound policy calibration.

[50] The 18 percent reduction is calculated based on the 2017 Scoping Plan's target of reducing per capita vehicle miles traveled in 2035 to 25 percent below 2005 levels. We note that the 2018 update to state targets under Senate Bill 375 scaled back the ambition: "Stronger SB 375 GHG emissions reduction targets will enable the State to make significant progress toward the Scoping Plan Update goals, but alone will not provide all of the reductions needed. While currently adopted SB 375 plans achieve, in aggregate, nearly an 18 percent reduction in statewide per capita GHG emissions relative to 2005 by 2035, the full reduction needed to meet our climate goals is on the order of a 25 percent reduction in statewide per capita GHG emissions by 2035" (CARB 2018f, p. 15).

[51] The 2030 strategy outlined in the Scoping Plan (CARB 2017a) set a 2030 goal of improving by 25 percent carbon emissions per freight-ton mile traveled. Evaluation of expected improvements in freight-truck efficiency shows that rising vehicle fuel economy on its own approximates the 25 percent level of improvement for on-road trucks. So, the efficiency improvement in this scenario is only applied to off-road freight vehicles.

[52] The precise result in the California EPS for the scenario combining all three of the policy sensitivities is 258.9 MMT of CO_2e in 2030, which is slightly above the target of 258.4 MMT of CO_2e. Such a difference is not substantial, however, in the context of a modeling exercise involving projections more than a decade into the future.

Figure 15. Additional policy effectiveness sensitivity results



To magnify results, the lower panel in the graphic zooms in on the years 2025-2030 and limits the range of emissions covered to between 250 and 350 MMT. Labels used in this figure are defined in Table 4.

Source: California EPS

9.2. ABILITY TO SHIFT PEAK ELECTRICITY SYSTEM DEMAND

This section investigates the implications of suboptimal policy—design, implementation, or both—that lead to missing the opportunities for cost-effective peak demand shifting portrayed in the main case.

In the electricity sector, the main results for the clean energy standard rely on a mix of battery storage and demand-shift services to provide flexibility services at lower cost. In the sensitivity case, it is assumed only battery storage is available to support power reliability at higher levels of decarbonization, resulting in 4 gigawatts of battery storage being added, compared to 2.5 gigawatts of battery storage and 2.5 gigawatts of demand-shift capacity to support the higher clean energy standard in the Current Trajectory Scenario.

The building electrification policy also anticipates benefits from shifting demand away from peak periods, reducing overall system costs. Billimoria et al. (2018) estimate additional potential demand shift savings in California, on a discounted, lifetime basis, at $1,000 per water heater and $2,000 per space heater. Despite the favorable economics, obstacles could block successful implementation of the policies needed to capture these benefits. The following sensitivity case eliminates these demand-shift benefits from the policy benefit-cost results for building electrification.

Table 5. Electricity and building sector policy cost sensitivity – inability to shift peak demand

	Economic impact	Economic + social impact
Clean energy standard		
With demand shift	$3.9 per metric ton	-$46 per metric ton
Without demand shift	$40 per metric ton	-$10 per metric ton
Building electrification		
With demand shift	-$58 per metric ton	-$120 per metric ton
Without demand shift	$52 per metric ton	-$13 per metric ton

As elsewhere, costs per ton are calculated as the net present value of the monetized impacts divided by the quantity of emission reductions (2022-2030), applying a 3 percent annual discount rate. Costs are expressed in 2017 dollars.

Source: California EPS

9.3. INDUSTRY SECTOR PRICE ELASTICITY

The next sensitivity analysis explores varying assumptions for the price elasticity of demand for natural gas in industry. In the Current Trajectory Scenario, this elasticity value is set to -0.5, a value aligning with a 2030 study of California carbon price expectations conducted by Borenstein et al. (2017). This represents a mid-term value for elasticity, in between the short- and long-runs, reflecting the 2030 timeframe under study.

