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Modeling California policy impacts on greenhouse gas emissions

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Energy Technologies Area

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Note

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including Supplementary Information which is included here as Appendix C.

Abstract

This paper examines policy and technology scenarios in California, emphasizing greenhouse gas (GHG) emissions in 2020 and 2030. Using CALGAPS, a new, validated model simulating GHG and criteria pollutant emissions in California from 2010 to 2050, four scenarios were developed: Committed Policies (S1), Uncommitted Policies (S2), Potential Policy and Technology Futures (S3), and Counterfactual (S0), which omits all GHG policies. Forty-nine individual policies were represented. For S1-S3, GHG emissions fall below the AB 32 policy 2020 target [427 million metric tons CO_2 equivalent ($MtCO_2e$) yr^{-1}], indicating that committed policies may be sufficient to meet mandated reductions. In 2030, emissions span 211 to 428 $MtCO_2e$ yr^{-1}, suggesting that policy choices made today can strongly affect outcomes over the next two decades. Long-term (2050) emissions were all well above the target set by Executive Order S-3-05 (85 $MtCO_2e$ yr^{-1}); additional policies or technology development (beyond the study scope) are likely needed to achieve this objective. Cumulative emissions suggest a different outcome, however: due to early emissions reductions, S3 achieves lower cumulative emissions in 2050 than a pathway that linearly reduces emissions between 2020 and 2050 policy targets. Sensitivity analysis provided quantification of individual policy GHG emissions reduction benefits.

Abbreviations

2DS, IEA (2012) 2°C Scenario;
AB, California Assembly Bill;
CALGAPS, Ca̲lifornia L̲BNL G̲HG (and criteria pollutant) A̲nalysis of P̲olicies S̲preadsheet;
CARB, California Air Resources Board;
CEC, California Energy Commission;
CHP, combined heat and power;
CPUC, California Public Utilities Commission;
CCS, CO_2 capture and sequestration;
E85, 85% (by volume) ethanol/15% gasoline blended fuel;
EPA, U.S. Environmental Protection Agency;
EO, California Executive Order;
GHG, greenhouse gas;
GSP, gross state product;
$GtCO_2e$, billion metric tons CO_2 equivalent;
GWP, global warming potential;
HDV, heavy-duty vehicle;
HFC, hydrofluorocarbon gas;
IEPR, Integrated Energy Policy Report;
LBNL, Lawrence Berkeley National Laboratory;
LCFS, Low Carbon Fuel Standard (EO S-01-07);
LDV, light-duty vehicle;
mpg, miles per gallon (equivalent to 0.425 km per liter);
$MtCO_2e$, million metric tons CO_2 equivalent;
NHTSA, U.S. National Highway Traffic Safety Administration;
PV, photovoltaic;
RPS, Renewable Portfolio Standard (SB 1078 and amendments);
SB, California Senate Bill;
SONGS, San Onofre Nuclear Generating Station;
SP, CARB (2008) Scoping Plan measure;
VMT, vehicle miles traveled (equivalent to 1.609 vehicle km travelled);
ZEV, zero-emission vehicle.

1 Introduction

California was the first state[1] in the U.S. to establish a comprehensive, binding policy for reducing greenhouse gas (GHG) emissions with the passage of California Assembly Bill (AB) 32 in 2006 (LegInfo, 2006), returning emissions to the 1990 level of 427 $MtCO_2e\ yr^{-1}$ in 2020 (CARB, 2013a).[2] Moreover, California Executive Order (EO) S-3-05 sets a target of reducing state GHG emissions to 80% below this level by 2050 (GO, 2005), and EO B-16-2012 ordered the state to reduce transportation sector GHG emissions to 80% below the 1990 level by 2050 (GO, 2012). The state is currently working to establish a mid-term (2030 era) GHG target to provide additional policy guidance (OPR, 2013; InsideEPA, 2013); in May 2014, the California Air Resources Board (CARB) proposed a 2030 target of ≥40% below the 1990 level (CARB, 2014a).

A large portion of the state's GHG reduction strategy, as enumerated in its first update (CARB, 2014a) to the Climate Change Scoping Plan (SP) (CARB, 2008), relies on many discrete measures to achieve reductions in specific sectors, in addition to its cap-and-trade system that reduces GHGs across sectors. A number of policies have been enacted as a result of AB 32, though some policies, such as the Pavley Global Warming Bill of 2002 (AB 1493), pre-date it but act in synchrony with AB 32 goals. Moreover, some federal laws, such as the Clean Water Act (SWRCB, 2013) and the U.S. Environmental Protection Agency (EPA) and National Highway Traffic Safety Administration (NHTSA) vehicle standards (EPA, 2011) have a direct impact on state GHG emissions.

This paper aimed to assess likely emissions pathways through 2020 and beyond. Because cap-and-trade was difficult to model without detailed economic information that was beyond the scope of this study, its effects were intentionally ignored, in order to determine the impact that other policies might have on state GHG emissions. The 2050 GHG target was also ignored, since current policy does not specify how to achieve it. Forty-nine existing and potential policies were modeled, grouped into three scenarios by implementation likelihood (ranging from fully committed to speculative). Details of scenarios and the policies comprising them are presented in sections 2.2 and 2.4.

Here is reported the first attempt to comprehensively model all relevant policies in order to assess their combined effect on reducing GHG emissions between 2010 and 2050. The usefulness of the analysis was in providing information to policymakers on the timing and GHG impacts of these policies, and how some policies might act in combination. The intention was to focus on potential emissions reductions through 2030 from a set of policies with explicit targets in the 2015-2030 timescale. A handful of policies had quantitative targets that extended beyond 2030, but for the most part, policies were limited to shorter timescales. Results are presented through 2050 to provide context regarding the longevity and cumulative emissions reductions that may result from various policies, but no effort was made to meet the 2050 emissions target.

To the author's knowledge, no previous study has included all existing and proposed California policies, and explored achievable ranges of emissions reductions for 2030. There have been a

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[1] Oregon and Washington have since enacted limits on GHG emissions between 2020 and 2050 (Busch, 2007; RCW, 2008). Oregon's 2020 target is 10% below its 1990 level, whereas Washington's 2020 target is equal to its 1990 level. However, the 2050 targets are less aggressive in percentage reduction terms than the California target.
[2] The 2020 target was recently revised to 431 $MtCO_2e\ yr^{-1}$, reflecting a change in how methane emissions are converted to CO_2 equivalent emissions (CARB, 2014a). Because all emissions factors for this study were developed prior to this change (and the change is also very small), the older definition and hence target value was retained.

number of previous efforts, however, to model future GHG emissions for California, which mostly focus on pathways to near-zero emissions in 2050 (CCST, 2011; ECF, 2010; Greenblatt and Long, 2012; Greenblatt, 2013; Jacobson et al., 2013; McCollum et al., 2012; Nelson et al., 2013; Roland-Holst, 2008; Wei et al., 2012, 2013; Williams et al., 2012; Yang et al., 2014). To reach the 2050 target, however, most of these studies modeled pathways that require policies and market growth for clean energy technologies that went beyond the policies modeled here.

Section 2 briefly describes the methods used to construct, validate and produce results from the model reported on here. Section 3 presents and discusses scenario and individual policy sensitivity results, including comparisons with previous studies. Section 4 presents conclusions and policy implications. Supplementary Information includes model improvements, uncertainty analysis, scenario-specific GHG emissions, modeling assumptions (including quantitative targets of each policy), model validation, summaries of previous studies, and criteria pollutant emissions.

2 Methods

2.1 Model overview

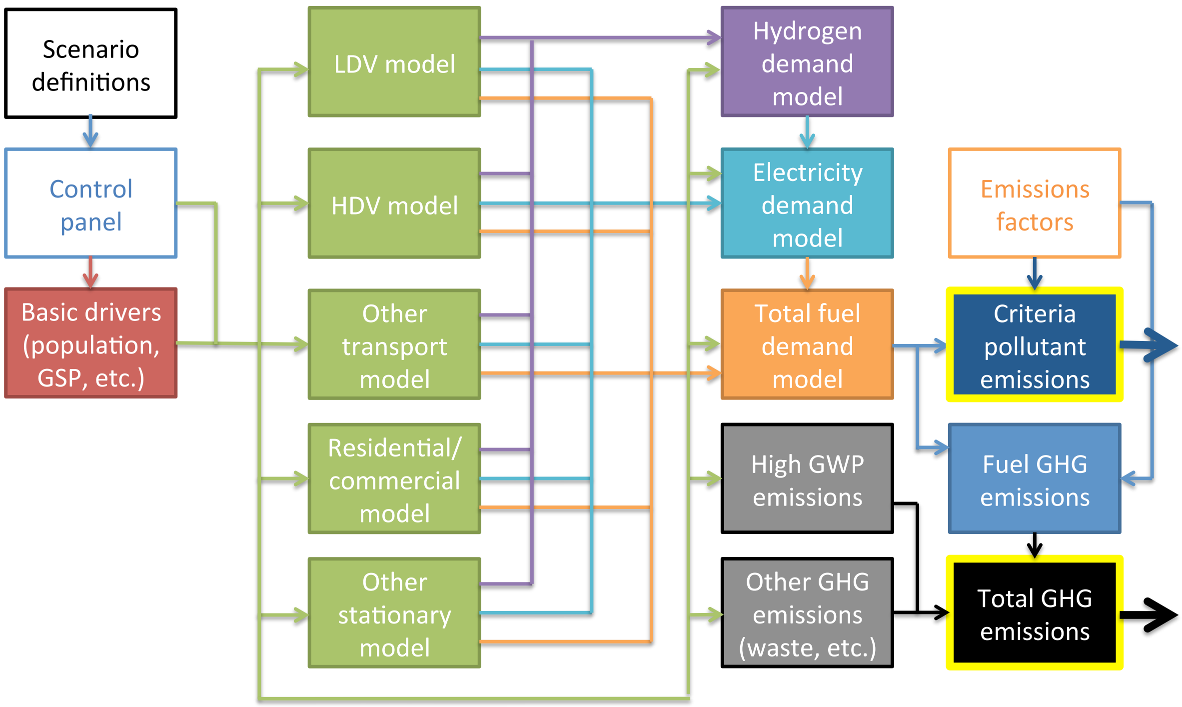
The California LBNL GHG (and criteria pollutant) Analysis of Policies Spreadsheet (CALGAPS)—formerly the GHG Inventory Spreadsheet (GHGIS) (Greenblatt, 2013)—was built in Microsoft Excel for Mac 2011 (Version 14.3.5) in 2013 and was subsequently revised in 2014. The model represents all GHG-emitting sectors within California between 2010 and 2050, including non-energy emissions in the high global warming potential (GWP)[3] gas, waste, agriculture and forest sectors. CALGAPS is in essence an energy and GHG inventory model; it is not driven by economics nor does it optimize anything. It uses historical and projected future trends in energy consumption (typically normalized by population or gross state product—GSP), GHG fuel intensities, and GHG emissions outside the energy sector, combined with prescriptive, policy-based assumptions. Energy and emissions metrics are calculated by sector and, occasionally, end-use subsector. CALGAPS calculates total consumption by fuel (natural gas, gasoline, etc.), and converts them into GHG emissions using time-varying GHG intensity coefficients. Three criteria pollutants (reactive organic gases, nitrogen oxides and fine particulate matter) are also calculated, but were not the focus of this study and are not reported on here. Upstream (fuel extraction, production and transport) and downstream (fuel combustion) GHG emissions are calculated separately; only in-state fractions of upstream fuel, imported electricity, and in-state fuel combustion emissions are included in final inventories.

Figure 1 depicts overall model structure. Each box represents one or more Excel worksheets, with arrows indicating data flow. The model begins with scenario specifications (white box/black outline), defining input assumptions including basic drivers like population and GSP (red box). Drivers help determine demand by sector and fuel. Scenarios (see section 2.2) are composed of individual policies, each typically focused on single sectors, and defined by quantitative targets over time (e.g., biomass fraction of diesel fuel, renewable fraction of electricity, number of zero-emission vehicles—ZEVs). The control panel (white box/blue outline) specifies details of all policies. Demand for energy are calculated by sector (green boxes) and aggregated to statewide demand. Demands for hydrogen (purple box) and electricity (blue-green box) contribute to total fuel demand (orange

[3] GWP is defined as cumulative radiative forcing per unit mass over a specified timescale (usually 100 years) relative to an equal mass of CO_2 (Myhre et al., 2013).

box). Emissions of GHGs (light-blue box) and criteria pollutants (dark-blue box) arise from total fuel demand, using emission factors (white box/orange outline). Emissions of GHGs from non-energy sectors (gray boxes) are added to obtain total GHGs (black box).

Figure 1. CALGAPS model structure and sequence of calculations



Input data was assembled from a combination of public and proprietary data supplied by a number of California agencies, including CARB, California Energy Commission (CEC), California Public Utilities Commission (CPUC) and the California Department of Finance. Some data was preliminary and/or unpublished when it was incorporated into CALGAPS, and may have subsequently undergone slight revision or may still be unavailable publicly. It was necessary to include these data sources, as official estimates were not always available at the desired level of detail. Appendix A provides a more in-depth summary of the model.

2.2 Scenarios

Four scenarios were developed to model possible futures for California. The Committed Policies (S1), Uncommitted Policies (S2) and Potential Policy and Technology Futures (S3) scenarios include a number of specific state and federal policies, including laws, EOs and agency regulations (49 in all), listed in Appendix B. S1 includes all policies either underway or extremely likely by 2020; while all require continued support and financial commitments, they were deemed achievable. S2 includes existing policies and targets that lack detailed implementation plans, financial commitments or unequivocal support. By contrast, S3 includes speculative policies, including extensions of S1 or S2 policies and targets proposed by non-governmental organizations; they vary in how easily achievable they are, but may also not reflect the maximum level of GHG reductions feasible. The counterfactual scenario (S0) was constructed by disabling all policies included in S1, and was used to estimate the impact of S1 policies.

2.3 Uncertainty analysis

Projections of the future are always uncertain, though this study was designed to somewhat constrain uncertainty by estimating the impacts of specific sets of policies if implemented as modeled. However, many underlying assumptions were not tied to specific policy targets and were therefore inherently uncertain. An analysis was developed for 10 parameters that were identified as being uncertain with measurable GHG emissions impacts, including population, economic growth, the in-state biofuel fraction of fuels, new and retrofit building efficiency parameters, and the efficiencies of electric generation technologies.

For each parameter, 95% confidence intervals were estimated and the range of potential values modeled using normal or log normal distribution functions as appropriate.[4] The impact of individual parameters on total GHG emissions was estimated, and a 1,000-sample Monte Carlo simulation was performed to estimate the simultaneous impact of varying all parameters within their uncertainty ranges. Results are presented in sections 3.2-3.4.

2.4 Policy sensitivities

Sensitivity analyses were performed to estimate the increase in GHG emissions of removing individual policy measures listed in Appendix B, as well as a number of policy combinations described in section 3.5.2. The sensitivity analysis began by starting with one of the scenarios (S1, S2 or S3, depending on the policy or policy combination) and then disabling one or more policies at a time, to quantify the change in GHG emissions in each decade between 2020 and 2050. Disabling all of the policies for a given scenario was equivalent to replacing it with the next less aggressive scenario. For example, disabling all policies in S2 was equivalent to S1, while disabling all policies in S1 was equivalent to S0. Results are presented in section 3.5.

3 Results and Discussion

3.1 Model validation

While CALGAPS was initialized using data mostly provided by state agencies, many assumptions remained, so it was important to compare GHG emissions from CALGAPS with the official CARB inventory (CARB, 2013d). The starting year of the model is 2010, whereas the CARB inventory data extends from 1990 to 2011; therefore, there are two overlapping years (2010 and 2011) that were used to compare GHG emissions at the sector level.[5]

Differences in emissions in most sectors are minor, with largest absolute differences in the electricity sector (6.0 $MtCO_2e$ yr^{-1} in 2010 and 10.1 $MtCO_2e$ yr^{-1} in 2011). For this sector, uncertainty analysis suggests an overall confidence level in the CALGAPS results of approximately

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[4] Parameters whose uncertainty distributions were essentially symmetrical were modeled as normal distributions, whereas those with asymmetrical distributions were modeled as log normal. Other distribution functions could have been used, but insufficient data were available to provide detailed uncertainty information needed to distinguish among function options, so this simple approach was used.

[5] Since this analysis was performed, CARB released a revised inventory with data through 2012 (CARB, 2014c). Differences between this inventory and CARB (2013d) for 2010-2011 were very small.

±2.0 $MtCO_2e\ yr^{-1}$ (95% confidence) in 2010-2011. However, analysis of year-to-year variation in electricity GHG inventory data since 1990, after correcting for long-term secular trends, amounts to ±12 $MtCO_2e\ yr^{-1}$. Large hydro generation, which varied by ±54% yr^{-1} over 1983-2007 (EnergyAlmanac, 2014), presumably drives much of this variation, assuming that natural gas generation supplements hydro shortfalls. CALGAPS, which is intended to model multi-decadal changes, used the long-term average hydro generation. Therefore, GHG differences in 2010-2011 are attributed to year-to-year variation in generation mix that is not captured by the model.

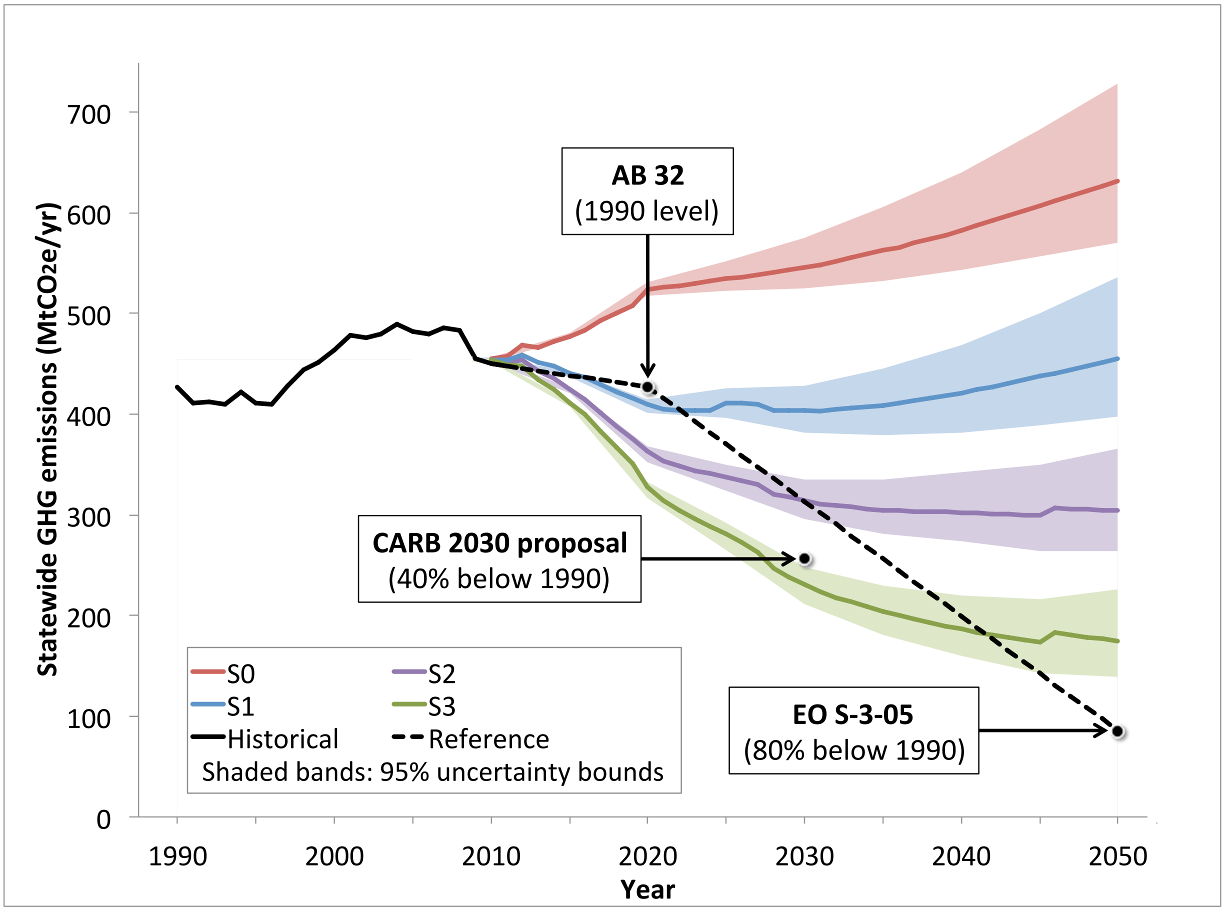
The next largest set of differences is in light-duty vehicles (LDVs), with 5-6 $MtCO_2e\ yr^{-1}$ greater emissions in CALGAPS than in the CARB inventory. This difference arises from slightly higher fuel consumption in CARB data provided for this study (J. Cunningham, pers. commun., 2013) versus CARB inventory data (CARB, 2013b, 2014b).[6] For heavy-duty vehicles (HDVs), CALGAPS emissions were lower than the CARB inventory by ~2 $MtCO_2e\ yr^{-1}$ but CALGAPS did not include buses or motorhomes, which were an inseparable part of HDV inventory data. For other parts of the transportation sector—rail, marine, airplanes and off-road—fuel consumption data supplied by CARB again differed slightly from CARB inventory data (lower for rail and marine, higher for airplanes), amounting to ~2 $MtCO_2e\ yr^{-1}$ lower emissions in CALGAPS than the CARB inventory. For the transportation sector as a whole, differences largely canceled, resulting in ≤0.4 $MtCO_2e\ yr^{-1}$ net discrepancies. Other sectors indicate small differences on the order of 1-3 $MtCO_2e\ yr^{-1}$. For the total inventory, CALGAPS emissions are higher than the CARB inventory by 5-6 $MtCO_2e\ yr^{-1}$, amounting to a ~1% overall difference.

3.2 GHG emissions of scenarios

Figure 2 displays total statewide GHG emissions between 2010 and 2050 for each scenario, along with historical emissions from 1990 through 2011, and a straight-line reference pathway between the 2020 and 2050 policy targets (427 and 85 $MtCO_2e\ yr^{-1}$, respectively). Uncertainty bounds (95% confidence intervals) for each scenario are shown as shaded bands. CARB's proposed 2030 target (CARB, 2014a) of 256 $MtCO_2e\ yr^{-1}$ is shown for reference.

[6] CARB oversees various mobile and stationary inventory efforts, some of which use inconsistent methodologies, a result of varying program goals. For example, CARB's EMFAC model (the output of which CALGAPS used) estimates vehicle GHG emissions through vehicle fleet populations, vehicle miles traveled (VMT) by vehicle classification, and corresponding vehicle GHG and fuel efficiency parameters; by contrast, the CARB inventory uses fuel sales records to estimate GHG emissions from vehicles, and can arrive at slightly different GHG estimates. Additionally, EMFAC used data from 2009 and 2010, whereas inventory data used more recent fuel records (J. Cunningham, pers. commun., 2014).

Figure 2. GHG emissions by scenario, with historical emissions and straight-line reference pathway between 2020 and 2050 GHG policy targets. Uncertainty bounds (95% confidence intervals) for each scenario are shown as shaded bands.



The first observation to note is that S1-S3 all meet or fall below the state target in 2020, indicating that its achievement appears feasible. Between S1 and S3 there is an emissions difference of more than 80 $MtCO_2e\ yr^{-1}$ in the central value, reflecting the possibility of significant additional reductions from new and/or strengthened policies introduced between now and 2020 (see section 3.5).

For 2030, S1 emissions lie 91^{+24}_{-22} $MtCO_2e\ yr^{-1}$ above the reference pathway, while S2 emissions lie effectively on the reference pathway (difference is 2^{+20}_{-19} $MtCO_2e\ yr^{-1}$), and S3 emissions lie 83^{+17}_{-19} $MtCO_2e\ yr^{-1}$ below it. This suggests that the state could meet or fall below the reference value if a number of uncommitted policies such as those found in S2 and/or S3 are implemented, and be well on its way to reaching the 2050 emissions target. CARB asserts that its proposed target, which straddles the S2 and S3 emissions levels, is achievable if a number of additional policies (including some represented in S2) are implemented (CARB, 2014a).

As noted in section 1, except for a few parameters that were taken from studies projecting market growth to 2050 or where policies would affect change beyond 2030, e.g., LDV VMT reductions (S1.3) or Diablo Canyon nuclear relicensing (S2.12), policy activity was frozen after 2030. There was no attempt made to reach 2050 emissions targets, but emissions after 2030 are accounted for, to reflect the impacts of potential policies and highlight remaining "gaps" after 2030.

Given these assumptions, it is unsurprising that no scenario achieves the 2050 target, with 2050 GHG emissions ranging from 455^{+80}_{-58} $MtCO_2e\ yr^{-1}$ (S1) or 107^{+19}_{-14}% of the 1990 level, to 175^{+52}_{-36}f $MtCO_2e\ yr^{-1}$ (S3) or 41^{+12}_{-8}% of the 1990 level. S2 remains essentially flat between 2030 and 2050 at ~300 $MtCO_2e\ yr^{-1}$, reaching 71^{+14}_{-9}% of the 1990 level in 2050. By comparison, S0 reaches 632^{+96}_{-61} $MtCO_2e\ yr^{-1}$ or 148^{+23}_{-14}% of the 1990 level in 2050. Only S3 continues to significantly decrease emissions beyond 2030, dropping an additional 56^{+34}_{-16} $MtCO_2e\ yr^{-1}$ by 2050.

These results suggests that while committed and uncommitted state policies (e.g., S1 and S2) will confer significant reduction benefits over S0 through 2050, these policies will not by themselves result in significant additional emission reductions beyond 2030, because with few exceptions they contain no additional quantitative targets between 2030 and 2050. New and/or strengthened policies (e.g., S3) will be needed for California to continue to reduce emissions through 2050, and to reach its 2050 target of 80% below the 1990 level, even more stringent measures than those represented in S3 will be required.

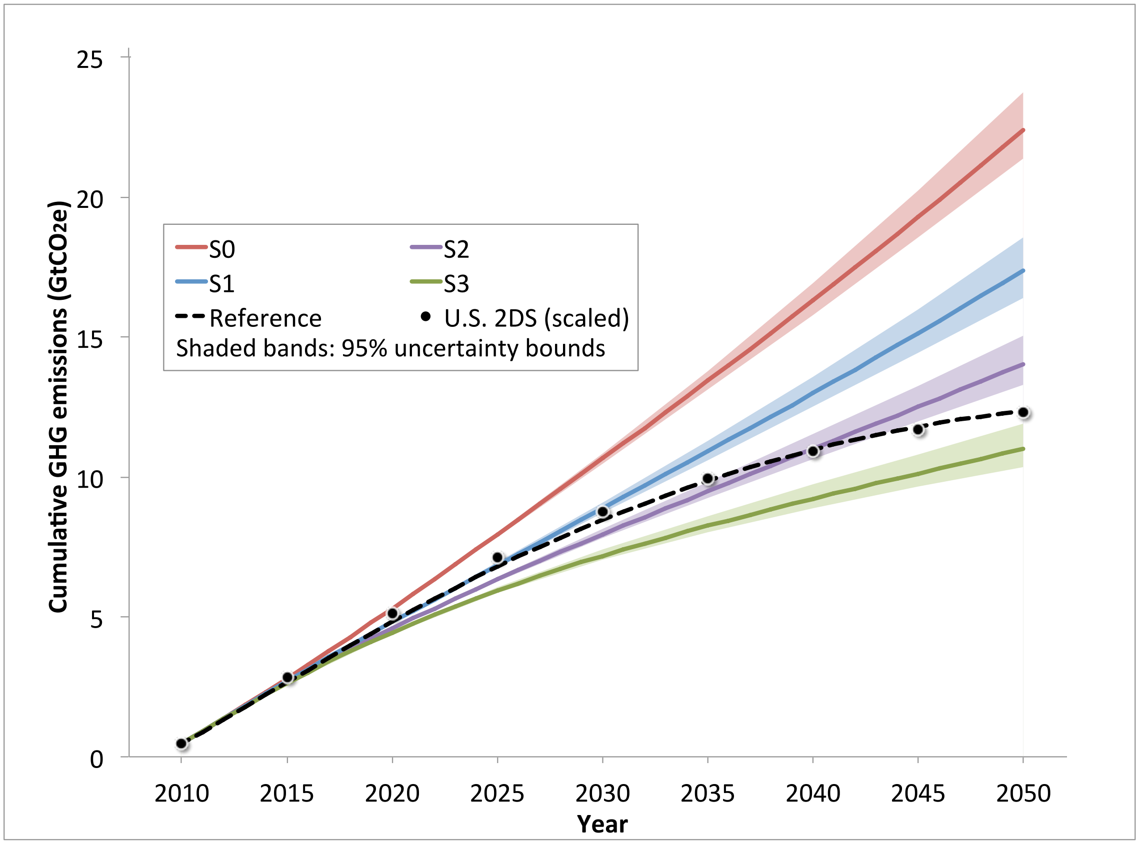
3.3 Cumulative GHG emissions of scenarios

As outlined in the Fifth Assessment of the Intergovernmental Panel on Climate Change, in order to stabilize global temperature rise at no more than 2°C by 2100, which is the primary goal driving international climate negotiations, cumulative global GHG emissions must remain within prescribed "budgets." (IPCC, 2013, 2014) To achieve this, all nations must take aggressive action, denoted by 2°C Scenario (2DS) emissions pathways (IEA, 2012) to curb global GHG emissions over the next 15 years (UNFCCC, 2009, 2010). Thus, it becomes critical to track and understand GHG emissions not just at some future point in time (e.g., 2020, 2030 or 2050), but cumulative emissions over time. It has been recognized for some time that cumulative GHG emissions are the principal determinant of climate change (e.g., Allen et al., 2009). However, Miller (2013) first suggested the idea of examining cumulative emissions in the context of California's GHG targets; this is also discussed in Morrison et al. (In review).

Figure 3 shows cumulative GHG emissions for each scenario, along with the reference and scaled 2DS emissions pathways for the U.S. (IEA, 2012).[7] For each scenario, 95% confidence interval bounds are shown as shaded bands. The reference and 2DS cumulative emissions pathways essentially lie on top of one another, as does S1 until 2025. S2 lies below the reference pathway through 2039±4, and S3 remains below it through 2050. The implication is that policies included in S2, if implemented as modeled, could reduce cumulative GHG emissions to the same level as a reference emissions reduction pathway through ~2040, whereas if all S3 policies were implemented, California could reduce cumulative emissions by more than the reference pathway through 2050, even without meeting the 2050 emissions target. However, additional policies would be needed to continue to keep cumulative emission below the reference target beyond 2050, and identifying those was beyond the scope of this study.

[7] The 2DS pathway was constructed as follows: U.S. absolute GHG emissions for the 2DS pathway suggested by IEA (2012) were normalized by dividing by 1990 U.S. emissions, then normalized data were multiplied by 1990 California GHG emissions, and integrated in 5-year steps to obtain scaled cumulative emissions.

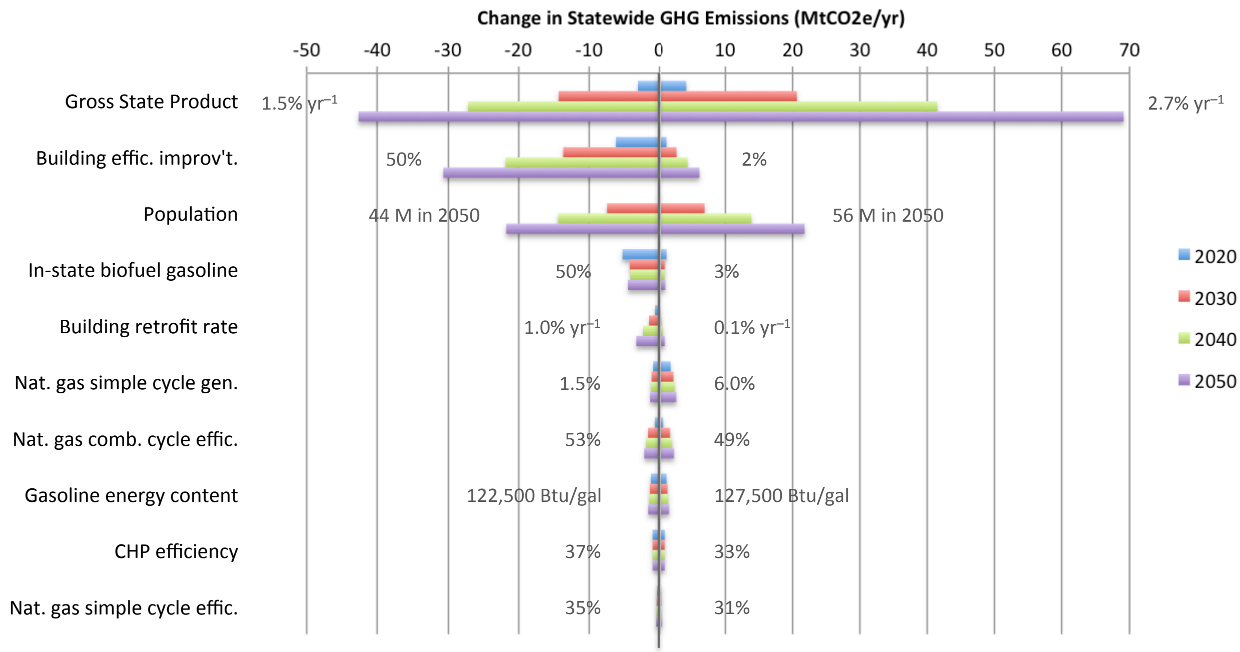
Figure 3. Cumulative GHG emissions for each scenario. Reference and scaled U.S. 2DS cumulative emissions pathways are also shown. Uncertainty bounds (95% confidence intervals) for each scenario are shown as shaded bands.



3.4 GHG emission sensitivities of uncertain parameters

Figure 2 and Figure 3 show the sensitivity of GHG emissions due to the combined uncertainty in all 10 parameters discussed in section 2.3. Figure 4 shows GHG sensitivities by decade to individual parameter uncertainties at lower and upper 95% confidence interval bounds. Population, GSP and building efficiency improvement are the dominant factors affecting GHG emissions uncertainty; other parameters are less important. Since population and economic growth are impossible to forecast precisely, they represent an irreducible source of uncertainty in GHG emissions projections.

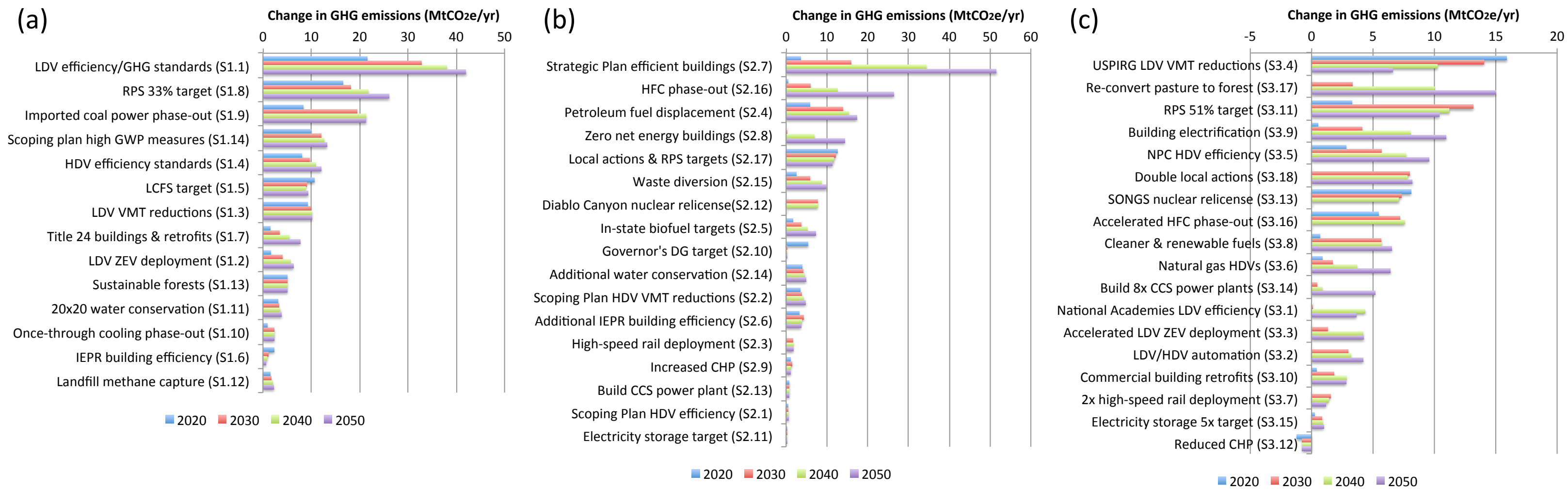
Figure 4. "Tornado" diagram showing sensitivity of statewide GHG emissions to each uncertain parameter varied in the analysis, by decade from 2020 to 2050.



3.5 GHG emission sensitivities of policies

The large differences found among the four scenarios modeled are the result of different policy combinations, but how much does each policy contribute to the whole? Figure 5 shows the sensitivity of GHG emissions for each individual policy by decade from 2020 to 2050, sorted in order from largest to smallest GHG impact for each scenario. Impacts range from >50 $MtCO_2e$ yr^{-1} (S2.7 in 2050) to <1 $MtCO_2e$ yr^{-1} (several policies in multiple decades). The average impact across all policies is 4 $MtCO_2e$ yr^{-1} in 2020, 6 $MtCO_2e$ yr^{-1} in 2030 and 8 $MtCO_2e$ yr^{-1} in 2050. Sections 3.5.1 and 3.5.2 further discuss the policies, both alone and in combination.

Figure 5. Changes in GHG emissions by decade (2020 to 2050) in the absence of each policy in scenario (a) S1, (b) S2 and (c) S3. For each scenario, policies are sorted in order from largest to smallest GHG impact in any decade.



3.5.1 *Largest-impact policies*

Five policies have individual GHG emissions impacts of >20 $MtCO_2e\ yr^{-1}$ in at least one decade between 2020 and 2050, summarized in Table 1. Each of these policies is discussed below. The three S1 policies are already underway and will almost certainly be fully implemented by the final target year (2020-2030 depending on the policy). The remaining policies are found in S2; the likelihood for implementation will be discussed below.

Table 1. Individual policies with GHG emissions impacts of >20 $MtCO_2e\ yr^{-1}$ in at least one decade

Policy description	Policy code	Increase in GHG emissions if policy not pursued ($MtCO_2e\ yr^{-1}$)			
		2020	2030	2040	2050
LDV efficiency/GHG standards	S1.1	21.6	32.8	38.0	42.0
RPS 33% target	S1.8	16.6	18.2	21.8	26.1
Imported coal power phase-out	S1.9	8.4	19.5	21.3	21.3
Strategic Plan efficient buildings	S2.7	3.6	15.9	34.3	51.5
HFC phase-out	S2.16	1.0	8.4	16.8	26.4

3.5.1.1 AB 1493 (Pavley) LDV efficiency/GHG standards (S1.1)

The Pavley Global Warming Bill of 2002 (AB 1493) serves to increase the fuel efficiency of new vehicles, raising on-road fleet-average efficiency relative to 2010 (~19 mpg) by more than 50% in 2030, and approximately doubling it by 2040. California's vehicle GHG emissions standards have been aligned with federal GHG and fuel economy standards of the EPA and NHTSA, respectively, and cover model years 2009-2025 (CARB, 2013b), so the effects of these savings are now being applied nationally. Since AB 1493 implementation began in 2009, it has already had a measurable effect on the LDV fleet. Therefore, even if S1.1 were disabled tomorrow, the fleet-average fuel efficiency of gasoline LDVs is still projected to increase; CARB estimates it would rise to 25 mpg by 2030 and remain approximately static thereafter (B. Chen, pers. commun., 2014).[8] Removing S1.1 increases GHG emissions by 22 $MtCO_2e\ yr^{-1}$ in 2020,[9] 33 $MtCO_2e\ yr^{-1}$ in 2030, and >40 $MtCO_2e\ yr^{-1}$ in 2050.

3.5.1.2 Renewable Portfolio Standard (RPS) 33% target (S1.8)

The RPS was first introduced in 2002 as a 20% target (California Senate Bill—SB—1078), but has

[8] AB 1493 standards are divided into "Pavley I" and "Pavley II," corresponding to vehicle model years 2009-2016 and 2017-2025, respectively. As the 2014 vehicle fleet already strongly reflects the impact of Pavley I, for modeling purposes, disabling S1.1 only removed the effects of Pavley II. Therefore, fuel efficiencies of new vehicles would still rise through 2016 due to Pavley I standards (CARB, 2014d), with impacts on fleet average fuel efficiency through ~2030, since vehicle lifetimes are ~15 years (B. Chen, pers. commun., 2014).

[9] These reductions are lower than the 32 $MtCO_2e\ yr^{-1}$ estimated in the CARB (2008) Scoping Plan that included the effects of both Pavley I and II. However, removing only Pavley II, as done in the current estimate, is probably a more accurately reflection of the impact of disabling S1.1. If instead efficiencies are frozen at 2010 levels, approximating the removal of both Pavley I and II, the impact would be 30 $MtCO_2e\ yr^{-1}$ in 2020, closer to the CARB estimate.

undergone several accelerations (SB 107, SB 2, and SP E-3) and currently requires that 33% of retail electricity sales be supplied by renewable sources in 2020 (CARB, 2013c). Large hydro is not included in the definition of "renewable" for this policy, nor is most decentralized solar photovoltaic (PV) because it is considered "on-site" generation and additional to the RPS target.[10] However, 3.0 GW of generation are included from the California Solar Initiative (SB 1) and related programs (GoSolarCA, 2014) by 2022. Currently, the state stands at approximately 20% renewables (CPUC, 2014). If S1.8 were removed and the percentage of renewable generation remained fixed at current levels, emissions in 2020 would be 17 $MtCO_2e$ yr^{-1} higher, increasing to 18 $MtCO_2e$ yr^{-1} in 2030 and 26 $MtCO_2e$ yr^{-1} by 2050.