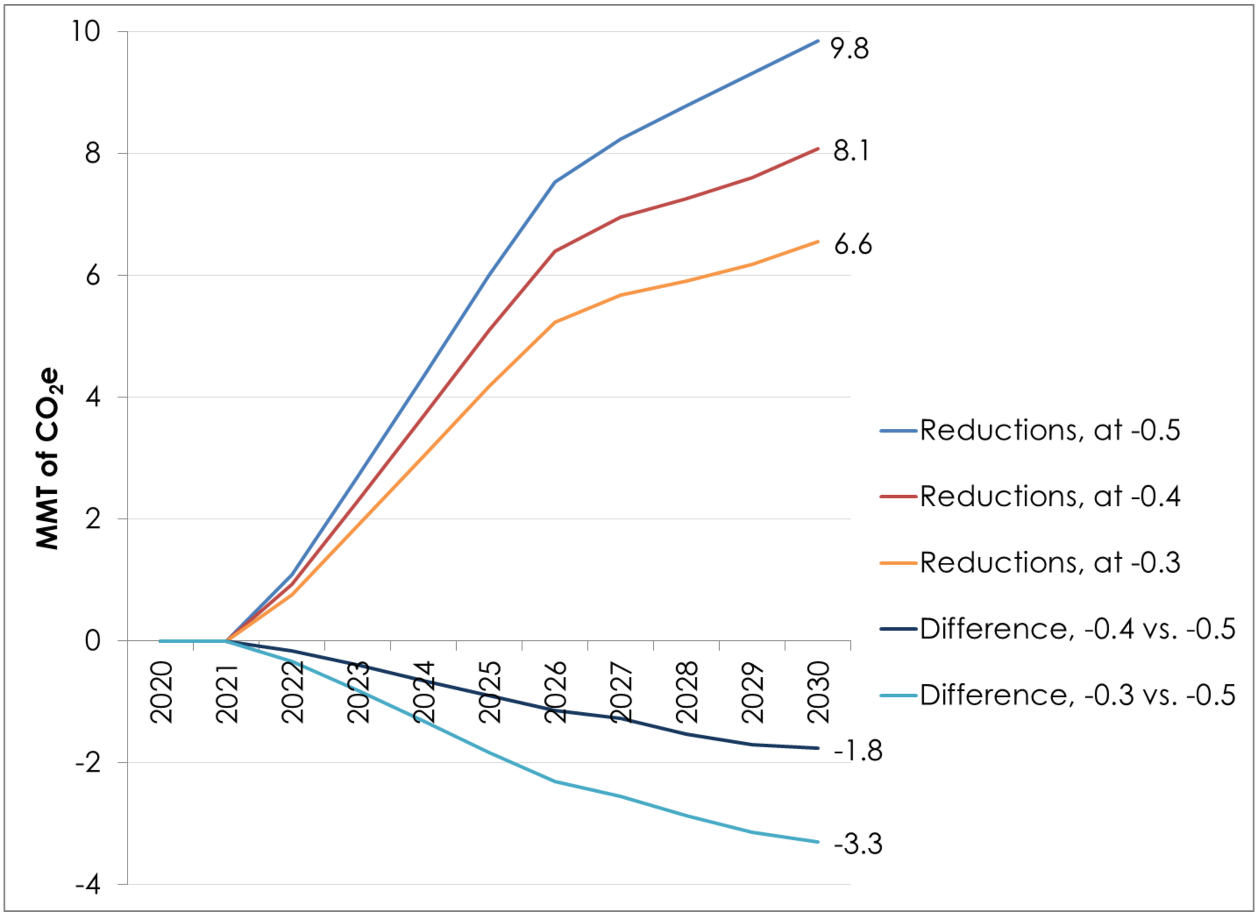
In their study of U.S. industrial competitiveness, Aldy and Pizer point to conditions under which a lower short-run elasticity could prevail for many years: “[T]he volatility in allowance market prices, such as in the EU Emission Trading Scheme for [CO_2] and other cap-and-trade programs may undermine firms’ abilities to predict and plan for carbon prices. In this case, a short-run response through our empirical approach may provide a plausible simulation of firm behavior under climate change regulation characterized by volatile carbon prices,” (Aldy and Pizer 2015, p. 2).

Price volatility has not been a problem in California, thanks to the program price floor. But carbon price effectiveness could be lower for other reasons. For example, some evidence suggests that free allocation to industry dampens the long-run price signal. The type of output-based allocation California uses is understood as conforming to global best practices for free allocation of allowances for the purpose of countering leakage and competitiveness concerns while maintaining incentives for environmental performance. This method is an obvious improvement over prior methods that rewarded greater emissions (“grandfathering”). In contrast, with output-based free allocation, the amount of free allowances received depends on production, creating an incentive for domestic production.

There is a strong basis for expecting the full price signal would be taken into account for short-term decisions, i.e., for operational cost minimization, including fuel use, taking capital stock as given. Yet even California’s best-practice approach to output-based free allocation may dampen the effectiveness of a carbon pricing policy for long-term decisions. In the context of a multi-year investment choice, the level of free output-based allocation certainly affects the profitability of carbon-emitting plants as compared to lower-emitting alternatives. A study commissioned by the EU found that output-based allocation weakens the price signal for long-term, large investments: “Summarizing the findings in literature, it can be concluded that free allocation does distort the CO_2 price signal to some extent, despite the theoretical independence between allocation method and abatement behavior” (European Commission 2015, p. 17).