3.5.1.3 SB 1368 imported coal power phase-out (S1.9)

In response to SB 1368, California is currently in the midst of phasing out reliance on imported coal power, with 3.9 GW of older, inefficient plants reaching contract terminations by 2030 (CCEF, 2012; CEC, 2014). CALGAPS assumes that these assets would be replaced with natural gas combined-cycle power. If S1.9 were abolished and coal plants remained in operation, emissions would be 8 $MtCO_2e$ yr^{-1} higher in 2020, growing to 20-21 $MtCO_2e$ yr^{-1} in 2030-2050. EPA's proposed GHG emissions standards for new fossil power plants, which would effectively eliminate new coal plants that do not employ CO_2 capture and sequestration (CCS) technology, could have similar impact nationally (EPA, 2014a).

3.5.1.4 CPUC Strategic Plan for efficient buildings (S2.7)

The CPUC Strategic Plan's aspirational targets for efficient buildings (CPUC, 2008) are meant to improve the efficiency of both new and existing buildings in the residential and commercial sectors. (Existing commercial buildings are not included in these aspirational targets, but the effect of including them was modeled in S3.10). The plan calls for ambitious efficiency targets for residential buildings and commercial new construction, with improvements between 40% and 60% relative to 2010 levels. However, it does not specify the rate of retrofits. For modeling purposes, it was assumed that 3% of residential building stock per year was retrofitted starting in 2020, so that every existing building was affected before 2050.[11] Without this policy, emissions would be 4 $MtCO_2e$ yr^{-1} higher in 2020, growing to 16 $MtCO_2e$ yr^{-1} in 2030 and >50 $MtCO_2e$ yr^{-1} by 2050—the largest long-term impact of any policy modeled here.

3.5.1.5 Hydrofluorocarbon (HFC) gas phase-out (S2.16)

HFCs were developed to replace ozone-destroying chlorofluorocarbons, but all these chemicals are

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[10] Note that on-site generation is typically not included in retail electricity sales. However, for modeling purposes, gross electricity consumption (which includes such generation) was used as the basis for estimating RPS targets, but as noted in the text, most solar PV was not included in this target.

[11] However, this rate was reduced after 2030 to avoid retrofitting more than 100% of the remaining building stock before 2050. The 100% target represents an aspirational goal of the policy. In reality, 100% of buildings would not be retrofitted, but the efficiency improvement target can be interpreted as an average impact per building. Therefore, some buildings would have a larger efficiency improvement, while others (e.g., those not retrofitted) would have zero improvement. Another way of representing the policy (but not what was chosen for this study) is to have a fixed percentage of "untouched" buildings retrofit each year, so that over time the fraction of buildings that have been retrofit approaches 100% without ever reaching (or exceeding) the total. Such an approach would produce similar results from a GHG perspective.

also potent GHGs. The U.S. and China have recently agreed to phase-out HFCs and persuade other countries to do so also, beginning gradually in 2020 and leading to full elimination by 2050 (WP, 2013); moreover, recent EPA proposed rules (EPA, 2014b, 2014c) provide an aggressive implementation plan for achieving much of this phase-out nationally. For modeling purposes, a modest 2.5% reduction was assumed in 2020 (including SP H-6 measures not included in S1.14), increasing to 25% in 2030 and 50% in 2040.[12] If this phase-out were not pursued, emissions in California would be little changed in 2020, but would be 8 $MtCO_2e\ yr^{-1}$ higher in 2030, increasing to 26 $MtCO_2e\ yr^{-1}$ by 2050.

3.5.2 Policy combinations

In addition to the five policies discussed in section 3.5.1, other policies in combination offered similar or greater levels of GHG reduction. Table 2 lists policy combinations grouped by sector, each of which confers emissions reductions of ≥20 $MtCO_2e\ yr^{-1}$ in at least one decade between 2020 and 2050. For policies operating in different sectors, the GHG impacts will typically have no interaction with each other; however, for policies affecting the same sector, there is a potential for interaction. For instance, if one policy affects the amount of fuel consumed (such as a vehicle efficiency standard) while another affects the GHG content of fuels (such as a biofuel policy), these interactions tend to lessen the impact of each individual policy. Policies can also work at cross-purposes (see section 3.5.2.4). In the tables below, the impact of policy combinations on GHG emissions are shown both individually (e.g., with only one policy disabled at a time), as well as in aggregate (e.g., with all policies in the group disabled). Each policy combination is discussed below in more detail.

Table 2. GHG reduction benefits of policy combinations

Policy description	**Policy code**	**Increase in GHG emissions if policy not pursued ($MtCO_2e\ yr^{-1}$)** 2020	2030	2040	2050
Transportation sector					
Light-duty zero-emission vehicles					
LDV ZEV deployment	S1.2	1.7	4.1	5.7	6.3
Accelerated LDV ZEV deployment	S3.3	0.0	1.3	4.2	4.2
Vehicle-miles traveled reductions					
LDV VMT reductions	S1.3	9.3	9.8	10.1	10.2
Scoping Plan HDV VMT reductions	S2.2	3.5	3.8	4.3	4.8
USPIRG LDV VMT reductions	S3.4	15.9	14.0	10.3	6.6
Efficiency improvements					
HDV efficiency standards	S1.4	8.1	9.6	10.9	12.1
Scoping Plan HDV efficiency	S2.1	0.4	0.5	0.5	0.6
National Academies LDV efficiency	S3.1	0.0	0.1	4.4	3.6
NPC HDV efficiency	S3.5	2.8	5.7	7.7	9.6
Vehicle automation					
LDV/HDV automation	S3.2	0.0	0.0	3.0	3.2
Natural gas vehicles					
Natural gas HDVs	S3.6	0.9	1.9	4.1	6.4
High-speed rail					
High-speed rail deployment	S2.3	0.0	1.7	1.8	1.8

[12] S3.16 represents a more aggressive HFC phase-out schedule; see section 3.5.2.5.

Doubled high-speed rail deployment	S3.7	0.0	1.5	1.4	1.2
Combined total (relative to S3)[a]		**41.6**	**56.1**	**71.3**	**81.9**
Fuels sector					
LCFS target	S1.5	10.6	9.0	8.8	9.3
Petroleum fuel displacement	S2.4	5.8	13.9	15.3	17.3
In-state biofuels targets	S2.5	1.6	3.7	5.2	7.3
Clean petroleum, renewable fuels	S3.8	0.7	5.9	6.1	6.5
Combined total (relative to S3)[a]		**16.1**	**25.3**	**23.0**	**21.1**
Buildings sector					
IEPR building efficiency	S1.6	2.3	1.1	0.8	0.6
Title 24 new buildings & retrofits	S1.7	1.5	3.4	5.5	7.7
Additional IEPR building efficiency	S2.6	3.2	4.3	3.8	3.6
Strategic Plan zero net energy buildings	S2.8	0.0	0.2	7.0	14.4
Building electrification	S3.9	0.5	4.1	8.1	11.0
Commercial building retrofits[b]	S3.10	0.4	1.8	2.8	2.8
Combined total (relative to S3)[a]		**7.9**	**17.9**	**30.7**	**35.9**
Electricity sector					
Once-through cooling					
Once-through cooling phase-out	S1.10	1.0	2.3	2.3	2.3
Combined heat and power					
Increased CHP	S2.9	1.1	1.5	1.1	1.1
Decreased CHP	S3.12	-1.2	-0.8	-0.8	-0.8
Distributed generation					
Governor's target	S2.10	5.4	0.0	0.0	0.0
Nuclear power					
Diablo Canyon nuclear relicense	S2.12	0.0	7.7	7.7	0.0
SONGS nuclear relicense/replacement	S3.13	8.1	7.5	7.5	0.0
CO_2 capture and sequestration					
Build CCS power	S2.13	0.8	0.7	0.7	0.7
Build 8x CCS power	S3.14	0.0	0.7	1.3	5.2
Renewable Portfolio Standard					
RPS 51% target	S3.11	3.3	13.4	11.6	10.4
Electricity storage					
Electricity storage target	S2.11	0.2	0.2	0.2	0.2
Electricity storage 5x target	S3.15	0.3	0.9	0.9	1.0
Combined total (relative to S3)[a]		**20.1**	**33.7**	**32.4**	**19.9**
Non-energy sector and other					
Water and waste reduction					
20x20 water conservation	S1.11	3.2	3.3	3.6	3.9
Additional water conservation	S2.13	4.0	4.2	4.5	4.9
Landfill methane capture	S1.12	1.5	1.7	2.0	2.3
Waste diversion	S2.14	2.5	5.9	8.7	9.8
Combined subtotal (relative to S2)[a]		**11.0**	**15.0**	**18.7**	**20.7**
Forests					
Sustainable forests	S1.13	5.0	5.0	5.0	5.0
Re-convert pasture to forest	S3.17	0.0	3.3	10.0	15.0
Combined subtotal (relative to S3)[a]		**5.0**	**8.3**	**15.0**	**20.0**
High GWP gases					
Scoping Plan high GWP measures	S1.14	9.9	12.0	12.6	13.2
Accelerated HFC phase-out	S3.16	5.5	7.2	7.6	0.0

Combined subtotal (relative to S3)[a]		**15.4**	**19.2**	**20.2**	**13.2**
Local actions					
Local actions & RPS targets	S2.17	12.6	12.2	11.7	11.3
Double local actions	S3.18	0.0	8.0	7.8	8.2
Combined subtotal (relative to S3)[a]		**12.6**	**20.2**	**19.7**	**19.4**
Combined total (relative to S3)[a]		**44.1**	**62.0**	**72.8**	**72.4**

[a] Individual policy GHG savings do not necessarily sum to combined totals, due to different reference points (S1, S2 or S3) for each policy, and interactive effects among policies that in some cases increase or decrease total GHG emissions. The combined totals presented here are all calculated starting from the S3 baseline and explicitly removing all listed policies.
[b] Residential zero net energy retrofits were also included in this policy, but do not contribute to GHG reductions because they are subsumed in the 12 GW distributed generation goal (S2.10).

3.5.2.1 Transportation sector

Aside from the LDV efficiency/GHG standards (S1.1), a number of transportation policies spanning the LDV, HDV and high-speed rail sub-sectors are included across S1-S3. These policies encompass higher numbers of LDV ZEVs (S1.2, S3.3), reductions in VMT (S1.3, S2.2, S3.4), vehicle efficiency improvements (S1.4, S2.1, S3.1, S3.5), vehicle automation (S3.2), fuel switching to natural gas HDVs (S3.6), and high-speed rail deployment (S2.3, S3.7). Some other policies, including electrification of ships while in port (CEPA, 2014), were included in S1 but were not explicitly listed due to their small GHG impacts (~0.2 $MtCO_2e\ yr^{-1}$; CARB, 2008). Note that policies focused on changing the GHG content of fuels are covered separately in section 3.5.2.2.

The dominant contributions by 2030 come from policies of decreased LDV VMT (S1.3, S3.4), increased HDV efficiency (S1.4, S3.5) and LDV ZEV deployment (S1.2). Perhaps surprising is the relatively modest impact from ZEV policy, but Governor Brown's goal of 1.5 million ZEVs by 2025 (CARB, 2012) is only 6% of LDV stock,[13] yet represents a dramatic increase from today (100,000 cumulative ZEVs sold between December 2010 and August 2014; PEV Collaborative, 2014). Also, the simultaneous deployment of policies to increase fuel efficiency, decrease VMT and decrease the GHG intensity of gasoline lessens the impact of switching to ZEVs in later years compared to today.

While the contribution from each policy individually is <16 $MtCO_2e\ yr^{-1}$ in any decade, in combination they result in much larger GHG reductions. Removing the effects of all policies would result in higher emissions relative to S3 of 42 $MtCO_2e\ yr^{-1}$ in 2020, 56 $MtCO_2e\ yr^{-1}$ in 2030 and >80 $MtCO_2e\ yr^{-1}$ in 2050. The combined impact is greater than S1.1, or any single "top five" policy.

3.5.2.2 Fuels sector

Several policies included in S1-S3 lower the GHG emissions from fuels. The Low Carbon Fuel Standard (LCFS) policy (S1.5) is an important contributor, increasing the biofuel energy content of liquid fuels by 18% in 2020. Two other policies, in-state biofuels targets (S2.5) and efforts to further reduce GHG emissions from petroleum and increase the renewable content of natural gas and jet fuel (S3.8), also contribute to GHG reductions. But S2.4, which results in a 20% petroleum displacement in 2020, increasing to 30% in 2030, provides the largest GHG emissions benefit of any

[13] The policy was modeled as increasing to 11% (3.0 million) ZEVs in 2035, leveling off to 13% by 2050, based on CARB inputs (J. Cuningham, pers. commun., 2013).

fuel policy modeled, amounting to 14 $MtCO_2e\ yr^{-1}$ in 2030 and 17 $MtCO_2e\ yr^{-1}$ by 2050. Combined, these four policies, if foregone, would increase GHG emissions 16 $MtCO_2e\ yr^{-1}$ in 2020, and >20 $MtCO_2e\ yr^{-1}$ in 2030 and beyond.

3.5.2.3 Buildings sector

Aside from the CPUC Strategic Plan for efficient buildings (S2.7), several other building policies, including Integrated Energy Policy Report (IEPR) building efficiency savings (S1.6, S2.6), Title 24 new buildings and retrofits (S1.7, S3.10), the CPUC Strategic Plan for zero net energy buildings (S2.8),[14] and building electrification (S3.9), when combined create a powerful GHG emissions reduction benefit of 18 $MtCO_2e\ yr^{-1}$ in 2030 and >30 $MtCO_2e\ yr^{-1}$ in 2040-2050, approaching the benefits conferred by S2.7. The building electrification and zero net energy policies are among the most impactful in the long-term, providing GHG benefits of >10 $MtCO_2e\ yr^{-1}$ each by 2050.

3.5.2.4 Electricity sector

The RPS 33% target (S1.8) and imported coal power phase-out (S1.9) are important electricity sector policies, but 11 other policies including once-through cooling power phase-out (S1.10), changes in combined heat and power (CHP) (S2.9, S3.12), relicensing of nuclear power (S2.12, S3.13), increased distributed generation (S2.10), CCS power plant deployment (S2.13, S3.14), a higher (51%) RPS target (S3.11), and electricity storage targets (S2.11, S3.15) can together confer large benefits, amounting to >20 $MtCO_2e\ yr^{-1}$ in all decades, and >30 $MtCO_2e\ yr^{-1}$ in 2030 and 2040. These GHG changes exceed those of either S1.8 or S1.9 through 2040.

The nuclear policies alone—the relicensing of Diablo Canyon (S2.12) and relicensing/replacement of San Onofre Nuclear Generating Station (SONGS) (S3.13)—each account for 7-8 $MtCO_2e\ yr^{-1}$ of GHG benefits in 2030 and 2040. That both policies assume retirements in 2046 (with the model replacing resulting shortfalls with natural gas combined-cycle generation) are the reason why emissions benefits from these 11 electricity policies are lower in 2050 than in earlier years. The RPS 51% target (S3.11) contributes most to the total benefit (>10 $MtCO_2e\ yr^{-1}$) in 2030 and beyond.

The impact of CCS technology on emissions reduction was necessarily modest, because the policies modeled (S2.13, S3.14) did not propose large-scale expansion of CCS technology, but simply small augmentations to existing electricity generation that would be dominated by renewables, with smaller amounts of natural gas, large hydro and nuclear. S2.13 in particular modeled the addition of a single 300 MW CCS facility in 2020, reflecting current plans in Southern California (HECA, 2013). The more ambitious S3.14 models an eight-fold increase in CCS capacity by 2050, largely to offset the loss of Diablo Canyon after 2045.

Note that while S2.9 increases CHP capacity, S3.12 decreases it. This latter policy reflects a trade-off between CHP and other generation resources, and was chosen to be included due to the overall modest effect of S2.9 on emissions. Emissions from CHP are higher than the natural gas combined-cycle technology they are modeled to replace, and are only barely offset by reductions in natural gas-based heating. Therefore, for S3, CHP capacity was reduced in order to make room in the generation mix for more effective GHG reduction technologies. This is an example of policies

[14] Residential zero net energy retrofits were not included in the CPUC Strategic Plan (S2.8) so they were added in S3.10; however, these retrofits provided no additional GHG benefit because the assumed solar PV required to offset demand from these buildings was subsumed in the 12 GW distributed generation target (S2.10).

operating at cross-purposes, the resolution of which was a modeling choice and may not represent the response of policymakers.

3.5.2.5 Non-energy sector and other

Each of the following groupings of non-energy policies reduces emissions by ≥20 $MtCO_2e\ yr^{-1}$ in at least one decade between 2030 and 2050:

Water and waste. SB X7-7 ("20x20") is a water conservation policy to reduce per capita consumption 20% in the residential and commercial sectors by 2020 (S1.11). SP W-1 through W-4 (S2.13) reduce water use by an estimated additional 26% per capita water savings in 2020. (Water conservation reduces GHG emissions by reducing the energy required to treat, move and heat water.) SP RW-1 (S1.12) increases landfill methane capture, which was equivalent to 10% reduction in landfill GHG emissions. Finally, AB 341 (S2.14) diverts 75% of organic matter from landfills in 2020, and 100% by 2035.

Forests. SP F-1, called "sustainable forest management" (S1.13), reduces GHG emissions by 5 $MtCO_2e\ yr^{-1}$ beginning in 2020. S3.17 expands these savings by assuming 1.6 million acres of California pasture are re-converted to forest between 2015 and 2050, saving an additional 3 $MtCO_2e\ yr^{-1}$ in 2030 and 15 $MtCO_2e\ yr^{-1}$ by 2050.

High GWP gases. Besides the HFC phase-out policy (S2.16), there are a number of Scoping Plan measures (H-1 through H-6) aimed at reducing high GWP gas emissions (S1.14). In addition, S3.16 phases out HFCs more quickly than S2.16, reaching 30% reduction in 2020, 55% in 2030 and 80% in 2040.

Local actions. Many city and county governments in California are pursuing more aggressive GHG reduction targets than prescribed by statewide policies. Among these targets are higher local RPS targets and additional actions including more aggressive local building codes, increased waste diversion, and other activities. S2.17 collectively represents these policies, using GHG estimates from CARB (R. McCarthy, pers. commun., 2013). S3.18 assumes double the level of local reduction activities by 2030, but does not include an increase in the RPS target since the S3 statewide target (S3.11) is also higher.

These 10 assorted policies, if foregone, would result in 44 $MtCO_2e\ yr^{-1}$ higher emissions in 2020 relative to S3, increasing to 62 $MtCO_2e\ yr^{-1}$ in 2030 and >70 $MtCO_2e\ yr^{-1}$ in 2040-2050. Savings magnitudes in 2020-2040 are larger than from the transportation sector, which otherwise comprises the policy combination with the largest GHG emissions impact (see section 3.5.2.1).

3.6 Comparison to previous studies

Here results are briefly compared to those of previous studies. Note that Morrison et al. (In review) makes more detailed comparisons among most of these studies.

As noted in section 1, the aim of most previous studies was to meet the 80% GHG emissions reduction target in 2050, whereas the current study explicitly avoided this target, opting instead to explore where existing and potential policies could lead. As a result, and perhaps unsurprisingly, the current study does not meet the 2050 target in any scenario. The S1 emissions pathway is roughly in line with those of most other studies' scenarios through 2030, though in later years, S1 emissions increase whereas other studies' emissions trajectories continue downward toward the

2050 target. The exception is the "Business as Usual" scenario in Yang et al. (2014) whose emissions closely parallel those of S1. The reason for the difference, as explained in section 3.2, is that policies in S1 are largely silent after 2030; as a result, no further GHG reductions occur, with population and GSP growth eventually driving emissions upward. Note that some studies (CCST, 2011; Greenblatt and Long, 2012; ECF, 2010) did not explicitly model emissions pathways, but focused on emissions in 2050.

The studies share many of the same conclusions, including the need for increased energy efficiency, reduced GHG intensities of both fuels and electricity, and a shift away from direct fuel combustion and toward electricity (particularly in transportation). ECF (2010) also emphasized district heating, solar water heating, industrial CCS technologies, landfill methane capture, improved agricultural and livestock management, and biological CO_2 sequestration (mainly in forests); a number of these approaches were also modeled in some of the other California studies as well as in the current study.