To explore the implications of a less robust price elasticity effect, we present two sensitivity cases, testing price elasticities of -0.3 and -0.4, respectively, compared to the value of -0.5 in the Current Trajectory Scenario. Figure 16 graphs the effects of these lower price responsiveness parameters, showing they lead to an estimated increase in 2030 CO_2e emissions of 1.8 - 3.3 MMT in 2030.

Figure 16. Sensitivity analysis of carbon price responsiveness in industry sector[53]



This graph shows emission reductions with the price elasticity of energy demand equal to -0.5 in the main results as well as results obtained with two lower price elasticities: -0.4 and -0.3. The difference curves below the horizontal axis calculate higher emissions results in the two sensitivity cases compared to the main results.

Source: California EPS

9.4. RATE OF INNOVATION

Next we investigate assumptions related to innovation in key technologies and the resulting cost reductions. Section 3.1.3. explains how the EPS models innovation, incorporating expected learning rates, initial deployment levels, and the level of additional deployment (i.e., greater installed capacity) due to policy strengthening. Figure 17 shows the change in direct economic impacts in the Energy Innovation Scenario when the rate of learning is doubled or reduced to zero, for both battery storage and electricity generation from solar and wind power technologies. A sensitivity analysis was also performed for carbon capture and storage. The

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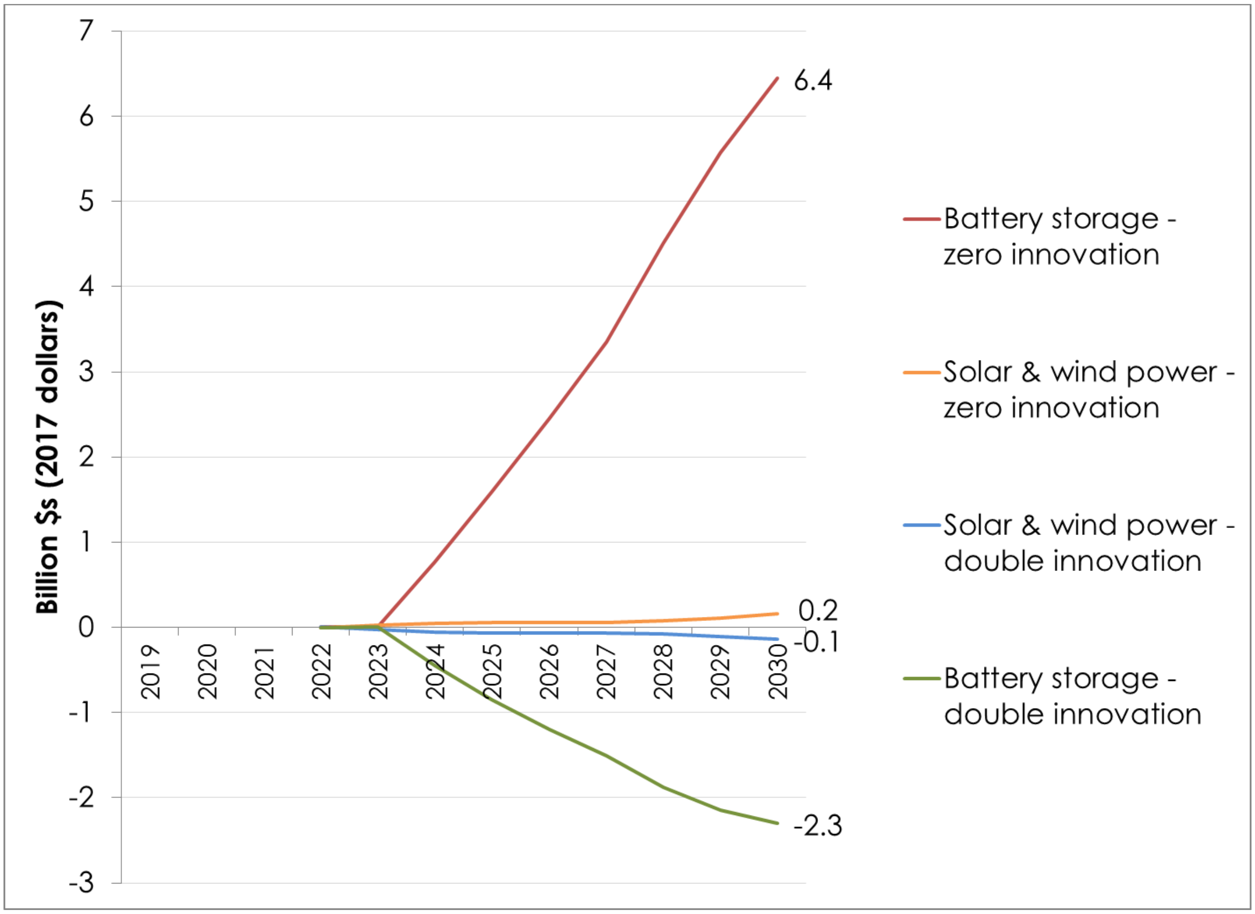
[53] Section 3.2.2. explains the procedure used to obtain consistent estimates of emission reduction effects between package-level and individual policy effects. An analogous approach is used to test the implications of varying the industry sector price elasticity of demand. Isolated consideration of the effect would produce inconsistent results. Complete policy benefit-cost curves for each of the sensitivity cases was calculated to achieve consistent estimates for carbon pricing.