For S2, emissions are lower than those of most other studies' scenarios through 2030, after which there is an abrupt departure, with S2 emissions remaining roughly constant at 300 $MtCO_2e\ yr^{-1}$ while emissions in other studies continue to decrease, passing the S2 emissions level on their way to the 2050 target. As for S1, the reason for this difference is largely because of policy silence beyond 2030. However, the GHG-Step and GHG-Line scenarios in Yang et al. (2014) are about as aggressive as S2 in the earlier years, following a similar emissions pathway through ~2030-2035.

A detailed sector-by-sector comparison through 2030 indicates a number of similar policy assumptions between S2 and the Yang et al. scenarios, but also a number of differences, which presumably stem from the economic assumptions that drive the optimization in the latter scenarios, whereas S2 is constrained by existing policy targets and assumptions. For instance, in the transportation and fuels sectors, S2 contains more aggressive fuel demand reductions—in keeping with policy targets—than in Yang et al., but less aggressive LDV efficiency improvements, and similar levels of HDV fuel efficiency, market shares of ZEVs, demand for biofuels, and fuel GHG intensities. In the stationary buildings sector, S2 contains significantly less aggressive improvements in both residential and commercial building efficiency—again, consistent with policy targets—than in Yang et al., and in the industrial sector, Yang et al. aggressively switches from fossil fuel to electric heating, whereas no CALGAPS scenario assumed any industrial fuel switching. For the electricity sector, S2 has lower electricity demand, mainly because it lacks the aggressive industrial electrification present in Yang et al. While the RPS target and coal phase-out assumptions in S2 are similar to that of Yang et al., S2 has more decentralized solar PV (because this technology is assumed for meeting zero net energy building targets), nuclear generation (Diablo Canyon is explicitly extended to 2045) and CHP (the Governor's target is explicitly met), and therefore less natural gas simple- and combined-cycle generation than in Yang et al. Also, Yang et al. did not model emissions outside the energy sector, but assumed they were reduced in line with energy-sector reductions; while convenient to model, this has little technical justification. Overall, however, GHG intensities are coincidentally similar—a ~50% reduction from the 2010 level.

Scenario S3 displays a more aggressive early GHG emissions reductions pathway than any previous study, but nonetheless other studies' emissions fall below it beyond ~2035. The likely explanation for this distinction is that most other studies perform (or assume) an economic optimization, which tends to produce less aggressive reductions in earlier years due to the discounting of future expenditures, making delayed implementation more economical. However, as discussed in section 3.3, early implementation of emissions reductions can lead to much lower cumulative emissions, which in the case of S3 is sufficient to fall below a 2050 cumulative emissions target based on the reference emissions pathway (see Figure 3). None of the other studies' emissions trajectories achieve lower cumulative emissions than S3 (Morrison et al., In review). That other studies achieve lower annual emissions in 2050, however, indicates that those scenarios are ultimately more aggressive than S3 in the long term. Since S3 did not attempt to reach the 80% reduction target in 2050, nor did the CAPGAPS model assess the economics of the policies it modeled, it is not known whether S3 is more or less cost-effective than one that reaches an 80% reduction level in 2050.

3.7 Shortcomings and future improvements

The approach taken in this paper was to evaluate GHG impacts of specific policies between 2010 and 2050, both alone and in combination. Policies were grouped into one of three scenarios, which loosely corresponded to the level of certainty of implementation. All policies were assumed to be technically feasible, but S1 policies carried an additional assumption that economic, political and social barriers to implementation were fairly low, and S2 policies were assumed to have slightly higher barriers in one or more factors. By contrast, S3 policies were presumed to potentially have more significant barriers.

However, beyond this simple, qualitative categorization, specific barriers to implementation were not evaluated. The lack of economic analysis is perhaps the most significant shortcoming of this paper; political and social factors, while also important, are more difficult to evaluate. The CALGAPS model also had several technical shortcomings. All of these issues could be addressed in future work, and some suggested improvements are described below.

3.7.1 Inclusion of economics

The lack of economics is a key drawback of CALGAPS. Ideally, full cost representation including macroeconomic feedbacks could be added, but such a model would also be significantly more complicated; dedicated models are now used for this purpose (e.g., Roland-Holst, 2008). A less challenging improvement would be to add cost estimates of incremental policy changes to the model, enabling it to compare costs of various pathways, perhaps using data from PATHWAYS (Williams et al., 2012) or CA-TIMES (Yang et al., 2014).

3.7.2 Model sophistication

Given time and platform constraints, CALGAPS was necessarily simplified in a number of key areas (described more fully below) and could be improved.

The electricity model employed in CALGAPS, while adequate for current purposes, only satisfies annual energy requirements without consideration of temporal or spatial variations in supply and demand, reliability constraints, or cost, and requires manual adjustment to adapt to new assumptions. Including a sophisticated electricity sector model such as employed in PATHWAYS, CA-TIMES or SWITCH (Wei et al., 2013; Nelson et al., 2013) would make the overall model much more complicated and time-consuming to execute, but a simpler, parameterized version of one of these electricity-sector models that addresses even some of these shortcomings would be a significant improvement.

For the residential and commercial buildings sectors, more sophisticated stock turnover models (e.g., with annual cohorts whose efficiencies change over time) would improve the representation of energy use, but to be effective would require more detailed energy-use data (see section 3.7.3).

The representation of the LDV and HDV transportation sub-sectors is more accurate in CALGAPS, but uses outputs from CARB's Vision model (CARB, 2012) and was therefore unable to rerun the model in response to different policy scenarios. An improvement would be to construct simplified stock turnover versions of the LDV and HDV Vision models, similar to the buildings sectors. Sufficient data is already available from CARB.

The representation of other transportation sub-sectors is much cruder in CALGAPS, and could be improved in a similar fashion using CARB's Vision models for those sectors, although they are less sophisticated than the LDV/HDV models.

The industrial sector is another area ripe for improvement; simple energy-intensity trends are currently used to project future energy use, whereas the sector consists of a diverse set of industries whose energy use and GHG emissions may change over time in complex ways. A disaggregation of the sector by major end use, with projections based on drivers other than GSP, would be a beneficial improvement. Several existing models, including PATHWAYS and CA-TIMES, could provide necessary inputs.

A more sophisticated representation of high GWP gases based on usage by sector would also be a useful improvement; CARB's detailed unpublished model (G. Gallagher, pers. commun., 2013) could be parameterized to provide the necessary inputs, though if HFCs are phased out as modeled in S2-S3, this sector may be less critical.

Finally, the representation of agriculture, waste and forest sectors was also very simplistic, and could benefit from more detailed treatment, but an appropriate starting model has not been identified.

3.7.3 Additional data

CALGAPS lacked data in some key areas, particularly buildings energy use disaggregated by building stock type and/or vintage. Also, transportation sector data used are not entirely self-consistent (see discussion in section 3.1), and less data is available outside the LDV/HDV sectors. Increasing the sophistication of other sectors as described in section 3.7.2 would also require more detailed data.

3.7.4 Flexibility and ease of use

CALGAPS could benefit from additional controls and interface improvements to make it more user-friendly. While implementation in Microsoft Excel has advantages (easy to construct, edit and share), it also limits how significantly the model can be modified, debugging is more challenging, and execution time can be slow if additional computation is required. Therefore, a long-term benefit would be to implement the model in a more versatile programming environment.

4 Conclusions and Policy Implications

CALGAPS was constructed, validated, and used to project California's GHG emissions from 2010 to 2050. Four scenarios were developed to explore a range of future policy options: Committed Policies (S1), Uncommitted Policies (S2), Potential Policy and Technology Futures (S3), and Counterfactual (S0), which assumed no policies included in S1. In a sensitivity study, the GHG impact of removing each policy individually was calculated, as well as the impact of removing groups of related policies. The overall model uncertainty was characterized using Monte Carlo simulation to explore variations in key uncertain parameters. Comparisons of results were made to previous studies, and shortcomings of the paper and possible remedies were discussed.

Among S1-S3, GHG emissions in 2020 span 410^{+5}_{-8} (S1) to 328^{+5}_{-11} (S3) $MtCO_2e\ yr^{-1}$, all below the AB 32 target of 427 $MtCO_2e\ yr^{-1}$, indicating that existing state policies will likely allow California to meet its target. By 2030, emissions range from 404^{+24}_{-22} (S1) to 230^{+17}_{-19} (S3) $MtCO_2yr^{-1}$, which span the reference pathway level of 312 $MtCO_2e\ yr^{-1}$ by more than ±80 $MtCO_2e\ yr^{-1}$. This range indicates that the choice of a mid-term (2030) GHG emissions target will strongly affect which state policies will be needed to achieve it. CARB's proposed 2030 target, which that agency emphasizes is achievable, straddles the S2 and S3 emissions levels; many of the policies included in S2-S3 would likely be needed if the state sets a mid-term target near this level.

For 2050, all scenarios fall well short of the 85 $MtCO_2e\ yr^{-1}$ target, ranging from 455^{+80}_{-58} (S1) to 175^{+52}_{-36} (S3) $MtCO_2e\ yr^{-1}$, so additional policies will likely be needed to allow the state to meet this long-term goal. In terms of cumulative GHG emissions, however, S2 and S3 could remain below the reference target pathway through ~2040 and beyond 2050, respectively, suggesting that a policy aimed at specifying a cumulative GHG emissions target may be easier to achieve by 2050. (Annual GHG emissions would need to continue to fall beyond 2050, however.) Such a target may also be more relevant for international climate goals.

Behind these scenarios is an innovative and comprehensive set of policies that collectively reduce statewide GHG emissions very significantly. The most effective individual policies—those that would each result in >20 $MtCO_2e\ yr^{-1}$ higher GHG emissions in one or more decades between 2020 and 2050 if omitted—are the AB 1493 (Pavley) LDV efficiency/GHG standards (S1.1), the CPUC Strategic Plan efficient buildings targets (S2.7), the RPS 33% target (S1.8), the SB 1368 imported coal power phase-out (S1.9) and an HFC phase-out (S2.16). However, combinations of other policies are also important for GHG reductions, and span the transportation, fuels, buildings, electricity, and non-energy sectors (including water and waste, forests, high GWP gases, and local actions). If omitted, these policy combinations would each increase emissions by ≥20 $MtCO_2e\ yr^{-1}$ in at least one decade between 2020 and 2050. Taken together (e.g., the S3 scenario), these 49 policies amount to reductions relative to S0 of ~200 $MtCO_2e\ yr^{-1}$ in 2020, increasing to ~300 $MtCO_2e\ yr^{-1}$ in 2030 and ~450 $MtCO_2e\ yr^{-1}$ by 2050, comparable to today's total GHG emissions.

In comparison to previous studies, S1 emissions are generally similar to those reported by others through 2030, but in later years, most other studies' emissions trajectories continue downward toward the 2050 target while S1 emissions increase slightly; this difference is due to the absence among most S1 policies of additional targets beyond 2030, and the steady increase in state population and GSP driving higher energy use. Scenario S2 emissions are generally lower than those of other studies through ~2030 with the exception of Yang et al. (2014), though there are a number of differences in assumptions between the scenarios, and Yang et al.'s scenarios meet the 2050 target whereas S2 does not. Scenario S3 achieves lower GHG emissions than that of any other reported study through 2035, but still falls short of the 2050 emissions target, unlike in most other studies. Cumulative emissions in S3, however, are lower than in any other study, and such a pathway of early emissions reductions may confer important climate benefits as well as offer compliance flexibility. Therefore, policymakers both in California and elsewhere might consider establishing cumulative emissions budgets in lieu of annual emissions targets when setting future policy targets.

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Appendix A. Model Overview

CALGAPS is organized into the following categories:

1. Control panels: current scenario specification, key parameters for each policy
2. General inputs: basic drivers, unit conversion, some emission factors
3. Data inputs by sector
4. Scenario calculations by sector
5. Summary results: energy use, GHG and criteria pollutant emissions
6. Confidence analysis: sensitivities, uncertainty analysis, model validation

Basic drivers of demand included population (DOF, 2013) and GSP from historical data (DOC, 2014) and state estimates (C. Kavalec, pers. commun., 2013; J. Cunningham, pers. commun., 2013). Section 2.1 in the main text describes the sequence of calculations depicted in Figure 1. GHG emissions included CO_2, CH_4, N_2O, and high GWP gases; excepting the latter, GHGs were not tracked separately. CALGAPS calculates impacts of four scenarios one at a time. Parameter uncertainty impacts are modeled using Monte Carlo simulation, configured for 10 variables and 1,000 iterations. Individual policy GHG sensitivities were calculated by manual adjustment of policy parameters and subtracting results from the appropriate reference scenario.

Major sectors are described below. More details and references can be found in the Supplemental Information.

A.1. LDVs and HDVs

LDVs were divided into 10 vehicle/fuel types [conventional gasoline, hybrid gasoline, plug-in hybrid gasoline, electric, hydrogen, 85% ethanol (E85), conventional diesel, hybrid diesel, plug-in hybrid diesel, natural gas]. HDVs were divided into eight vehicle/fuel types (all LDV except plug-in hybrid gasoline and E85) and three vehicle classes (in-state heavy heavy-duty, out-of-state heavy heavy-duty, and medium heavy-duty). CARB (2012), supplemented by estimates (J. Cunningham, pers. commun., 2013), provided stock market shares, energy use, VMT and criteria pollutant emissions. Scenarios can customize these parameters but CALGAPS cannot calculate stock rollovers, only changes in stock.

A.2. Other transport

CARB (J. Cunningham, pers. commun., 2013) supplied energy use data for rail, air, marine, and off-road. Data were normalized by GSP for scenario projections. High-speed rail data was provided by the High-Speed Rail Authority (M. Cederoth, pers. commun., 2014) to estimate penetrations and airplane/LDV displacements.

A.3. Stationary

The preliminary IEPR (C. Kavalec, pers. commun., 2013) provided historical and projected (2010-2024) electricity and natural gas use, and metrics (commercial floorspace, etc.) for residential, commercial, industrial and agricultural sectors. Navigant Consulting (S. Swamy, pers. commun., 2013) provided additional demand savings estimates. Residential and commercial water savings estimates were included (CEC, 2005; D. P. Waters, pers. commun., 2013). New construction and retrofit rates, efficiency savings, and water savings were adjustable.

A.4. Hydrogen

Hydrogen demand was aggregated across sectors and satisfied by a user-specified supply mix (including electrolysis, natural gas reforming, coal gasification, biomass gasification, direct solar, and some CCS variants). Conversion efficiencies (Kreutz and Williams, 2004, DOE, 2012; JCAP, pers. commun., 2013) and transmission/storage losses (Hammerschlag and Mazza, 2005; Bossel et al., 2003; DOE, 2012) were estimated.

A.5. Electricity

The most detailed CALGAPS sector was electricity, consisting of fossil (CHP, simple and combined cycle natural gas, once-through cooling, coal, diesel, and several CCS options), nuclear, large hydro, renewables (biomass, geothermal, small hydro, central and distributed solar PV, solar thermal, wind, and generic distributed), storage and export. Imported electricity provided nine additional categories. Market shares were adjustable by year, and care was taken so S1 closely reflected plans through 2030. Demand was satisfied first by renewables, then nuclear, large hydro, coal, imports, exports, once-through cooling, CHP, CCS, load-following (storage and natural gas simple cycle), and remaining fossil last. Several sources provided performance metrics and other data.

A.6. Fuels

Demand in nine fuel categories—gasoline, E85, diesel, natural gas, jet fuel, aviation gasoline, fuel oil, coal, and biomass (for electricity)—were summed across sectors. Biomass and in-state production fractions in the first six categories were adjustable. CARB (J. Cunningham, pers. commun., 2013) provided GHG intensities, base case biomass and in-state production fractions, and upstream criteria pollutant emissions.

A.7. High GWP gases

Emissions projections were provided by CARB (G. Gallagher, pers. commun., 2013; CARB, 2013a) for 29 categories and normalized by population, GSP or number of vehicles as appropriate. Projections included chlorofluorocarbons and hydrochlorofluorocarbons, but were not counted in total GHGs due to planned phase-outs. The HFC phase-out schedule was adjustable.

A.8. Other

Emissions from non-energy industry, agriculture, waste and forestry sectors were derived from inventory data (CARB, 2013d) from 2000-2011, and normalized by population or GSP as appropriate to provide a basis for projections. Cap and trade capability was also included, along with offsets used to quantify local reduction actions.

Appendix B. Detailed List of Policies Included in Scenarios S1-S3

State and federal policies included in scenarios S1-S3 are shown in Tables B.1 through B.3, respectively.

Table B.1. Policies included in Committed Policies scenario (S1)

Sector	Policy Name	Code	Quantitative Targets and References
Trans-portation	Pavley LDV efficiency/GHG standards (AB 1493)	S1.1	Reduce GHG emissions from LDVs through 2025, resulting in doubled fleet efficiency to 40 mpg by 2040 (CARB, 2013b)
	LDV ZEV deployment (EO B-16-2012)	S1.2	6% (~1.5 M) of fleet by 2025 (11% by 2035, 13% by 2050) (GO, 2012)
	LDV VMT reductions (SB 375)	S1.3	7.6% below S0 in 2020, 12% below S0 in 2035 (LegInfo, 2008; J. Cunningham, pers. commun., 2013)
	HDV efficiency standards (EPA/NHTSA)	S1.4	Heavy heavy-duty diesel ~7 mpg; medium heavy-duty gasoline ~11 mpg, diesel ~14 mpg by 2020 (EPA, 2011; J. Cunningham, pers. commun., 2013)
Fuels	LCFS target (EO S-01-07)	S1.5	10% reduction in GHG emissions by 2020 (22% biofuel gasoline, 5% biofuel diesel) (GO, 2007)
Buildings	IEPR building efficiency (includes AB 1109, AB 1470)	S1.6	Extrapolated from C. Kavalec (pers. commun., 2013) to 2050: 5-8% normalized reduction in natural gas and -1 to +3% change in electricity in 2020
	Title 24 efficient buildings & retrofits	S1.7	10% better efficiency than 2010 baseline for new construction & retrofits; 0.3% yr^{-1} retrofit rate[a] (CEC, 2008)
Electricity	RPS 33% target (SB 1078, SB 107, SP E-3, SB 2; includes SB 1)	S1.8	Increase renewable electricity generation to 33% by 2020 (CARB, 2013c; S. Grant, pers. commun., 2013; GoSolarCA, 2014)
	Imported coal power phase-out (SB 1368)	S1.9	Phase out 3.9 GW of capacity by 2030 (CCEF, 2012; CEC, 2014)
	Once-through cooling phase-out (Clean Water Act)[b]	S1.10	Phase out 15.6 GW of capacity by 2030 (CCEF, 2011; SWRCB, 2013)
Non-energy and other	20x20 water conservation (SB X7-7)	S1.11	Reduce residential/commercial water use 20% per capita in 2020 (DWR, 2014)
	Landfill methane capture (SP RW-1)	S1.12	Reduce GHG emissions 1.5 $MtCO_2e$ yr^{-1} in 2020, equal to 10% reduction in gross emissions (CARB, 2008)

	Sustainable forests (SP F-1)	S1.13	Sequestration of 5 $MtCO_2e$ yr^{-1} in forests in 2020 (CARB, 2008)
	Scoping Plan high GWP measures (SP H-1 through H-5, some H-6)	S1.14	Reduction of 10 $MtCO_2e$ yr^{-1} in 2020 (CARB, 2008; R. McCarthy, pers. commun., 2013)

Notes:
[a] Reflects continuation of current activities. Efficiency improvements and retrofit rates were difficult to estimate; in the uncertainty analysis, efficiency improvements were varied relative to 2010 baseline from 2% to 50%, and retrofit rates from 0.1% to 1.0% yr^{-1}. See Supplementary Information for details.
[b] The California State Water Resources Control Board implements the Federal Clean Water Act §316(b) regulations on cooling water intake structures. On May 4, 2010, California adopted a Policy on the Use of Coastal and Estuarine Waters for Power Plant Cooling (SWRCB, 2013), which initiated a phase-out of 15.6 GW of once-through cooling.

Table B.2. Policies included in Uncommitted Policies scenario (S2), in addition to those in S1

Sector	Policy Description	Code	Quantitative Targets and References
Trans-portation	Scoping Plan HDV efficiency (SP T-8)	S2.1	Reduction of 0.5 $MtCO_2e\ yr^{-1}$ in 2020 (CARB, 2008), by increasing efficiency 1.3% for all vehicle types
	Scoping Plan HDV VMT (goods movement) reductions (SP T-2)	S2.2	Reduction of 3.5 $MtCO_2e\ yr^{-1}$ in 2020 (CARB, 2008), by reducing VMT 9.5% relative to baseline
	High-speed rail deployment (SP T-9)	S2.3	Deploy high-speed rail in 2022, growing to ridership of 27 M yr^{-1} by 2030 (M. Cederoth, pers. commun., 2014)
Fuels	Petroleum fuel displacement (AB 2076, AB 1007)	S2.4	20% petroleum displacement by 2020, 26% by 2022, 30% by 2030 (CEC, 2005, 2007)
	In-state biofuels targets (EO S-06-06)	S2.5	Minimum of 40% in-state biofuels by 2020, 75% by 2050 (GO, 2006)
Buildings	Additional IEPR building efficiency	S2.6	Additional reductions of 1-7% in energy use electricity and 1-4% in natural gas by 2025 (S. Swamy, pers. commun., 2013)
	CPUC Strategic Plan efficient buildings (includes AB 758)	S2.7	Residential: new construction 53% over baseline; retrofits 40% by 2020, 3% yr^{-1} retrofit rate.[a] Commercial: new construction 60% by 2030; no additional retrofits (CPUC, 2008; Brook et al., 2012)
	CPUC Strategic Plan zero net energy buildings	S2.8	Fraction of buildings: Residential new construction: 100% by 2020; no retrofits. Commercial: new construction 100%, retrofits 50% by 2030 (CPUC, 2008)
Electricity	Increased CHP (SP E-2 and Governor's target)	S2.9	Additional 30 TWh yr^{-1} by 2020 (CARB, 2008) and 6.5 GW capacity by 2030 (GO, 2011)
	Governor's distributed generation target	S2.10	12 GW by 2020, modeled as solar PV (GO, 2011)
	Electricity storage target	S2.11	1.3 GW by 2020 (CPUC, 2010)
	Diablo Canyon nuclear power relicense	S2.12	Maintain 2.2 GW capacity through 2045 (NRC, 2013)
	Build CCS power	S2.13	300 MW by 2020 (HECA, 2013)
Non-energy and other	Additional water conservation (SP W-1 through W-4)	S2.14	Additional 4 $MtCO_2e\ yr^{-1}$ reduction (CARB, 2008), equivalent to additional 26% savings in residential & commercial sectors

	Waste diversion (AB 341)	S2.15	Divert 75% of waste from landfills by 2020, 100% by 2035 (LegInfo, 2011)
	HFC phase-out (includes SP H-6)[b]	S2.16	Reduce HFCs 25% in 2030, 100% by 2050 (CARB, 2008; WP, 2013; author estimates)
	Local actions and RPS targets	S2.17	Additional 4% RPS and 8.2 $MtCO_2e\ yr^{-1}$ other GHG reductions by 2020 (R. McCarthy, pers. commun., 2013)

Notes:
[a] This retrofit rate was chosen to allow all existing buildings to be retrofit by 2050. In fact, retrofit rates had to be reduced after 2030 to avoid retrofitting more than 100% of building stock in 2050.
[b] Includes SP H-6 measures not include in S1 (foam recovery and destruction, fire suppressants, and residential refrigerator retirement).

Table B.3. Policies included in Potential Policy and Technology Futures scenario (S3), in addition to those in S2

Sector	Code	Policy Description	Quantitative Targets and References
Trans-portation	S3.1	National Academies LDV efficiency	Average fleet gasoline efficiency is 54 mpg by 2050 (NAS, 2013)
	S3.2	LDV/HDV automation	LDV: 5% savings in 2030, growing to 25% by 2050 (Barth & Boriboonsomsin, 2008; author estimates); HDV 2% savings in 2030+
	S3.3	Accelerated LDV ZEV deployment	25% of fleet by 2035 (60% by 2050) (Wei et al., 2012, 2013)
	S3.4	USPIRG LDV VMT reductions	Additional 14% reduction by 2020, 25% by 2040 (USPIRG, 2013)
	S3.5	NPC HDV efficiency	Heavy heavy-duty diesel ~9 mpg by 2020, diesel & natural gas ~13 mpg by 2050 (NPC, 2012a)
	S3.6	Natural gas HDVs	5% by 2020, heavy heavy-duty 45% and medium heavy-duty 29% by 2050 (NPC, 2012a)
	S3.7	Doubled high-speed rail deployment	Grow ridership to 54 M yr^{-1} by 2030 (author estimates)
Fuels	S3.8	Cleaner petroleum (SP I-2 and I-3), renewable natural gas and jet fuel	Additional 6% biofuel in gasoline & diesel by 2030 (CARB, 2008); 3% in natural gas by 2035 (NPC, 2012b); 1% in jet fuel by 2015 (Gibbons, 2013)
Buildings	S3.9	Building electrification	Phase out building natural gas by 2050, replace with electric heat pumps (Greenblatt et al., 2012; Wei et al., 2012, 2013; author estimates)
	S3.10	Commercial building (and residential zero net energy) retrofits	3% yr^{-1} commercial retrofits by 2020; 50% residential zero net energy retrofits by 2030 (author estimates)[a]
Electricity	S3.11	RPS 51% target (AB 177[b])	40% renewable electricity by 2020, 51% by 2030 (LegInfo, 2013)
	S3.12	Reduced CHP	Reduce to 6.0 GW by 2020, 1.5 GW by 2050 (author estimates)
	S3.13	SONGS nuclear power relicense/replacement	Add 2.2 GW nuclear capacity (SCE, 2013) by 2020
	S3.14	Build 8x CCS power	2.5 GW capacity by 2050 (author

			estimate)
	S3.15	Electricity storage 5x target	6.8 GW by 2030 (author estimate)
Non-energy and other	S3.16	Accelerated HFC phase-out (includes SP H-7)	Reduce HFCs by 30% in 2020, 55% in 2030, 100% by 2050 (CARB, 2008 and author estimate)
	S3.17	Re-convert pasture to forest	Sequester 5 $MtCO_2e\ yr^{-1}$ by 2035 (15 $MtCO_2e\ yr^{-1}$ by 2050) (Brown et al., 2004 and author estimates)
	S3.18	Double local actions	Double GHG reductions to 16.4 $MtCO_2e\ yr^{-1}$ by 2030 (author estimate)

Notes:

[a] As for S2.7, the commercial retrofit rate was reduced after 2025 to avoid retrofitting more than 100% of building stock in 2050. The rate of phase-out was faster than in the residential sector, with retrofit rates falling to zero in 2040.

[b] This bill never passed into law.

Appendix C. Supplementary Information

1 Model improvements

Since publication of Greenblatt (2013), the California LBNL Greenhouse gas (GHG) and criteria pollutant Analysis of Policies Spreadsheet (CALGAPS) model has undergone a number of model improvements, detailed below.

1.1 Inclusion of Counterfactual scenario

A Counterfactual scenario (S0) is now included in the analysis to allow quantification of the GHG impact of all policies included in S1. This scenario was obtained by "reversing" the effects of each modeled policy, reflecting an alternative future where no climate-oriented policies are enacted. When specific information was absent on changes produced by a policy, parameters were simply fixed at 2010-2014 values in order to reflect no further progress (in e.g., efficiency, renewable electricity, zero emission vehicles, etc.) In other cases, progress relative to a baseline reference was available and could be "undone" (e.g., light-duty vehicle (LDV) vehicle miles traveled (VMT) reductions, or LDV fleet efficiencies; see details below).

1.2 Estimation of cumulative GHG emissions

Unlike Greenblatt (2013), cumulative GHG emissions were examined for each scenario in addition to annual emissions. To facilitate comparison to the larger policy context, a scaled version of the IEA (2012) 2°C Scenario (2DS) emissions pathway (consistent with stabilized global temperature rise of 2°C) was included for the U.S. The U.S. projected emissions data were normalized by dividing by 1990 U.S. GHG emissions. Normalized data were then multiplied by 1990 California emissions, and integrated in 5-year steps to obtain scaled cumulative emissions. The resulting curve lies almost exactly on top of the "straight line" cumulative emissions pathway.

1.3 More complete sensitivity analysis

Unlike in Greenblatt (2013), a GHG sensitivity has now been included for every policy in each of the scenarios S1-S3. Sensitivities are organized around evaluation of the GHG reduction efficacy of each policy.

1.4 Uncertainty analysis

An estimate of model uncertainty has been included by identifying parameters not constrained by any policy, and for which precise values are not known. Distribution functions were developed for each parameter, and a Monte Carlo simulation was performed to estimate the combined impact on GHG emissions of the uncertainty in these parameters. Results are summarized in section 3 of the main text and discussed in detail in section 2 here.

1.5 Better high-speed rail representation

While high-speed rail was included in Greenblatt (2013), it estimated that its use would only displace air travel and crudely estimated the amount displaced. The treatment of high-speed rail has now been improved using data provided by the High-Speed Rail Authority (M. Cederoth, pers. commun., 2014) that provides more accurate estimates of the amount of air travel as well as LDV travel displacement. The capacity of high-speed rail assumed in S2 has also been increased to the "high" scenario estimated by the High-Speed Rail Authority, based on their assumption that the "low" scenario reflected a less plausible future with lower gasoline and airfare costs that at present. This "high" scenario estimate was doubled in S3.

1.6 Consistent use of higher heating value (HHV) for fuels

A mistake in the November 2013 version of the model (Greenblatt, 2013) resulted in the incorrect use of lower heating values (LHV) for all fuels, when California Air Resources Board (CARB) estimates of fuel consumption in the LDV and heavy-duty vehicle (HDV) sectors had used HHV. GHG fuel intensities, however, had used the LHV convention. The model has since been corrected to use HHV throughout. This has resulted in a downward revision to GHG emissions from fuels, bringing totals for 2010 and 2011 more in line with official CARB inventory values.

1.7 Inclusion of downstream GHG emissions from biofuels

Greenblatt (2013) assumed all biofuels had a downstream GHG emissions intensity of zero. However, the author was subsequently made aware that the CARB inventory includes downstream GHG emissions from all fuels, but that the in-state portion of biofuels are, by definition, offset with GHG reductions due to biomass growth. For consistency with CARB inventory accounting, downstream GHG emissions are included for all fuels, and a corresponding offset is subtracted in the agricultural sector for the in-state biofuel portion of fuels. GHG emissions from the out of state portion of biofuels (and all fossil fuels) are not subtracted, however.

1.8 Addition of advanced biofuels

Transition to advanced biofuels is now included in the scenarios. Advanced (drop-in) biofuels have lower upstream GHG intensities than current (ethanol-based) biofuels. Advanced biofuels were used for gasoline/aviation gasoline, diesel/fuel oil, jet fuel and natural gas.

1.9 Inclusion of building electrification in S3

Greenblatt (2013) did not include a treatment of building electrification in any scenario. As many other studies (ECF, 2010; CCST, 2011; Greenblatt et al., 2012; McCollum et al., 2012; Williams et al., 2012; Wei et al., 2012, 2013; Yang et al., 2014) include electrification as a key strategy for reducing GHGs by 2050, the author felt it was necessary to include it in the most aggressive scenario (S3).

1.10 More realistic treatment of combined heat and power (CHP)

In Greenblatt (2013), no decreases in heating demand were assumed when CHP was increased. This has now been added, where any increases in CHP from 2010 are offset by a proportional decrease in heating demand. CHP efficiencies were also updated to better reflect current usage. Assumed were an electrical efficiency of 33% (11,500 Btu/kWh) and a heating demand displacement of 5,000 Btu natural gas per kWh electricity generated (assuming 80% efficient natural gas combustion, this corresponds to a thermal efficiency of 4,000 Btu/kWh). These values are consistent with mid-range values of CHP technologies (Table 4 in Choudhary et al., 2013). A CHP capacity of 8.5 GW (Wisland and Nelson, 2014) and 42,320 GWh/yr generation in 2010 was assumed, corresponding to a capacity factor of 57% that was retained in future years.

1.11 Updated water energy data

The water energy data has been updated from what was used in Greenblatt (2013), which was based on statewide California Energy Commission (CEC) data from 2001 for residential and commercial electricity and natural gas consumption (CEC, 2005). These values now use more recent estimates developed by CARB (D. P. Waters, pers. commun., 2013) that are 21% and 4% more efficient in the residential and commercial sectors, respectively, for electricity use. These same efficiency improvements were applied for natural gas, obtaining the final metrics for baseline water energy use shown in Section 4.1.5.1 (Table 28).

1.12 Validation with CARB inventory

The completed model was carefully compared to the CARB inventory for 2010 and 2011, after making adjustments to sector categories to reflect as accurately as possible which emissions were included. This comparison resulted in some important changes to the model (most notably, the identification and correction of the inconsistent use of HHV data for fuels). A detailed comparison with CALGAPS results is presented in Section 6.

1.13 Availability of spreadsheet file

For readers with a special interest in having comprehensive data inputs or details of the calculations, the author will consider making relevant portions of the model available upon request. However, due to the proprietary and/or unofficial nature of some of the data, the model is not generally available for download. To make a request, please send an e-mail to jbgreenblatt@lbl.gov.

2 Uncertainty analysis

Projections of the future are always uncertain, though this study was designed to constrain uncertainty by estimating the impacts of specific sets of policies if executed as modeled. However, many underlying assumptions were not tied to specific policy targets and were therefore inherently uncertain, including a number of important parameters such as population and economic growth that drive energy demand and hence GHG emissions.

An analysis was developed for 10 parameters identified as being uncertain and potentially influential on GHG outcomes, summarized in Table 3. For each parameter, 95% confidence intervals were estimated to guide the choice of distribution function parameters. As noted in the main text, parameters whose uncertainty distributions were essentially symmetrical were modeled as normal distributions, whereas those with asymmetrical distributions were modeled as log normal. Other distribution functions could have been used, but insufficient data were available to provide the detailed uncertainty information needed to distinguish among function options, so this simple two-function approach was used. A 1,000-sample Monte Carlo simulation was performed to analyze the simultaneous impact of varying all of the above parameters within their uncertainty ranges.

Table 3. Parameters and distributions used in uncertainty analysis

Parameter			Distribution function[a]			95% confidence interval values[b]	
Name	**Base value**	**Units**	**Type**	**μ**	**σ**	**Lower**	**Upper**
Population	**50.4**	Million (2050)	Normal	0.0%	6.0%	44.4	56.3
Gross state product (GSP)	**2.0%**	Annual growth rate (2018+)	Log normal	2.0%	15%	1.5%	2.7%
Building retrofit rate	**0.3%**	Annual fraction of building stocks	Log normal	0.3%	61%	0.09%	1.0%
Building efficiency improvement	**10%**	Improvement over 2010	Log normal	10%	82%	2.0%	50%
In-state biofuel gasoline	**12.0%**	Fraction of total Btu	Log normal	12.0%	73%	2.9%	50%
Natural gas simple cycle (NGSC)	**3.0%**	Fraction of gross TWh	Log normal	3.0%	35%	1.5%	6.0%
	33.2%	Efficiency (HHV)	Normal	33.2%	1.0%	31.2%	35.2%
Natural gas combined cycle (NGCC)	**51.1%**	Efficiency (HHV)	Normal	51.1%	1.0%	49.1%	53.1%
CHP	**35.0%**	Efficiency (HHV)	Normal	35.0%	1.0%	33.0%	37.0%
Gasoline energy content	**125,000**	Btu per gge (HHV)	Normal	0.0%	1.0%	122,500	127,500

Notes:

[a] Normal = $\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(x-\mu)^2}{2\sigma^2}}$; log normal = $\frac{1}{x\sigma\sqrt{2\pi}}e^{-\frac{(\ln x-\ln\mu)^2}{2\sigma^2}}$, where x is parameter value.

[b] The lower 95% confidence interval bound is the parameter value for which the cumulative probability of the distribution function equals 2.5%; the upper 95% confidence interval bound is the parameter value for which the cumulative probability equals 97.5%. The cumulative probability between these two bounds is therefore 95%.

The population forecast by DOF (2013) did not include any uncertainty estimates, so low and high fertility variants were examined for the United Nations U.S. population forecasts through 2050 (UNPD, 2012) as a proxy for the California population forecast. The U.S. population forecast variants differ from the reference (medium fertility) case by −12% and +12% respectively in 2050; these relative differences were used to set the 95% confidence intervals for the uncertainty in California's population in 2050 (normal distribution). The absolute differences in growth rates in the U.S. forecasts are larger in 2050 than in any other year, thus using these values for the entire time period represents a conservative (e.g., generous) set of uncertainty bounds.

Historical California growth rates in GSP from 1988-2011 (DOC, 2014) were used to guide the choice of future growth rate. The base value of 2.0% was derived from the average growth rate in 2000-2011, while the upper confidence interval value (2.7%) was derived from the average growth rate over the entire period (1988-2011). The lower confidence interval value (1.5%) was obtained from an uncertainty analysis of the 2000-2011 growth rate itself, and represents the lower 95% confidence interval value of that estimate. The resulting distribution was slightly asymmetric, so a log normal function was used in the analysis.

Both the building retrofit rate and efficiency improvement parameters were difficult to estimate with much accuracy, so their uncertainty distributions were necessarily quite broad; log normal distributions were used with ranges of ±3.3 and ±5 times their base values (0.3% yr^{-1} and 10%), respectively. The base values were conservative estimates provided by building efficiency experts (M. Borgeson and M. Zimring, pers. commun., 2013). These values were applied from 2011-2050, and primarily affected S1, though the retrofit rate was used for the commercial sector in S2 and affected all three scenarios (both residential and commercial) from 2011-2014. The efficiency improvement parameter only affected S1.

CARB provided the in-state biofuel gasoline portion reference value, and because of uncertainty over future biofuel policy, this parameter was varied by approximately a factor of four (up and down), resulting in a log normal distribution from 2.9% to 50% (95% confidence interval). This parameter was applied to S1 (and S0) between 2020-2050 (for earlier years, the model ramped linearly from the 2012 value of 12%. The parameter also affected the 2020 target for S2-S3, but the value was doubled; the model then linearly interpolated to a fixed 2030 target of 28%, after which the parameter was fixed by the scenario assumptions (increasing to 75% in 2050).

For NGSC electricity generation, the amount of capacity assumed in the model was not well constrained by data, so it was bounded with the range of a factor of two in each direction, resulting in a log normal distribution from 1.5% to 6% (95% confidence interval). For the efficiency of the NGSC technology itself (33.2%), a normal distribution was assumed with an uncertainty of ±1% in actual efficiencies (so a relative uncertainty of approximately ±3%), because this value, while based on quantitative data from Cai et al. (2012), represented national averages and may not accurately reflect California.

Similarly, for NGCC and CHP efficiencies, normal distributions were assumed with uncertainties of ±1% in actual efficiencies, for the same argument as above.

Finally, different sources provided slightly different values of the HHV energy content of fuels. While CALGAPS used the recommended values provided by CARB for gasoline, ethanol, diesel and natural gas, it seemed prudent to assign an uncertainty to these values. As the observed variation by source was approximately ±1%, this range was adopted (normal distribution) for the uncertainty analysis. Only the uncertainty in gasoline had any effect on results; the effects of varying the energy content of ethanol, diesel and natural gas were undetectable, so those parameters were not included in the final analysis.

3 Statewide GHG emissions by scenario

While statewide GHG emissions by scenario are provided in the main text in a Figure, numerical values at decadal intervals are shown in Table 4, for both base case values and lower and higher 95% confidence interval bounds, for the convenience of readers.