Energy Innovation Scenario is least reliant on this technology, however, so the effects are too small to be visible in the graph.

Figure 17. Economic impacts of innovation sensitivity analysis



Source: California EPS

Compared to the Current Trajectory Scenario, the Energy Innovation Scenario doubles the amount of battery capacity installed in California, a function of both additional uptake in electric vehicles and greater use of battery storage for electricity reliability purposes. In contrast, ratcheting up the clean energy standard in the Energy Innovation Scenario leads to a 12 percent increase in solar and wind power capacity over the Current Trajectory Scenario. This greater reliance on battery storage in the Energy Innovation Scenario is crucial to understanding why battery storage prices cause much larger sensitivity impacts than do solar and wind power.

The relative maturity of solar and wind power technologies is another factor explaining the greater sensitivity to variation in the battery storage assumption. Innovation is generally fastest for emerging technologies, because they start from a lower installed capacity, which increases the relative importance of each additional unit of deployment. Between 2020 and 2030, the Energy Innovation Scenario projects solar and wind power capacity to roughly double, while installed battery capacity grows by more than a factor of seven. The larger effect of innovation on the expected cost of battery storage means that doubling the learning rate or setting it to zero has a larger impact.

10. DISCUSSION

10.1. CAVEATS

The California EPS offers new visibility into the combined effects of carbon pricing and sector-specific policies and insights on priority areas for policy strengthening, representing dozens of policy options. Nonetheless, no single model can provide a definitive and exhaustive policy recipe. More specialized models at the sector level will always have the capacity to capture more detail within their respective domains than is possible in a multi-sector, economy-wide context. Further analysis of each recommendation using more narrowly tailored modeling is recommended. Follow-on modeling can illuminate other supportive policies that may be beyond the scope of the EPS, while also refining policy design.

EPS outputs do not differentiate results by income level or at the community scale; impacts are presented at the statewide level. More fine-grained analysis of the spatial distribution of emissions could attempt downscaling, but this initial report does not do so. Therefore, many prominent equity issues, including affordability effects on lower-income households and the effects on neighborhoods that have historically borne a disproportionate pollution burden, are beyond the current scope of the model.

Having acknowledged this limitation, we note the important equity dimensions of the work. First, EPS outputs automatically integrate the type of social impact analysis called for in California's Assembly Bill 197. More emphasis on such metrics was a priority identified by the Environmental Justice Advisory Committee to the California Environmental Protection Agency. Second and even more fundamentally, battling climate change is a matter of intergenerational equity. Future generations will rightly condemn our delay if we disregard our obligation to pursue responsible decarbonization.

Another caveat relates to relatively optimistic assumptions regarding policy implementation success. The BAU Scenario should not be thought of as a minimum "guaranteed" outcome. Both the BAU Scenario and Current Trajectory Scenario assume that policies induce emission reductions as policymakers intend, typically through using expected outcomes portrayed in the 2017 Scoping Plan analysis as modeling inputs.

Real-world policy effectiveness could fall short of anticipated efficacy. For example, the BAU Scenario assumes deep emission reductions from substitutes for ozone-depleting substances, which fall 45 percent from the 2017 level. Yet inventory data show that such emissions have steadily risen since 2000, never demonstrating a year-over-year reduction. Different levels of policy efficacy are specifically evaluated in the model as part of sensitivity analyses. Those analyses mainly consider differences in the success of the sustainable communities policies and carbon pricing, however. It is worth more broadly emphasizing that significant effort will be required to deliver the level of policy success portrayed in the BAU and Current Trajectory scenarios.

A final caveat relates to the level of emission reduction ambition. The level achieved with the recommended policy enhancements should not be thought of as a suggested ceiling for action. Initial modeling has sought to provide new insights into the current emission trajectory and identifies policies to reach the 2030 target.