Table 4. Statewide GHG emissions by decade and scenario, evaluated at base case values (highlighted) and lower and higher 95% confidence interval bounds

		Statewide GHG emissions ($MtCO_2e\ yr^{-1}$)				
Scenario	**Sensitivity**	**2010**	**2020**	**2030**	**2040**	**2050**
S0	Lower bound	452.3	517.3	524.2	542.7	570.2
	Base case	454.4	523.4	545.2	582.0	631.5
	Upper bound	456.3	530.5	574.7	639.9	727.8
S1	Lower bound	452.2	401.4	381.5	381.5	396.8
	Base case	454.2	409.9	403.8	420.5	455.1
	Upper bound	456.2	415.0	428.2	469.0	535.2
S2	Lower bound	451.2	352.4	295.8	273.1	264.1
	Base case	453.2	363.5	314.7	302.5	304.0
	Upper bound	455.1	368.6	334.9	342.4	365.9
S3	Lower bound	451.2	317.0	211.1	159.8	139.0
	Base case	453.3	327.6	230.2	186.4	174.6
	Upper bound	455.2	332.4	247.6	219.8	226.2

4 Complete list of policies included in scenarios

4.1 Committed Policies scenario (S1)

4.1.1 Transportation

4.1.1.1 California Assembly Bill (AB) 1493 (Pavley) LDV efficiency/GHG standards (S1.1)

Based on data from CARB Vision (CARB, 2012), the following fuel efficiencies were assumed for LDVs (linearly interpolated for intervening years):

Table 5. LDV efficiencies (S1.1)

Year	Fuel efficiency (mpg)			
	Average gasoline (input parameter)	Gasoline internal combustion engine vehicle (ICEV) (derived)	Gasoline hybrid electric vehicle (HEV) (derived)	Gasoline plug-in hybrid electric vehicle (PHEV) (derived)
2010	19.32	19.32	29.06	30.08
2013	21.09	21.08	35.71	34.37
2021	26.85	29.72	51.63	45.37
2025	29.92	29.72	51.63	45.37
2030	34.50	39.03	63.21	62.90
2040	39.50	39.03	63.21	62.90
2050	40.90	40.42	64.83	67.23

The following fuel efficiencies do not change with scenario, but are listed here for completeness:

Table 6. Non-electric LDV fuel efficiencies (all scenarios)

Year	Fuel efficiency (mpgge, input parameters)					
	H_2 fuel cell vehicle	E-85 flex fuel vehicle	Conventional diesel	Diesel HEV	Diesel-electric PHEV	Natural gas vehicle
2010	39.35	15.18	32.15	48.35	50.05	20.28
2013	45.27	18.21	30.28	51.30	49.38	24.90
2021	58.54	23.11	31.39	55.61	50.77	33.06
2025	61.57	24.84	33.93	58.96	51.81	35.54
2030	70.84	27.48	37.53	62.00	52.82	37.57
2040	84.76	25.96	43.73	70.83	70.48	39.91
2050	88.72	27.40	46.85	75.14	77.92	40.45

Table 7. Electric LDV efficiencies (all scenarios)

Year	Electric efficiency (kWh/mi, input parameters)		
	Gasoline PHEV	Battery electric vehicle	Diesel PHEV
2010	0.775	0.864	0.466
2013	0.551	0.633	0.384
2021	0.252	0.371	0.214
2025	0.208	0.324	0.182
2030	0.177	0.289	0.162
2040	0.168	0.255	0.150
2050	0.164	0.248	0.142

4.1.1.2 LDV zero-emission vehicle (ZEV) deployment (S1.2)

The ZEV policy was based on CARB Vision (CARB, 2012), which reflected the state policy goal of 1.5 million ZEVs in the LDV stock by 2025; the total stock increased to approximately 2.5 times this number by 2050. However, because this scenario used higher population growth assumptions than were used in CALGAPS (Greenblatt, 2013), the number of ZEVs in 2025 in CALGAPS is slightly lower than this target (1.4 million). As the impact of this discrepancy on GHG emissions in 2025 is very modest (0.2 $MtCO_2e\ yr^{-1}$), the ZEV fraction was left unadjusted, for consistency with the CARB scenario. The share of ZEVs by technology type was also provided by the CARB Vision model and was the same for all scenarios. Values were linearly interpolated for intervening years. See Table 8.

Table 8. ZEV fraction of LDVs (S1.2)

Year	ZEV fraction of LDV stock (input parameter)	Number of ZEVs (derived, thousands)	Share of total ZEVs (same for all scenarios)			
			Battery electric vehicle	H_2 fuel cell vehicle	Gasoline PHEV	Diesel PHEV
2010	0.03%	7	47.71%	5.98%	46.32%	0.00%
2013	0.44%	97	47.71%	5.98%	46.32%	0.00%
2020	2.93%	685	34.09%	7.54%	58.38%	0.00%
2025	5.80%	1,405	30.57%	10.73%	58.69%	0.00%
2035	11.39%	2,961	27.46%	15.64%	56.91%	0.00%
2050	12.85%	3,654	27.01%	16.72%	56.27%	0.00%

The fraction of miles driven by PHEVs using fuel rather than electricity as the energy source changes over time but is the same in all scenarios. Table 9 provides the set of assumptions used. Values are linearly interpolated for intervening years.

Table 9. PHEV non-electric miles fraction (same for all scenarios)

Year	Gasoline PHEV (input parameter)	Diesel PHEV (input parameter)
2010	80.30%	80.30%
2020	64.25%	64.25%
2030	43.00%	43.00%
2050	34.70%	34.70%

4.1.1.3 LDV VMT reductions (S1.3)

The CARB Vision scenario (CARB, 2012) provided LDV VMT that incorporated the VMT reduction effects of California Senate Bill (SB) 375 (S1.3). CARB estimates these reductions to amount to a 7.6% reduction from a counterfactual baseline in 2020, and a 12% reduction in 2035 (J. Cunningham, pers. commun., 2013). Because these reductions were already included in the Vision scenario, changes in VMT were expressed relative to this. See Table 10.

Table 10. LDV VMT scenario (S1.3)

Year	Change in VMT per vehicle (input parameter)	VMT per vehicle (mi/yr)	Total VMT (10^9 mi/yr)	Change in total VMT relative to 2010
		(derived)		
2010	0.00%	12,406	272.36	0.00%
2020	0.00%	12,237	286.13	5.06%
2030	0.00%	11,385	286.10	5.05%
2035	0.00%	11,071	287.70	5.63%
2040	0.00%	11,103	298.74	9.68%
2050	0.00%	11,050	314.28	15.39%

4.1.1.4 U.S. Environmental Protection Agency (EPA)/National Highway Transportation Safety Administration (NHTSA) HDV efficiency standards (S1.4)

EPA and NHTSA policies (EPA, 2011) impose efficiency improvements to all types of HDVs, which are built into the baseline provided by CARB Vision (CARB, 2012; J. Cunningham, pers. commun., 2013), so changes are expressed relative to this baseline in the model. Table 11 provides values used for in-state heavy heavy-duty (HHD), out-of-state (OOS) HHD, and medium heavy-duty (MHD) vehicles.

Table 11. EPA/NHTSA HDV efficiency standards (S1.4)

Year	Change relative to baseline (input parameters)			Fuel efficiency (mi/gge, derived)				
				In-state HHD		OOS HHD	MHD	
	In-state HHD	OOS HHD	MHD	Diesel	Natural gas	Diesel	Gasoline	Diesel
2010	0.00%	0.00%	0.00%	5.67	3.81	5.59	9.84	12.51
2020	0.00%	0.00%	0.00%	7.00	5.08	6.86	10.98	14.62
2030	0.00%	0.00%	0.00%	7.03	6.45	6.86	11.10	14.30
2050	0.00%	0.00%	0.00%	7.02	6.88	6.84	11.25	14.07

While not a specific policy for S1, Table 12 shows the fraction and number of natural gas HDVs assumed (this is increased in S2 and decreased in S0):

Table 12. Natural gas HDV assumptions (S1)

Year	Fraction of natural gas vehicles by class (input parameter)			Number of natural gas vehicles (derived)		
	In-state HHD	OOS HHD	MHD	In-state HHD	OOS HHD	MHD
2010	0.05%	0.00%	0.00%	83	0	0
2020	0.67%	0.00%	0.00%	1,509	0	0
2030	1.07%	0.00%	0.00%	2,912	0	0
2050	1.11%	0.00%	0.00%	4,207	0	0

4.1.2 Fuels

4.1.2.1 Low Carbon Fuel Standard (LCFS) target (S1.5)

The LCFS [Executive Order (EO) S-01-07] (GO, 2007) requires a 10% reduction in the GHG content of fuels by 2020, which has translated into policy as specific biomass content targets for different fuels (gasoline and diesel) by CARB (J. Cunningham, pers. commun., 2013). These targets will likely continue to exceed the Federal renewable fuel standard; the 2014 proposed targets are 9.2% gasoline (as ethanol) and 1.2% diesel (EPA, 2013a). Table 13 provides scenario assumptions for the LCFS.

Table 13. Biomass fraction of fuels (S1.5)

Year	Biomass fraction of fuels (% by energy content)							
	Gaso-line	E-85	Diesel	Natural gas	Jet fuel	Avia-tion gaso-line, fuel oil	Average (petro-leum fuels)	Average (all)
	(input parameter)						(derived)	
2010	6.80%	85.00%	5.00%	0.00%	0.00%	0.00%	6.34%	3.00%
2015	14.54%	85.00%	5.00%	0.00%	0.00%	0.00%	12.36%	5.51%
2020	22.28%	85.00%	5.00%	0.00%	0.00%	0.00%	17.79%	7.97%
2022	22.28%	85.00%	5.00%	0.00%	0.00%	0.00%	17.47%	7.64%
2030	22.28%	85.00%	5.00%	0.00%	0.00%	0.00%	16.13%	6.25%
2050	22.28%	85.00%	5.00%	0.00%	0.00%	0.00%	14.42%	5.30%

Based on data provided by CARB (J. Cunningham, pers. commun., 2013), assumptions were made about the in-state fraction of biofuels; see Table 14. (Some of these values are changed by policy S2.5; see below).

Table 14. In-state fraction of biofuels (S1)

Year	In-state fraction of biofuels (%)					
	Gasoline, aviation gasoline	E-85	Diesel, fuel oil	Natural gas	Jet fuel	Weighted average (derived)
	(input parameter)					
2010	12%	12%	100%	100%	100%	23%
2012	12%	12%	100%	100%	100%	21%
2020	12%	12%	100%	100%	100%	18%
2030	12%	12%	100%	100%	100%	20%
2040	12%	12%	100%	100%	100%	22%
2050	12%	12%	100%	100%	100%	24%

Although not specified in any policy, assumptions were also made about the fraction provided by advanced technologies (with lower total GHG intensities); see Table 15. However, because of the small in-state fractions of biofuels, the changes in GHG intensities were negligible. (Some of these values were changed for S2 and S3; see below under S2.4 and S3.8).

Table 15. Advanced biofuel fraction of fuels (S1)

Year	Advanced biofuel fraction of fuel (%, input parameter)			Total biofuel GHG intensity (in-state portion, $kgCO_2e$/MBtu, derived)		
	Gasoline, E-85	E-85	Diesel	Gasoline, E-85	E-85	Diesel
2010	0.00%	0.00%	0.00%	62.98	62.98	5.65
2015	0.00%	0.00%	0.00%	62.98	62.98	5.65
2020	5.00%	5.00%	5.00%	63.02	63.02	5.58
2022	6.00%	6.00%	6.00%	63.03	63.03	5.56
2030	10.00%	10.00%	10.00%	63.06	63.06	5.50
2050	30.00%	30.00%	30.00%	63.22	63.22	5.18

Fuel parameters (same for all scenarios) are summarized in Table 16.

Table 16. Fuel energy and GHG parameters (all scenarios)

			Energy density			
			Gasoline, aviation gasoline	**Ethanol**	**Diesel, Jet fuel, fuel oil**	**Natural gas**
			(Btu HHV/gal)			**(Btu HHV/scf)**
			125,000	84,000	138,000	1,019
			GHG intensity (gCO_2e/MJ HHV)			
			Gasoline, E-85, aviation gasoline	**Diesel, fuel oil**	**Jet fuel**	**Natural gas**
Downstream	Proportional to in-state fraction	Fossil	68.2	70.0	67.2	52.1
		Current biofuel	64.0	70.0	N/A	N/A
		Advanced biofuel	68.2	70.0	67.2	52.1
Upstream	Proportional to in-state fraction	Fossil	6.5	6.5	10.0	7.4
		Current biofuel	26.4	5.4	N/A	N/A
		Advanced biofuel	3.9	3.9	0.0	10.2
	Fixed emissions (in-state)	Fossil	14.4	11.4	0.0	1.9
		Current biofuel	0.2	0.0	N/A	N/A
		Advanced biofuel	0.0	0.0	1.0	0.0

4.1.3 Buildings

4.1.3.1 Integrated Energy Policy Report building efficiency (S1.6)

The CEC Integrated Energy Policy Report draft data provided by C. Kavalec (pers. commun., 2013) was used to estimate energy consumption in residential and commercial buildings through 2024, and extrapolated trends normalized to population and GSP through 2050. See Table 17.

Table 17. Stock building efficiency (S1.6)

Year	Number of units (same for all scenarios)		Unit efficiency of remaining stock			
			Residential		Commercial	
	Residential	Commercial	Electricity	Natural gas	Electricity	Natural gas
	10^6 hh*	10^6 sf*	kWh/hh	therms/hh	kWh/sf	therms/sf
2010	12.87	7,059	6,976	406.1	14.24	0.2806
2011	12.94	7,086	7,039	412.6	14.23	0.2825
2015	13.25	7,389	7,163	386.4	14.05	0.2673
2020	13.88	7,795	7,207	374.1	14.03	0.2663
2025	14.41	8,013	7,582	367.0	14.14	0.2616
2030	14.98	8,247	7,775	356.9	14.20	0.2588
2040	16.04	8,935	8,063	342.9	14.28	0.2547
2050	16.87	9,976	8,268	333.5	14.33	0.2519

* hh = households; sf = square feet

4.1.3.2 Title 24 efficient buildings and retrofits (S1.7)

Using data from C. Kavalec (pers. commun., 2013) as a starting point, assumptions were made about the efficiency of new construction and retrofits relative to existing 2010 building stock to reflect Title 24 requirements (CEC, 2008). These assumptions were intended to be reflective to AB 758 (Brook et al., 2012); however, this law does not yet provide quantitative targets from which to model policy (AB 758 measures are incorporated in S2.7). Therefore a baseline assumption was used for the efficiency of both new construction and retrofits of 10% better than 2010 buildings (this parameter was varied in the uncertainty analysis between 2% and 50%). This parameter was added to existing building efficiency trends to arrive at final efficiency values. Rates of new construction were derived from differences between total stock and demolition estimated from national data (EIA, 2010), while rates of retrofits were estimated to be 0.3% (with a range in the uncertainty analysis of 0.1% to 1.0%). See Table 18 through Table 21.

Table 18. Residential building efficiencies - new construction (S1.7)

Year	Annual rates* (input parameters)	Number of buildings* (derived)	Efficiency over 2010 (input parameters)		Efficiencies (derived)	
			Electricity	Natural gas	Electricity	Natural gas
	%/yr	10^6 hh/yr	%	%	kWh/hh	therms/hh
2010	2.85%	367.0	2.00%	0.00%	6,836	406.0
2011	0.55%	71.0	9.08%	8.37%	6,342	372.0
2015	0.88%	116.5	7.31%	14.83%	6,466	345.8
2020	1.15%	159.3	6.69%	17.85%	6,509	333.5
2025	1.15%	165.4	0.63%	19.42%	6,932	327.1
2030	1.15%	171.9	0.63%	19.42%	6,932	327.1
2040	1.15%	184.1	0.63%	19.42%	6,932	327.1
2050	1.15%	193.6	0.63%	19.42%	6,932	327.1

* Annual rates and number of buildings are identical for all scenarios

Table 19. Residential building efficiencies - retrofits (S1.7)

Year	Annual rates (input parameters)	Number of buildings (derived)	Efficiency over 2010 (input parameters)		Efficiencies (derived)	
			Electricity	Natural gas	Electricity	Natural gas
	%/yr	10^3 hh/yr	%	%	kWh/hh	therms/hh
2010	0.00%	-	0.00%	0.00%	6,975	406.0
2011	0.30%	38.81	9.08%	8.37%	6,342	372.0
2015	0.30%	39.76	7.31%	14.83%	6,466	345.8
2020	0.30%	41.63	6.69%	17.85%	6,509	333.5
2025	0.30%	43.22	0.63%	19.42%	6,932	327.1
2030	0.30%	44.93	0.63%	19.42%	6,932	327.1
2040	0.30%	48.12	0.63%	19.42%	6,932	327.1
2050	0.30%	50.61	0.63%	19.42%	6,932	327.1

Table 20. Commercial building efficiencies - new construction (S1.7)

	Annual rates* (input parameters)	Number of buildings* (derived)	Efficiency over 2010 (input parameters)		Efficiencies (derived)	
			Electricity	Natural gas	Electricity	Natural gas
Year	%/yr	10^6 sf/yr	%	%	kWh/sf	therms/sf
2010	1.32%	93.2	11.00%	17.00%	12.65	0.2324
2011	0.88%	62.5	9.91%	9.11%	12.81	0.2545
2015	1.90%	140.7	11.15%	14.52%	12.63	0.2393
2020	1.71%	133.5	11.32%	14.89%	12.61	0.2383
2025	1.66%	133.4	10.40%	16.73%	12.74	0.2332
2030	1.66%	137.3	10.40%	16.73%	12.74	0.2332
2040	1.66%	148.7	10.40%	16.73%	12.74	0.2332
2050	1.66%	166.1	10.40%	16.73%	12.74	0.2332

* Annual rates and number of buildings are identical for all scenarios

Table 21. Commercial building efficiencies - retrofits (S1.7)

	Annual rates (input parameters)	Number of buildings (derived)	Efficiency over 2010 (input parameters)		Efficiencies (derived)	
			Electricity	Natural gas	Electricity	Natural gas
Year	%/yr	10^6 sf/yr	%	%	kWh/sf	therms/sf
2010	0.00%	-	0.00%	0.00%	14.21	0.2800
2011	0.30%	21.26	9.91%	9.11%	12.81	0.2545
2015	0.30%	22.17	11.15%	14.52%	12.63	0.2393
2020	0.30%	23.39	11.32%	14.89%	12.61	0.2383
2025	0.30%	24.04	10.40%	16.73%	12.74	0.2332
2030	0.30%	24.74	10.40%	16.73%	12.74	0.2332
2040	0.30%	26.81	10.40%	16.73%	12.74	0.2332
2050	0.30%	29.93	10.40%	16.73%	12.74	0.2332

4.1.4 Electricity

Input data for the electricity sector came from numerous sources, including Cai et al. (2012), CCEF (2011, 2012), CEC (2009, 2013), Choudhary et al. (2013), S. Grant (pers. commun., 2013), and Wisland and Nelson (2014).

4.1.4.1 Renewable Portfolio Standard (RPS) 33% target (S1.8)

The state RPS target [SB 1078, SB 107, CARB (2008) Scoping Plan (SP) measure E-3, SB 2] (CARB, 2013a) is 33% of eligible renewable electricity generation by 2020. Ineligible demand includes some distributed solar photovoltaic (PV) and renewable self-generation. As noted in the main text, 3.0 GW of solar PV capacity was included from the California Solar Initiative (SB 1) and related programs (GoSolarCA, 2014) by 2022, but this target is for 2016, whereas the model linearly interpolated annual capacity between zero in 2010 and 3.5 GW in 2022, so it does not accurately reflect the 2016 target, which will likely be met (capacity was 2.05 GW as of May 21, 2014; GoSolarCA, 2014). Table 22 specifies model assumptions, while Table 23 shows the breakdown by renewable generation technology.

Table 22. RPS 33% target (S1.8)

				Ineligible demand			
	RPS target (input para-meter)	RPS genera-tion	RPS-eligible demand	Distributed solar PV not subject to RPS	Additional solar PV for zero net energy targets	Other self-generation	Gross demand
Year	% of eligible	TWh/yr (derived)					
2010	11.3%	32.5	286.4	-	-	12.4	298.8
2011	10.0%	28.7	287.4	0.2	-	12.6	300.1
2016	20.0%	58.3	291.4	1.1	-	13.4	305.9
2020	33.0%	97.8	296.5	1.8	-	13.5	311.8
2030	33.0%	105.7	320.3	2.2	-	15.2	337.6
2040	33.0%	114.5	346.9	2.2	-	17.9	367.0
2050	33.0%	124.6	377.4	2.2	-	21.2	400.8

Table 23. Breakdown by renewable generation type (S1.8)

Year	Biomass	Geothermal	Small hydro	RPS-eligible solar (PV and concentrating thermal)	Wind	Other
	% of renewable generation (input parameters)					
2011	15.1%	33.2%	1.5%	2.8%	19.9%	27.4%
2016	16.0%	28.7%	1.3%	18.6%	23.7%	11.7%
2020	14.2%	17.7%	0.8%	35.9%	24.4%	7.0%
2030	14.5%	18.0%	0.8%	36.6%	24.8%	5.3%
2040	14.5%	18.0%	0.8%	36.6%	24.8%	5.3%
2050	14.5%	18.0%	0.8%	36.6%	24.8%	5.4%
	GW installed capacity (derived)					
2010	1.02	2.59	0.14	0.36	2.37	1.66
2011	1.02	1.89	0.14	0.36	2.38	1.61
2016	1.88	3.31	0.25	4.54	5.77	1.31
2020	2.35	3.42	0.25	12.62	9.97	1.07
2030	2.56	3.76	0.28	13.87	10.96	0.79
2040	2.77	4.07	0.30	15.02	11.87	0.86
2050	3.02	4.43	0.33	16.34	12.92	0.94

4.1.4.2 Imported coal power phase-out (S1.9)

SB 1368 establishes a standard for baseload generation of 500 kg CO_2/MWh, which effectively requires the phase-out of all OOS coal plants by 2030 (CCEF, 2012; CEC, 2014). The CEC has developed a retirement schedule (CCEF, 2012) that was assembled into an annual capacity and generation schedule shown in Table 24. The assumed heat rate for all imported coal was 11,765 Btu/kWh (Cai et al., 2012).