10.2. THE COSTS OF DELAY VS. THE BENEFITS OF OPTIONALITY

Recent work by the Energy Futures Initiative highlights the benefits of optionality and flexibility (Energy Futures Initiative 2019). We agree with cautions against "silver bullet" solutions. There are benefits to diverse energy supplies and risks to overreliance on too narrow a set of energy technologies. We further agree with emphasizing increased investment in research and technology to expand deep decarbonization options.

Yet the assertion that "[t]he ability to delay a capital commitment has value" (Energy Futures Initiative 2019, p. 21) begs context. The principle is certainly valid in isolation. This is a core insight from finance. The virtues of optionality are not iron clad, however, and policymakers must also recognize the costs of delay. Scientists have proved that the earth has a limited ability to absorb further CO_2 emissions before crossing thresholds recognized as presenting dangerous risks.

The costs of delay include potentially higher costs of emission reduction, due to the failure to take full advantage of the opportunities presented by natural capital stock turnover (Harvey and Aggarwal 2013). Appliance end of life is an opportune moment for policy intervention because it is more cost effective to set requirements for new investment decisions than to mandate premature retirement of still operational devices or equipment. If the policy signal is insufficient, some cost-effective options may be missed, which could result in higher future costs, especially if the new equipment ends up requiring early retirement.

The costs of delay are a function of the expected severity of climate damage, which is emerging more quickly and more intensely than had been expected. Oreskes et al. (2019) illuminate the social and psychological factors that have led climate scientists to underestimate risks. They find the scientific community's premium on reaching consensus and experts' reluctance to venture opinions except when empirical data provide clear signals have the effect of weakening conclusions. They also detect a prevailing view among climate scientists that there is little reputational risk to under-estimating a threat but a significant risk of losing credibility if they over-estimate a threat.

Compounding this problem is new evidence of a similar dynamic in economics. DeFries et al. (2019) find that economic studies have "omitted or grossly underestimated" many of the most serious climate risks. Difficulties facing economists include insufficient data, not least because of the prospect of significant change far beyond the bounds of recorded human experience. Combine the substantive challenges with the sense of political risk, and risk aversion is activated.

If a researcher is even willing to tackle the question, the same asymmetric perception risk exists, with under-estimation perceived as safer and over-estimation carrying reputational threat.

For these reasons, policy makers must assume that climate risk assessments have systematically underestimated the magnitude of climate damage, the probability of catastrophic outcomes, and the risk of associated economic harm. These realities imply a more urgent need to transition away from activities causing GHG emissions, and, as a corollary, higher costs of delay.

With California at the leading frontier of climate policy, attention to cost is understandable and appropriate. We are cautiously optimistic because of model results identifying opportunities for policy strengthening that appear to yield net economic benefits, as well as past experience, including faster-than-expected innovation in electricity supply technologies and strong economic performance in concert with the ratcheting up of climate policies over time.

Any analysis stretching more than a decade into the future should acknowledge the substantial and undeniable uncertainties. California has developed a range of cost containment approaches that have meaningfully advanced the state of the art in environmental policy. Key features include direct cost containment design features as well as technology neutrality and flexibility. With respect to direct cost controls, the price ceiling in the cap-and-trade program is the most straightforward example. If demand at auction threatens to push the settlement price above the price ceiling, additional permits are injected until supply matches demand at the price ceiling price.

Technology neutrality means that a variety of compliance pathways are possible for arriving at the desired emission reduction target. Flexibility allows for heterogeneous responses by regulated entities, such as through policies that reward overcompliance with credits that can be sold to other emitters. Together, flexible and technology-neutral policy design allows emitters to discover the lowest-cost approaches, and encourages the most innovative, cost-effective emitters to carry a larger share of the emission reduction effort. The state's zero emission vehicle mandate and low carbon fuel standard are both policies that reflect these design features. They create markets for tradable compliance units and do not prescribe technology. For example, both battery electric and hydrogen fuel-cell vehicles qualify under the zero emission vehicle mandate.

11. CONCLUSION

For more than a decade, California's climate program has been at the forefront of global efforts to reduce carbon emissions. California hit its 2020 target four years early, in 2016, even though a decade ago that goal was viewed as daunting. This real-world progress and the state's vigorous leadership have helped to sustain international momentum to confront the climate crisis.

The next milestone on the state's decarbonization journey is to reduce emissions 40 percent below 1990 levels by 2030. This report first assesses the expected emission trajectory to 2030 under current policy. Results from the California EPS find current policies are unlikely to bend the emissions curve downward quickly enough to meet the 40 percent reduction target by 2030. We use the model to identify six policy opportunities that, when implemented together, achieve the 2030 goal while returning net economic and social benefits estimated to cumulatively total $21 billion through 2030.

California's policymakers have a challenging job, working at the forefront of global climate action. In effect, they are inventing a sophisticated climate policy machine without obvious precedent. The California EPS adds new capabilities to the field of climate policy modeling, and results provide evidence for optimism regarding the feasibility and impacts of reaching the 2030 goal.

The state's continued success is essential. We hope the model will prove useful in California's long-range climate policy planning. The next iteration of California's Scoping Plan is expected by 2022. We look forward to further explaining the model, receiving feedback, and seeing how the model can be most helpful. We hope the California EPS contributes in some small way to the state's continued success in its decarbonization journey.

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APPENDIX

The Appendix discusses carbon pricing more thoroughly, starting with a look back at historical prices, considering market fundamentals and policy developments, and finally covering analyses from top academics and carbon market advisory firms. A more detailed description of the approach and reasoning for the input assumptions in the Current Trajectory Analysis serves as a preface to this background.

CARBON PRICE IN THE CURRENT TRAJECTORY ANALYSIS

The method used to set expected future carbon prices under existing policy is based on a constant projection method, meaning a past value is carried forward to determine future values. The May 2019 allowance auction—the most recent auction at the time of carbon price scenario specification—yielded a price 11.6 percent above the floor price (in both cases referring to the price in 2019 dollars), rounded to 12 percent in the body of the document. To impute the value of the price floor in future years, this 11.6 percent increment is applied to the anticipated future price floor under current rules, which provide for the price floor to rise annually at a rate of 5 percent before inflation (though the use of 2017 dollars in the California EPS means the inflation component is excluded). The 2030 floor price is calculated at $25.6 per metric ton, resulting in the $28.6 per metric ton price in 2030 in the Current Trajectory Scenario, which is rounded to $29 per metric ton in the body of the document.

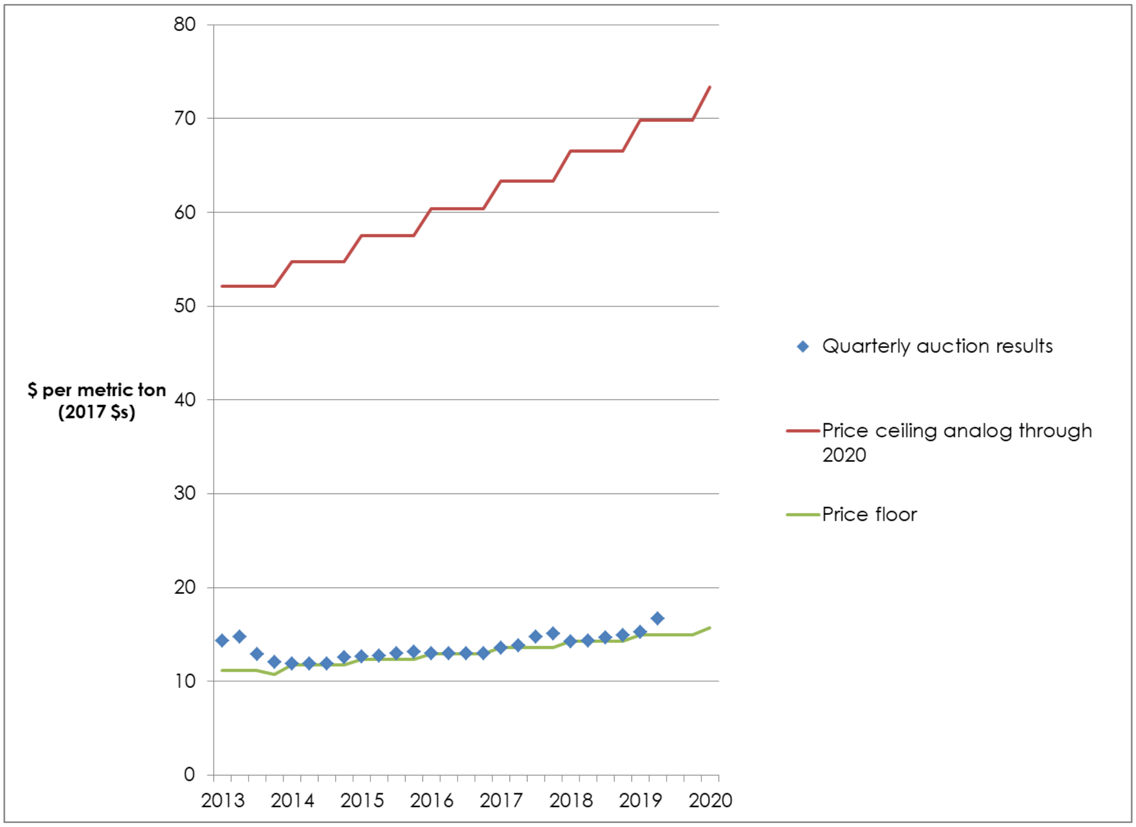
The constant projection method is used because it is considered a relatively assumption-free approach to projecting future values, which is appropriate in light of uncertainty about what the actual future level will be. Current market fundamentals certainly suggest low prices could persist for years, but the behavior of speculative investors in the market is difficult to predict.