Table 24. Imported coal phase-out schedule (S1.9)

Year	Remaining capacity (MW)	Remaining generation (TWh/yr)
2010	3,893	29.605
2011	3,893	29.605
2012	3,893	29.605
2013	3,893	29.605
2014	3,821	28.693
2015	3,344	23.292
2016	3,344	23.292
2017	2,624	18.554
2018	2,624	18.554
2019	2,482	17.524
2020	2,482	17.524
2021	1,996	11.774
2022	1,996	11.774
2023	1,996	11.774
2024	1,996	11.774
2025	1,996	11.774
2026	1,996	11.774
2027	1,996	11.774
2028	374	2.516
2029	374	2.516
2030	374	2.516
2031+	-	-

4.1.4.3 Once-through cooling power plant phase-out (S1.10)

Similarly to imported coal, the state requires the phase-out of once-through cooling power plants by 2030 (CCEF, 2011; SWRCB, 2013). Based on CCEF (2011), a schedule was assembled of annual capacity, generation and average heat rates in Table 25.

Table 25. Once-through cooling power retirement schedule (S1.10)

Year	Remaining capacity (MW)	Remaining generation (TWh/yr)	Weighted average heat rate of remaining generation (Btu/kWh)
2010	15,568	15.347	9,963
2011	14,903	14.426	9,842
2012	14,903	14.426	9,842
2013	14,451	13.893	9,789
2014	12,907	12.187	9,853
2015	12,907	12.187	9,853
2016	11,472	11.228	9,691
2017	11,472	11.228	9,691
2018	7,367	6.479	10,419
2019	7,367	6.479	10,419
2020	7,367	6.479	10,419
2021	1,615	2.953	9,101
2022	1,615	2.953	9,101
2023	1,615	2.953	9,101
2024	1,615	2.953	9,101
2025	1,248	2.502	8,574
2026	1,248	2.502	8,574
2027	1,248	2.502	8,574
2028	1,248	2.502	8,574
2029	1,248	2.502	8,574
2030	-	-	-

Table 26 shows a summary of all fossil generation assumptions, while Table 27 shows a summary of all low-carbon generation assumptions. Note that California operated two nuclear power plants until 2012, when San Onofre Nuclear Generating Station (SONGS) was taken off-line permanently to begin decommissioning (SONGS, 2013). Diablo Canyon remains as the state's only nuclear power plant, scheduled for shut-down in 2024. Besides this capacity, a small amount of imported nuclear power was included in California's generation mix through 2050. Future large hydro generation is based on average historical output between 1983 and 2011.

Table 26. Fossil generation (S1)

Year	Imported coal	Once-through cooling	CHP	NGSC	NGCC	Other coal	Other
	% of gross demand (input parameters)						
2010	9.91%	4.81%	14.10%	2.37%	13.88%	1.17%	13.43%
2011	9.86%	4.81%	14.10%	2.37%	15.54%	0.85%	12.92%
2016	7.61%	3.67%	13.83%	2.72%	19.68%	0.90%	10.32%
2020	5.62%	2.08%	13.57%	3.00%	14.10%	0.41%	8.24%
2030	0.75%	0.00%	12.53%	3.00%	31.29%	0.00%	5.65%
2040	0.00%	0.00%	11.53%	3.00%	33.54%	0.00%	5.65%
2050	0.00%	0.00%	10.56%	3.00%	34.97%	0.00%	5.65%
	GW installed capacity (derived)						
2010	3.89	15.57	8.50	26.95	11.43	0.40	7.26
2011	3.89	14.90	8.50	27.07	12.86	0.29	7.36
2016	3.34	11.47	8.50	31.66	16.59	0.31	7.67
2020	2.48	7.37	8.50	35.59	12.11	0.15	7.39
2030	0.37	-	8.50	38.54	29.11	-	8.32
2040	-	-	8.50	41.89	33.92	-	9.77
2050	-	-	8.50	45.75	38.62	-	11.59

Table 27. Low-carbon non-RPS generation (S1)

Year	Coal with carbon capture and sequestration (CCS)	Nuclear	Large hydro	Non-RPS solar PV	Other non-RPS	Exports	Im-ports	Storage
	% of gross demand (input parameters)							
2010	0.00%	14.95%	11.99%	0.06%	4.16%	-1.69%	33.67%	0.00%
2011	0.00%	14.79%	12.68%	0.06%	4.19%	-1.71%	32.71%	0.00%
2016	0.00%	7.98%	11.15%	0.35%	4.38%	-1.67%	25.87%	0.00%
2020	0.00%	7.46%	10.87%	0.58%	4.33%	-1.64%	20.21%	0.00%
2030	0.00%	1.13%	9.97%	0.64%	4.50%	-0.76%	10.75%	0.00%
2040	0.00%	1.13%	9.19%	0.59%	4.87%	-0.69%	10.00%	0.00%
2050	0.00%	1.13%	8.43%	0.54%	5.29%	-0.64%	10.00%	0.00%
	GW installed capacity (derived)							
2010	-	5.43	11.39	0.10	6.79	N/A	N/A	-
2011	-	5.40	12.10	0.10	6.89	N/A	N/A	-
2016	-	2.97	10.85	1.13	7.34	N/A	N/A	-
2020	-	2.83	10.78	5.25	7.39	N/A	N/A	-
2030	-	0.46	10.70	5.87	8.32	N/A	N/A	-
2040	-	0.50	10.72	6.26	9.77	N/A	N/A	-
2050	-	0.55	10.74	6.70	11.59	N/A	N/A	-

4.1.5 Non-energy and other

4.1.5.1 20x20 water conservation (S1.11)

The "20x20" water conservation policy (SB X7-7; DWR, 2014) aims to reduce statewide urban (residential and commercial sector) per capita water use by 20% relative to today in 2020. Table 28 shows the current (2013-era) estimated electricity and natural gas water energy use metrics for these sectors, against which savings are calculated. Data are based on CEC (2005) and D. P. Waters (pers. commun., 2013). See Table 28.

Table 28. Current (2013-era) electricity and natural gas energy use from water consumption (S1.11)

Sector	Electricity use kWh/yr/capita	Natural gas use therms/yr/sf
Residential	426	48.66
Commercial	1.77	0.0398

Table 29 shows the calculated electricity and natural gas savings in the residential and commercial sectors from implementation of water savings.

Table 29. Energy savings from water conservation (S1.11)

	Residential			Commercial		
	Energy savings	Electricity savings	Natural gas savings	Energy savings	Electricity savings	Natural gas savings
Year	% of 2010	kWh/yr/ capita	Therms/ yr/capita	% of 2010	kWh/yr/sf	therms/ yr/10^3 sf
2010	0%	-	-	0%	-	-
2020	20%	85.1	9.73	20%	0.353	7.97
2030	20%	85.1	9.73	20%	0.353	7.97
2040	20%	85.1	9.73	20%	0.353	7.97
2050	20%	85.1	9.73	20%	0.353	7.97

4.1.5.2 Landfill methane capture (S1.12)

S1.12 represents increased landfill methane capture reflected in CARB Scoping Plan measure RW-1, which CARB estimates amounts to 1.5 $MtCO_2e\ yr^{-1}$ in 2020 (CARB, 2008). From 2000 to 2010, about 50% of landfill gas emissions were captured; these emissions have been subtracted from gross emissions in state inventories. An additional 1.5 $MtCO_2e\ yr^{-1}$ savings was calculated to be equivalent to increasing this capture fraction to 60%, as shown below in Table 30.

Table 30. Reduction in emissions from landfills (S1.12)

	Gross emissions	Biogenic share of total	Net emissions
Year	$kgCO_2\ person^{-1}\ yr^{-1}$	%	$MtCO_2e\ yr^{-1}$
2010	372	50.3	6.90
2020	397	59.6	6.52
2030	424	59.6	7.58
2040	452	59.6	8.71
2050	482	59.6	9.82

4.1.5.3 Sustainable forests (S1.13)

CARB (2008) Scoping Plan targets an additional 5 $MtCO_2e\ yr^{-1}$ in 2020 from sustainable forests (SP F-1). Net emissions from forests were estimated at a ~4 $MtCO_2e$ reduction in 2010 from the state inventory; this was extended to 5 $MtCO_2e\ yr^{-1}$ in 2020 and beyond to reflect the goals of this policy. See Table 31.

Table 31. Forest GHG emissions (S1.13)

Year	Forest emissions reductions ($MtCO_2e\ yr^{-1}$)
2010	3.76
2020	5.00
2030	5.00
2040	5.00
2050	5.00

4.1.5.4 Scoping Plan high global warming potential (GWP) measures (S1.14)

In S1, CARB (2008) Scoping Plan measures to reduce GWP emissions (SP H-1 through H-5 and some H-6) were included in the baseline data provided by CARB (G. Gallagher, pers. commun., 2013), so the relative level of hydrofluorocarbon (HFC) reduction was unchanged at 100%. See Table 32 for a breakdown in high GWP gases by sector. Note that gases are mainly HFCs, with some other gases (SF_6 and NF_3) also represented. Note that chlorofluorocarbon and hydrochlorofluorocarbon gases, while included in the model, were not included in statewide inventories in keeping with CARB conventions, because these gases are already being phased out.

Table 32. Scoping Plan high GWP measures (S1.14)

Year	HFC emissions (% of baseline, input parameter)	Residen-tial	Commer-cial	Industrial	LDV	HDV	Other transport	Total
		$MtCO_2e\ yr^{-1}$ (derived)						
2010	100%	2.89	5.81	0.77	2.48	1.00	0.27	13.23
2020	100%	6.73	8.69	0.93	1.87	1.34	0.32	19.87
2030	100%	9.27	10.58	1.01	1.08	1.74	0.33	24.02
2040	100%	9.95	11.02	1.05	0.70	2.20	0.34	25.27
2050	100%	10.13	11.55	1.08	0.51	2.81	0.36	26.43

4.2 Uncommitted Policies scenario (S2)

4.2.1 *Transportation*

4.2.1.1 Scoping Plan HDV efficiency (S2.1)

SP T-8 estimates a reduction of 0.5 $MtCO_2e$ yr^{-1} in 2020 (CARB, 2008) from HDV efficiency improvements, which was modeled with an increase over baseline CARB Vision (J. Cunningham, pers. commun., 2013) efficiencies 1.3% for all vehicle types in 2020 and beyond. See Table 33.

Table 33. HDV efficiency improvements (S2.1)

Year	Change relative to baseline (%, input parameter)			Fuel efficiency (mi/gge, derived)				
				In-state HHD		OOS HHD	MHD	
	In-state HHD	OOS HHD	MHD	Diesel	Natural gas	Diesel	Gasoline	Diesel
2010	0.00%	0.00%	0.00%	5.67	3.81	5.59	9.84	12.51
2020	1.30%	1.30%	1.30%	7.09	5.15	6.95	11.12	14.81
2030	1.30%	1.30%	1.30%	7.12	6.54	6.95	11.25	14.49
2050	1.30%	1.30%	1.30%	7.11	6.97	6.93	11.40	14.25

4.2.1.2 Scoping Plan HDV VMT (goods movement) reductions (S2.2)

The CARB (2008) Scoping Plan includes measure SP T-2 to improve goods movement efficiency, translating into HDV VMT reductions. CARB estimates a reduction of 3.5 $MtCO_2e$ yr^{-1} in 2020, which was achieved in the model by reducing baseline VMT by 9.5%. See Table 34.

Table 34. HDV VMT reductions (S2.2)

Year	Change relative to baseline (%, input parameter)			VMT per vehicle (mi/yr, derived)		
	In-state HHD	OOS HHD	MHD	In-state HHD	OOS HHD	MHD
2010	0.00%	0.00%	0.00%	40,766	85,755	14,316
2020	9.50%	9.50%	9.50%	37,357	79,560	12,202
2030	9.50%	9.50%	9.50%	38,324	67,418	12,023
2050	9.50%	9.50%	9.50%	36,436	62,913	11,548

4.2.1.3 High-speed rail deployment (S2.3)

High-speed rail is included as SP T-9. The High-Speed Rail Authority (M. Cederoth, pers. commun., 2014) assumes as its most likely (base) case the high ridership case from the High-Speed Rail Authority plan. The first year of high-speed rail operation is 2022; before this year, the impact of high-speed rail is zero. The High-Speed Rail Authority estimates that 27% of high-speed rail rides displace air travel, with the rest assumed to reduce LDV VMT. See Table 35.

Table 35. High-speed rail deployment (S2.3)

	Ridership (input parameter)	High-speed rail energy increase (derived)	Fraction aviation displacement (input parameter)	Aviation energy reduction (derived)	VMT decrease per rider (derived)	
Year	**10^6/yr**	**TWh/yr**	**% of flights**	**10^{12} Btu/yr**	**mi/rider**	**10^9 mi/yr**
2022	2.10	0.22	27%	0.68	425	0.89
2025	10.50	1.12	27%	3.40	271	2.84
2030	26.80	2.87	27%	8.68	150	4.01
2040	32.60	3.49	27%	10.56	150	4.88
2050	34.30	3.67	27%	11.11	150	5.14

4.2.2 Fuels

4.2.2.1 Petroleum fuel displacement (S2.4)

AB 2076 and AB 1007 specify 20% petroleum displacement by 2020, 26% by 2022, 30% by 2030 (CEC, 2003, 2007). These values were achieved by adjusting the amount of biofuels in gasoline and diesel fuel (but other fuels, which had no precedent for biofuel content other than E-85, by definition). See Table 36.

Table 36. Biomass fraction of fuels (S2.4)

Year	Biomass fraction of fuels (input parameter, % by energy content)							
	Gaso-line	E-85	Diesel	Natural gas	Jet fuel	Avia-tion gaso-line, fuel oil	Average (petro-leum)	Average (all)
	(input parameter)						(derived)	
2010	6.80%	85.00%	5.00%	0.00%	0.00%	0.00%	6.34%	3.03%
2015	14.54%	85.00%	12.00%	0.00%	0.00%	0.00%	13.73%	6.29%
2020	22.28%	85.00%	22.00%	0.00%	0.00%	0.00%	21.55%	10.50%
2022	27.00%	85.00%	27.00%	0.00%	0.00%	0.00%	26.07%	12.53%
2030	31.00%	85.00%	31.00%	0.00%	0.00%	0.00%	29.67%	13.57%
2050	31.00%	85.00%	31.00%	0.00%	0.00%	0.00%	29.15%	13.79%

4.2.2.2 In-state biofuel targets (S2.5)

EO S-06-06 (GO, 2006) requires a minimum of 20% in-state biofuels by 2010, 40% by 2020, and 75% by 2050. Scenario S1 already meets this criterion in 2010 (23%). Because S1 includes 100% in-state diesel in 2020, the amount of gasoline, aviation gasoline and E-85 assumptions were adjusted to 24%, so that the 40% target was met in aggregate. Between 2021 and 2050, the in-state fractions of all fuels except natural gas were linearly scaled to reach 75% in 2050 (thus diesel and jet fuel fractions actually decrease). See Table 37.

Table 37. In-state fraction of biofuels (S2.5)

Year	In-state fraction of biofuels (%)					
	Gasoline, aviation gasoline	E-85	Diesel, fuel oil	Natural gas	Jet fuel	Weighted average (derived)
	(input parameter)					
2010	12%	12%	100%	100%	100%	23%
2012	12%	12%	100%	100%	100%	25%
2020	24%	24%	100%	100%	100%	40%
2030	41%	41%	92%	100%	92%	57%
2040	58%	58%	83%	100%	83%	67%
2050	75%	75%	75%	100%	75%	75%

Although not specified in state policy, assumptions about the fraction provided by advanced technologies were updated from S1 (see S1.5) to be more aggressive, in keeping with the philosophy of pursuing biofuels with lower GHG intensities. See Table 38.

Table 38. Advanced biofuel fraction of fuels (S2)

Year	Advanced biofuel fraction of fuel (%, input parameter)			Total biofuel GHG content (in-state portion only, $kgCO_2e$/MBtu, derived)		
	Gasoline, E-85	E-85	Diesel	Gasoline, E-85	E-85	Diesel
2010	0.00%	0.00%	0.00%	62.98	62.98	5.65
2015	0.00%	0.00%	0.00%	61.19	61.19	5.65
2020	5.00%	5.00%	5.00%	58.09	58.09	5.58
2022	8.00%	8.00%	8.00%	56.58	56.58	6.67
2030	20.00%	20.00%	20.00%	49.99	49.99	11.05
2050	50.00%	50.00%	50.00%	29.51	29.51	22.12

4.2.3 Buildings

4.2.3.1 Additional Integrated Energy Policy Report building efficiency (S2.6)

Draft results from Navigant Consulting's *Potentials, Goals and Targets* (PGT) model (S. Swamy, pers. commun., 2013) were used to increase the energy savings of existing buildings relative to Integrated Energy Policy Report savings projected in S1. See Table 39.

Table 39. Stock building efficiency (S2.6)

Year	Number of units (same for all scenarios)		Energy consumption of remaining stock			
			Residential		Commercial	
	Residential	Commercial	Electricity	Natural gas	Electricity	Natural gas
	10^6 hh*	10^6 sf*	kWh/hh	therms/hh	kWh/sf	therms/sf
2010	12.87	7,059	6,976	406.1	14.24	0.2806
2011	12.94	7,086	7,039	412.6	14.23	0.2825
2015	13.25	7,389	7,130	386.0	13.93	0.2660
2020	13.88	7,795	7,058	370.6	13.48	0.2587
2025	14.41	8,013	7,396	359.9	13.21	0.2485
2030	14.98	8,247	7,584	350.1	13.26	0.2458
2040	16.04	8,935	7,865	336.3	13.33	0.2419
2050	16.87	9,976	8,065	327.1	13.38	0.2392

* hh = households; sf = square feet

4.2.3.2 California Public Utilities Commission (CPUC) Strategic Plan for efficient buildings (S2.7)

CPUC's strategic plan (CPUC, 2008) targets efficiency improvements over Title 24 standards for residential and commercial buildings, for both new construction and retrofits, between 2011 and 2020. Such targets are also qualitatively reflective of AB 758 (Brook et al., 2012) once fully implemented. These targets were simplified by expressing the Title 24 standards relative to the baseline building stock efficiencies for 2010. Note that the residential retrofit rate was chosen to allow all existing buildings to be retrofit by 2050. In fact, retrofit rates had to be reduced after 2030 to avoid retrofitting more than 100% of building stock in 2050. Commercial retrofits are not specified in the Strategic Plan, and are thus kept at the S1 level (0.3% yr^{-1}); these rates are increased in a separate policy (S3.10). See Table 40 through Table 43.

Table 40. Residential building efficiencies - new construction (S2.7)

Year	Annual rates* (input parameters)	Number of buildings* (derived)	Efficiency over 2010 (input parameters)		Efficiencies (derived)	
			Electricity	Natural gas	Electricity	Natural gas
	%/yr	10^6 hh/yr	%	%	kWh/hh	therms/hh
2010	2.85%	367.0	2.00%	0.00%	6,836	406.0
2011	0.55%	71.0	23.00%	23.00%	5,371	312.6
2015	0.88%	116.5	40.00%	40.00%	4,185	243.6
2020	1.15%	159.3	53.00%	53.00%	3,278	190.8
2025	1.15%	165.4	53.00%	53.00%	3,278	190.8
2030	1.15%	171.9	53.00%	53.00%	3,278	190.8
2040	1.15%	184.1	53.00%	53.00%	3,278	190.8
2050	1.15%	193.6	53.00%	53.00%	3,278	190.8

* Annual rates and number of buildings are identical for all scenarios

Table 41. Residential building efficiencies - retrofits (S2.7)

Year	Annual rates (input parameters)	Number of buildings (derived)	Efficiency over 2010 (input parameters)		Efficiencies (derived)	
			Electricity	Natural gas	Electricity	Natural gas
	%/yr	10^3 hh/yr	%	%	kWh/hh	therms/hh
2010	0.00%	-	0.00%	0.00%	6,975	406.0
2011	0.30%	38.8	9.08%	8.37%	6,342	372.0
2015	1.00%	132.5	20.00%	20.00%	5,580	324.8
2020	3.00%	416.3	40.00%	40.00%	4,185	243.6
2025	3.00%	432.2	40.00%	40.00%	4,185	243.6
2030	3.00%	449.3	40.00%	40.00%	4,185	243.6
2040	0.69%	110.7	40.00%	40.00%	4,185	243.6
2050	0.69%	116.4	40.00%	40.00%	4,185	243.6

Table 42. Commercial building efficiencies - new construction (S2.7)

Year	Annual rates* (input parameters)	Number of buildings* (derived)	Efficiency over 2010 (input parameters)		Efficiencies (derived)	
			Electricity	Natural gas	Electricity	Natural gas
	%/yr	10^6 sf/yr	%	%	kWh/sf	therms/sf
2010	1.32%	93.2	11.00%	17.00%	12.65	0.2324
2011	0.88%	62.5	9.91%	9.11%	12.81	0.2545
2015	1.90%	140.7	11.15%	14.52%	12.63	0.2393
2020	1.71%	133.5	11.32%	14.89%	12.61	0.2383
2025	1.66%	133.4	35.66%	37.44%	9.15	0.1752
2030	1.66%	137.3	60.00%	60.00%	5.69	0.1120
2040	1.66%	148.7	60.00%	60.00%	5.69	0.1120
2050	1.66%	166.1	60.00%	60.00%	5.69	0.1120

* Annual rates and number of buildings are identical for all scenarios

Table 43. Commercial building efficiencies - retrofits (S2.7)

Year	Annual rates (input parameters)	Number of buildings (derived)	Efficiency over 2010 (input parameters)		Efficiencies (derived)	
			Electricity	Natural gas	Electricity	Natural gas
	%/yr	10^6 sf/yr	%	%	kWh/sf	therms/sf
2010	0.00%	-	0.00%	0.00%	14.21	0.2800
2011	0.30%	21.26	9.91%	9.11%	12.81	0.2545
2015	0.30%	22.17	11.15%	14.52%	12.63	0.2393
2020	0.30%	23.39	11.32%	14.89%	12.61	0.2383
2025	0.30%	24.04	10.40%	16.73%	12.74	0.2332
2030	0.30%	24.74	10.40%	16.73%	12.74	0.2332
2040	0.30%	26.81	10.40%	16.73%	12.74	0.2332
2050	0.30%	29.93	10.40%	16.73%	12.74	0.2332

4.2.3.3 CPUC Strategic Plan for zero net energy buildings (S2.8)

The CPUC Strategic Plan (CPUC, 2008) specifies a fraction of new and existing buildings to become zero net energy by specific target years. Linear interpolation between these target years was performed to obtain annual fractions in the scenarios. Note that residential retrofits are not specified in the targets, but they were included in S3.10. See Table 44 and Table 45.