CARBON PRICE HISTORY

Since 2014, prices have been at or near the price floor—the minimum price the state accepts at auction. The price floor started at $10 per metric ton and increases at 5 percent plus an annual inflation adjustment.

Figure 18 shows that after some early exuberance, California carbon prices have settled at or near the floor since 2014. Prices endured significant downward pressure on demand in 2016 and 2017 due to political and legal uncertainty. During this period, over 100 million allowances failed to sell at auction, and auction results equaled the floor price throughout 2016. In September 2017, Senate Bill 398 was enacted with a two-thirds majority, establishing the program's legal authority through 2030 and eliminating program uncertainty. Since then, unsold allowances have mostly re-entered the market, demand for allowances returned such that every auction has completely sold out the available allotment, leading prices to rise above the price floor.

Figure 18. Historical carbon prices for California emission permits



The "price ceiling analog through 2020" shows the highest price tier of the Allowance Price Containment Reserve, which served as the main cost-containment approach in the initial design. It involves a supply of allowances to be released if prices reach pre-determined levels, rising at the same rate as the price floor, an annual rate of 5 percent plus inflation. Senate Bill 398 directs that a price ceiling, which is not quantity limited, replace this initial approach starting in 2021.

Source: Energy Innovation graphic with data from CARB

MARKET FUNDAMENTALS AND POLICY DEVELOPMENTS

The relatively low carbon prices for California emission permits, particularly since adoption of Senate Bill 398, are in part traceable to the buildup of the "private bank" of emission permits—surplus emission permits that can be held indefinitely (i.e., banked). Concerns have been raised that the growing private bank will weigh down prices, potentially leaving the cap-and-trade program unable to fulfill its role under the 2017 Scoping Plan as the "gap closer" in meeting the 2030 target.[54]

Energy Innovation's 2017 research into the trends driving the accumulation of surplus allowances was one of the first publicly available reports on the subject (Busch 2017). The state Legislative Analyst's Office released an analysis with similar findings around the same time (Legislative Analyst's Office 2017). The nonprofit NearZero has developed a regularly updated

[54] The role of cap-and-trade in the 2030 strategy is further discussed in section 2.2.

open-source model to track the carbon market's balance of supply and demand over time, offering several metrics. (Inman et al. 2018; Inman et al. 2019).

Carbon Pulse recently summarized the market balance, also referencing the fact that California's market is linked with a similar program in Quebec under the banner of the Western Climate Initiative (Lithgow 2019a):

> California and Quebec entities continued to stretch the joint cap-and-trade program's vast permit surplus even further after picking up additional unsold allowances during the first quarter of 2019, according to [Western Climate Initiative] data. Both California's Independent Emissions Advisory Market Committee and state legislators have sought to address the allowance supply glut that observers believe could minimize (sic) the need for regulated entities to reduce emissions in the post-2020 period. However, [CARB] has declined to take action on the issue and disputed concerns that the surplus will hinder the state's ability to reach its 2030 climate goal. According to the WCI's quarterly compliance report . . . market participants in both jurisdictions were holding 193.9 million [vintage 2013 – vintage 2017] allowances at the end of [the first quarter of] 2019.

Banking in and of itself is not the problem and in fact can help to smooth prices over the years. The challenge is that the methods for optimizing cap-and-trade design are rudimentary. No clear-cut formula exists to distinguish the threshold between acceptable and problematic levels of banking. The problem became obvious enough that two of the other widely known cap-and-trade programs, one covering the EU and the other covering northeastern US states, found it necessary to take steps to counter the allowance surpluses that emerged in those programs in order to produce adequate environmental impact. Notably, the private bank of surplus emission permits in California is below the level of oversupply that developed in the EU and northeastern states' programs. In those programs, surplus permits representing more than an entire year's worth of emissions had accumulated in the market.

California officials have identified the price jump that occurred after the European carbon pricing program adjusted the supply of permits as a cautionary tale. In a matter of months, that program's carbon price more than tripled, though it has since levelized in a range of 20-30 Euros per allowance. This design change certainly led to sharp adjustments—effectively a step change in price compared to historical price movements.

Sharp price changes are undesirable, without question, but it is also worth acknowledging that even the current higher prices in the EU program are significantly below the minimum level recommended by experts such as the World Bank's High-Level Commission on Carbon Prices, which concluded that—on a generic basis without recognizing differentiated responsibilities—"the explicit carbon-price level consistent with achieving the Paris temperature target is at least US$40–80/t$CO_2$ by 2020" (Stiglitz et al. 2017).

CARB has argued that three design features make it likely for the program to deliver the reductions expected from the cap-and-trade program: the price floor, holding limits that constrain how many permits any one entity may possess, and the self-ratcheting mechanism to remove unsold auction allowances from the market. Each feature is considered in turn:

(1) The program's price floor is one of its outstanding features. Nonetheless, the analysis here suggests that a rising price trend, which is part of the Current Trajectory Scenario, does not in and of itself provide a guarantee of sufficiency.
(2) Holding limits certainly prevent companies covered under the program from building up larger surpluses than the designated limit, but holding limits do not set an absolute limit on emissions or guarantee a particular level of environmental performance. This feature is designed to restrict the ability of any one actor to control the market. Accordingly, the rules limit the amount of allowances a given entity may control but do not provide an absolute limit on emissions. There is no limit on the number of speculative investors who may enter the market, and each new entrant can add to the maximum allowable holdings.
(3) The "self-ratcheting mechanism" is a valuable policy innovation, yet it has done little to change the supply of allowances in the recent buildup of surplus allowances. The role for speculative capital with deep pockets to snatch up allowances means that auction demand may not correlate with current market fundamentals, and auction demand is what triggers the existing self-ratcheting mechanism.

For these reasons, we are not confident that current design features are sufficient to deliver reductions at the level anticipated in the Scoping Plan.

Despite these concerns, it should be acknowledged CARB has emphasized that it stands ready to adjust program design if needed. And the agency has taken incremental steps to answer doubts about whether current policy design will allow cap-and-trade to "close the gap" between the emission reductions expected from sector policies and the 2030 target as portrayed in the strategy set forth in the 2017 Scoping Plan. When the Board approved the 2018 regulatory adjustments required by Assembly Bill 398, it also voted to include a resolution committing to evaluate the level of the surplus: "[T]he Board directs the Executive Officer to quantify and report to the Board, by December 31, 2021, the volume of unused allowances from 2013 through 2020," (CARB 2018c, p. 11).

RESEARCH LITERATURE

For evidence from other analysis, we first turn to research from Berkeley and Stanford scholars (Borenstein et al. 2017), which uses econometrics techniques to forecast a probability distribution for prices, finding a 47 percent chance prices will be at the floor and a 33 percent chance prices will be at the ceiling.

Since the article was released, two noteworthy events have placed further downward pressure on prices. First, the Canadian province of Ontario chose to end its carbon cap-and-trade program, severing its Western Climate Initiative linkage with California and Quebec. Borenstein et al. (2017) expect linkage with Canada to provide a net 100 MMT of CO_2 in demand for California's allowance permits. Current expectations for net allowance demand from Canada are sharply lower due to Ontario's departure. While Quebec remains a linked partner, Ontario's emissions are about four times larger.

Second, California adopted Senate Bill 100 in September 2018, establishing a 60 percent renewable electricity standard for 2030 (and a 100 percent carbon-free standard for 2045). The Borenstein et al. (2017) work is based on the 50 percent standard. Shortly before finalization of the California EPS for public release, an updated version of the earlier paper by Borenstein et al. was published in the *American Economic Review* (Borenstein et al. 2019).

Forecasts from carbon market advisory firms tend to show prices lifting away from the floor by the latter part of the 2020s. For example, Clear Blue Markets forecasted a price of $59.55[55] in 2030 as cited in media reports (Lithgow 2019b), and The Brattle Group has published a similar forecast: "We find that GHG prices in the Current Trends scenario would rise to $55/ton in 2030, ranging from approximately $35/ton to $80/ton," (Yang et al. 2019).

Future price analyses conducted by carbon market advisory firms are, as a rule, more versed in the practicalities of the market, but their underlying methodologies are less than transparent in general. Though the lack of any role for speculative investors is a limitation of Borenstein et al. (2017), on balance we find this research to be more persuasive.

[55] We hypothesize these are expressed in current dollar value, i.e., as 2019 dollars, but the article does not specify.