Table 44. Zero net energy building rates and energy savings (S2.8)

Year	Fraction of buildings affected				Total savings (GWh/yr equivalent)			
	Residential		Commercial		Residential		Commercial	
	New const.*	Retrofits	New const.	Retrofits	New const.	Retrofits	New const.	Retrofits
2010	0.0%	0.0%	0.0%	0.0%	-	-	-	-
2011	0.0%	0.0%	0.0%	0.0%	-	-	-	-
2015	50.0%	0.0%	25.0%	12.5%	712	-	276	24
2020	100.0%	0.0%	50.0%	25.0%	4,820	-	1,227	105
2025	100.0%	0.0%	75.0%	37.5%	9,392	-	4,038	244
2030	100.0%	0.0%	100.0%	50.0%	14,144	-	11,099	441
2040	100.0%	0.0%	100.0%	75.0%	24,180	-	25,452	1,028
2050	100.0%	0.0%	100.0%	100.0%	34,817	-	41,265	1,909

* New construction

Table 45. Zero net energy building energy savings breakdown (S2.8)

Year	Electricity savings (GWh/yr)				Natural gas savings (10^6 therms/yr)			
	Residential		Commercial		Residential		Commercial	
	New const.	Retrofits	New const.	Retrofits	New const.	Retrofits	New const.	Retrofits
2010	-	-	-	-	-	-	-	-
2011	-	-	-	-	-	-	-	-
2015	478	-	227	20	26	-	5	0
2020	3,192	-	1,003	87	183	-	25	2
2025	6,203	-	3,348	198	358	-	77	5
2030	9,331	-	9,316	354	540	-	200	10
2040	15,941	-	21,526	818	925	-	441	24
2050	22,946	-	34,978	1,510	1,332	-	706	45

4.2.4 Electricity

4.2.4.1 Increased CHP (S2.9)

SP E-2 sets a target of an additional 30 TWh/yr of CHP by 2020 (CARB, 2008), and Governor Brown's *Clean Energy Jobs Plan* calls for an additional 6.5 GW of capacity by 2030 (GO, 2011). Due to the amount of required other generation in this scenario, the 2020 CHP target was not able to be met without reducing NGCC generation below zero, so this increase was limited to 15 TWh/yr increase (total generation 57.3 TWh in 2020). The 2030 target was achievable; however, by 2040, because of the increases in other non-fossil resources, the CHP capacity again had to be reduced to 13.5 GW to avoid negative NGCC generation until nuclear power was removed in 2046 (see S2.12). See Table 46.

Table 46. Fossil generation, showing CHP targets (S2.9)

Year	Imported coal	Once-through cooling	CHP	NGSC	NGCC	Other coal	Other
	% of gross demand (input parameters)						
2010	9.91%	4.82%	14.14%	2.33%	13.08%	1.17%	13.43%
2011	9.89%	4.82%	14.14%	2.33%	15.19%	0.83%	12.54%
2016	7.87%	3.79%	16.83%	2.48%	15.17%	0.69%	8.06%
2020	6.06%	2.24%	19.83%	2.60%	1.66%	0.01%	4.47%
2030	0.88%	0.00%	26.15%	2.60%	5.95%	0.00%	0.00%
2040	0.00%	0.00%	23.50%	2.60%	3.29%	0.00%	0.00%
2050	0.00%	0.00%	22.81%	2.60%	4.52%	0.00%	0.00%
	GW installed capacity (derived)						
2010	3.89	15.57	8.50	26.49	10.77	0.40	7.25
2011	3.89	14.90	8.50	26.54	12.53	0.28	7.35
2016	3.34	11.47	10.01	27.94	12.38	0.23	7.59
2020	2.48	7.37	11.51	28.60	1.32	0.00	7.39
2030	0.37	-	15.00	28.26	4.69	-	9.88
2040	-	-	13.50	28.30	2.60	-	11.68
2050	-	-	13.50	29.15	3.67	-	13.60

4.2.4.2 Governor's distributed generation target (S2.10)

Governor Brown's *Clean Energy Jobs Plan* calls for an ambitious goal of 12 GW of distributed generation by 2020 (GO, 2011). This capacity was modeled as solar PV with 24% capacity factor, resulting in 25 TWh yr^{-1} of generation. This capacity is additional to state RPS targets, which are also 4% higher in 2020 to reflect local efforts with targets greater than the statewide goal of 33% (S2.17). Note that some additional solar PV not included in the above are built in response to zero net energy building targets (S2.8); these targets are not as large as the demand implied in Table 44 because some of this generation is satisfied by the distributed generation target, which covers all zero net energy demand until 2030. Table 47 and Table 48 summarize renewable energy assumptions of S2.

Table 47. RPS, distributed generation and zero net energy goals (S2.8, S2.9, S2.17)

Year	RPS target (input para-meter)	RPS genera-tion	RPS-eligible demand	Ineligible demand: Distributed solar PV not subject to RPS	Ineligible demand: Additional solar PV for zero net energy targets	Ineligible demand: Other self-generation	Gross demand
	% of eligible	TWh/yr (derived)					
2010	11.3%	32.5	286.4	-	-	12.4	298.8
2011	10.0%	28.4	284.2	2.5	-	12.6	299.3
2016	20.0%	53.5	267.7	15.0	-	13.4	296.1
2020	37.0%	92.7	250.6	25.0	-	13.5	289.1
2030	37.0%	89.5	241.9	25.0	0.7	18.1	285.6
2040	37.0%	79.2	214.0	25.0	25.7	21.4	286.0
2050	37.0%	71.0	191.8	25.0	53.0	24.9	294.6

Table 48. Breakdown by renewable generation type (S2)

Year	Biomass	Geothermal	Small hydro	RPS-eligible solar (PV and concentrating thermal)	Wind	Other
	% of renewable generation (input parameters)					
2011	15.3%	33.5%	1.6%	2.8%	20.1%	26.7%
2016	16.3%	29.3%	1.4%	19.0%	24.2%	9.8%
2020	14.6%	18.1%	0.8%	36.9%	25.0%	4.5%
2030	15.1%	18.7%	0.9%	37.9%	25.7%	1.7%
2040	15.1%	18.7%	0.9%	37.9%	25.7%	1.7%
2050	15.1%	18.7%	0.9%	37.9%	25.7%	1.7%
	GW installed capacity (derived)					
2010	1.02	2.59	0.14	0.36	2.38	1.66
2011	1.02	1.89	0.14	0.36	2.39	1.55
2016	1.75	3.11	0.23	4.26	5.41	0.99
2020	2.26	3.33	0.25	12.27	9.70	0.54
2030	2.21	3.30	0.25	12.19	9.63	0.00
2040	1.96	2.92	0.22	10.78	8.52	0.00
2050	1.75	2.62	0.20	9.66	7.64	0.00

4.2.4.3 Electricity storage target (S2.11), Diablo Canyon nuclear plant relicensed (S2.12) and build CCS power (S2.13)

These three policies are summarized in Table 49 below. A storage capacity equal to 0.4% of gross energy generated in 2020 (1.3 GW, assuming 10% capacity factor) was modeled (CPUC, 2010), along with extending the Diablo Canyon nuclear power plant to 2046 (NRC, 2013) and construction of a 300 MW CCS power plant (assumed to use coal as the fuel) in 2020 (HECA, 2013).

Table 49. Low-carbon non-RPS generation (S2.11-S2.13)

Year	Coal with CCS	Nuclear	Large hydro	Non-RPS solar PV	Other non-RPS	Exports	Imports	Storage
	% of gross demand (input parameters)							
2010	0.00%	14.95%	11.99%	0.84%	4.16%	-1.69%	33.67%	0.00%
2011	0.00%	14.75%	12.69%	0.84%	4.21%	-1.72%	32.07%	0.04%
2016	0.00%	7.73%	11.43%	5.07%	4.53%	-1.72%	22.12%	0.24%
2020	0.77%	7.16%	11.56%	8.65%	4.67%	-1.76%	13.98%	0.40%
2030	0.78%	6.34%	11.53%	8.99%	6.33%	-0.89%	0.88%	0.40%
2040	0.78%	6.34%	11.52%	17.71%	7.47%	-0.89%	0.00%	0.40%
2050	0.76%	0.00%	11.18%	26.47%	8.44%	-0.87%	0.00%	0.40%
	GW installed capacity (derived)							
2010	-	5.43	11.39	1.37	6.79	N/A	N/A	-
2011	-	5.37	12.08	1.37	6.89	N/A	N/A	0.14
2016	-	2.78	10.76	8.72	7.34	N/A	N/A	0.81
2020	0.30	2.52	10.63	17.82	7.39	N/A	N/A	1.32
2030	0.30	2.20	10.47	18.17	9.88	N/A	N/A	1.30
2040	0.30	2.20	10.47	31.36	11.68	N/A	N/A	1.31
2050	0.30	0.00	10.47	45.93	13.60	N/A	N/A	1.35

4.2.5 Non-energy and other

4.2.5.1 Additional water conservation (S2.14)

CARB (2008) Scoping Plan water conservation measures W-1 through W-4 (additional water use efficiency, water recycling, pumping and treatment efficiency, and urban runoff re-use) sufficient to save an additional 4 $MtCO_2e$ yr^{-1} in 2020 was included in S2.14, by increasing per capita water savings by an additional 26% over S1.11.

Table 50. Energy savings from water conservation (S2.14)

Year	Residential			Commercial		
	Energy savings	Electricity savings	Natural gas savings	Energy savings	Electricity savings	Natural gas savings
	% of 2010	kWh/yr/ capita	Therms/ yr/capita	% of 2010	kWh/yr/sf	therms/ yr/10^3 sf
2010	0%	-	-	0%	-	-
2020	46%	195.8	22.39	46%	0.812	18.33
2030	46%	195.8	22.39	46%	0.812	18.33
2040	46%	195.8	22.39	46%	0.812	18.33
2050	46%	195.8	22.39	46%	0.812	18.33

4.2.5.2 Waste diversion (S2.15)

AB 341 calls for 75% waste diversion from landfills by 2020 and net zero landfill emissions by 2035 (CA LegInfo, 2011). Because it is not clear how these goals will be achieved, they were included in S2 rather than S1. The effect of these policies were modeled by increasing the biogenic share of landfill emissions accordingly, reducing net GHG emissions. See Table 51.

Table 51. Reduction in emissions from landfills (S2.15)

Year	Gross emissions	Biogenic share of total	Net emissions
	$kgCO_2$ $person^{-1}$ yr^{-1}	%	$MtCO_2e$ yr^{-1}
2010	372	50.3	6.90
2020	397	75.0	4.04
2030	424	90.9	1.72
2035	438	100.0	-
2050	482	100.0	-

4.2.5.3 HFC phase-out (S2.16)

As discussed in the main text, the U.S. and China have recently agreed to an HFC phase-out beginning in 2020, leading to a complete ban by 2050 (WP, 2013). Here a gradual phase-out was assumed in California, beginning with 2.5% reduction in 2020 (reflecting SP H-6; CARB, 2008) and growing to 25% reduction in 2030, 50% in 2040 and 100% in 2050. Table 52 breaks down these emissions by sector.

Table 52. HFC phase-out (S2.16)

Year	HFC emissions (% of baseline, input parameter)	Residen-tial	Commer-cial	Industrial	LDV	HDV	Other transport	Total
		$MtCO_2e\ yr^{-1}$ (derived)						
2010	100%	2.89	5.81	0.77	2.48	1.00	0.27	13.23
2020	97.5%	6.56	8.47	0.91	1.82	1.30	0.31	19.37
2030	75%	6.95	7.94	0.76	0.81	1.31	0.25	18.01
2040	50%	4.98	5.51	0.52	0.35	1.10	0.17	12.63
2050	0%	-	-	-	-	-	-	-

4.2.5.4 Local reductions beyond state targets (S2.17)

In addition to local RPS targets that exceed the state target (described above under S2.10), CARB estimates that other local actions may reduce statewide GHG emissions by 8.2 $MtCO_2e\ yr^{-1}$ in 2020 (R. McCarthy, pers. commun., 2013). Table 53 summarizes the assumptions for both RPS targets and additional GHG offsets which together constitute the effects of S2.16.

Table 53. Local actions (S2.17)

Year	RPS target (% of eligible)	RPS incremental to S1 (% of eligible)	Additional GHG offsets ($MtCO_2e\ yr^{-1}$)
2010	11.3%	-	-
2015	18.0%	-	2.34
2020	37.0%	4.0%	8.20
2030	37.0%	4.0%	8.20
2040	37.0%	4.0%	8.20
2050	37.0%	4.0%	8.20

4.3 Potential Policy and Technology Futures scenario (S3)

4.3.1 Transportation

4.3.1.1 National Academies LDV efficiency (S3.1) and LDV automation (S3.2)

The LDV efficiency targets in S3.1 are based on mid-case assumptions from NAS (2013) for new vehicles sold in 2030 and 2050; the efficiencies of vehicle stock (which was modeled) were delayed by 10 years relative to these targets, and the target efficiencies reduced by an on-road correction factor of 0.833 (20%). For years prior to 2030, the average gasoline engine efficiency was adjusted to match S1.1, since derived NAS values were actually slightly lower. Additional savings due to LDV automation (S3.2) were also assumed, including smoother acceleration and braking, vehicle platooning, trip planning, etc., based on Barth and Boriboonsomsin (2008) and the author's own estimates. This effect gradually increased efficiency starting with 5% savings in 2030 and reaching 25% by 2050. Final average gasoline efficiencies were linearly interpolated for intervening years. See Table 54. Note that S3.2 also included HDV automation; see discussion under S3.5 below.

Table 54. LDV efficiency parameters (S3.1 and S3.2)

Year	Fuel efficiency (mpg)					
	Average gasoline	Automation savings	Final average gasoline	Gasoline ICEV	Gasoline HEV	Gasoline PHEV
	(input parameter)		(derived)			
2010	19.32	0%	19.32	19.32	29.06	30.08
2013	21.09	0%	21.09	21.08	35.71	34.37
2021	26.85	0%	26.85	26.71	47.31	43.20
2025	29.92	0%	29.92	29.72	51.63	45.37
2030	34.57	5%	36.39	36.12	59.67	50.83
2040	46.23	10%	51.37	50.76	82.20	81.80
2050	53.94	25%	71.92	71.08	114.00	118.23

4.3.1.2 Accelerated LDV ZEV deployment (S3.3)

S3.3 assumes that ZEVs will be deployed more rapidly than in S1.2, reaching 25% of vehicle stock by 2035 and 60% in 2050. The scenario was based on Wei et al. (2012, 2013). See Table 55.

Table 55. ZEV fraction of LDVs (S3.3)

Year	ZEV fraction of LDV stock (input parameter)	Number of ZEVs (derived, thousands)
2010	0.03%	7
2013	0.44%	97
2020	2.93%	685
2025	5.80%	1,405
2035	24.54%	6,378
2050	59.83%	17,017

4.3.1.3 USPIRG LDV VMT reductions (S3.4)

S3.4 follow the projections of USPIRG (2013), which was an estimate of total VMT for the U.S. as a whole, declining by 15% in 2025 and then staying approximately constant through 2040. This scenario was adapted for California by converting the relative change in total VMT to the change in VMT per vehicle relative to S1.3. This scenario reduces VMT per vehicle by 14% relative to S1.3 in 2020, 21% in 2030, and 25% by 2040; the decrease is then assumed constant through 2050. See Table 56. Note that, in addition, there is a decrease in VMT due to double the high-speed rail deployment (S3.7) that is included in this table so that the total impact on VMT can be shown. See section 4.3.1.6 for details.

Table 56. VMT scenario (S3.4) and double high-speed rail deployment (S3.7)

Year	Change in VMT per vehicle	Additional change in VMT per vehicle due to high-speed rail	Total change in VMT per vehicle	Total VMT per vehicle (mi/yr)	Total VMT (10^9 mi/yr)	Change in total VMT relative to 2010
	(input parameter)		(derived)			
2010	0.00%	0.00%	0.00%	12,406	272.36	0.00%
2020	-14.28%	0.00%	-14.28%	10,490	245.28	-9.94%
2030	-20.64%	-2.81%	-23.44%	8,716	219.00	-19.59%
2040	-24.71%	-3.27%	-27.98%	7,997	215.15	-21.01%
2050	-24.71%	-3.27%	-27.98%	7,958	226.35	-16.89%

4.3.1.4 NPC HDV efficiency (S3.5) and HDV automation (S3.2)

Efficiency improvements estimated by NPC (2012a) were used for HDVs (S3.5), adding an additional 2% efficiency savings after 2030 to account for HDV automation in the HHD sub-sector (S3.2) based on the author's own estimate of 12% savings in 15% of HDV VMT. See Table 57.

Table 57. HDV efficiency improvements (S3.5 and S3.2)

Year	Change relative to baseline (input parameters)			Fuel efficiency (mi/gge, derived)				
				In-state HHD		OOS HHD	MHD	
	In-state HHD	OOS HHD	MHD	Diesel	Natural gas	Diesel	Gasoline	Diesel
2010	0.00%	0.00%	0.00%	5.67	3.81	5.59	9.84	12.51
2020	18.00%	18.00%	1.30%	8.54	6.20	8.36	11.12	14.81
2030	37.00%	37.00%	1.30%	11.16	10.24	10.88	11.25	14.49
2050	47.00%	47.00%	10.00%	13.24	12.98	12.91	12.50	15.63

4.3.1.5 Natural gas HDVs (S3.6)

NPC (2012a) estimates of increasing shares of natural gas HDVs were used (natural gas is a fuel with lower particulate and GHG emissions). See Table 58.

Table 58. Natural gas HDVs (S3.6)

Year	Fraction of natural gas vehicles by class (input parameter)			Number of natural gas vehicles (derived)		
	In-state HHD	OOS HHD	MHD	In-state HHD	OOS HHD	MHD
2010	0.05%	0.00%	0.00%	83	0	0
2020	5.00%	5.00%	5.00%	11,273	2,440	82,612
2030	15.00%	15.00%	10.00%	40,981	10,289	192,208
2050	45.00%	45.00%	29.00%	170,586	41,411	669,526

4.3.1.6 Double high-speed rail deployment (S3.7)

Here it is assumed that high-speed rail ridership levels are double that of S2.3. See Table 59.

Table 59. Double high-speed rail deployment (S3.7)

	Ridership (input parameter)	High-speed rail energy increase (derived)	Fraction aviation displacement (input parameter)	Aviation energy reduction (derived)	VMT decrease per rider (derived)	
Year	10^6/yr	TWh/yr	% of flights	10^{12} Btu/yr	mi/rider	10^9 mi/yr
2022	4.20	0.45	27%	1.36	425	1.78
2025	21.00	2.25	27%	6.80	271	5.68
2030	53.60	5.73	27%	17.37	150	8.03
2040	65.20	6.97	27%	21.12	150	9.77
2050	68.60	7.33	27%	22.23	150	10.27

4.3.2 Fuels

4.3.2.1 Cleaner petroleum fuels, renewable natural gas and jet fuel (S3.8)

Policies included are:

1. SP I-2 and I-3, which address emissions from oil and gas extraction and transmission. CARB (2008) projects that these measures will reduce statewide GHG emissions by 1.1 $MtCO_2e$ yr^{-1} in 2020. This results in an average fuel GHG intensity reduction of 5 gCO_2e/MJ (according to LCFS accounting rules which include OOS emissions) by 2030. This was accomplished by increasing the biomass portion of fuels by an additional 6% for gasoline and diesel. The amount of renewable fuels in gasoline and diesel was further adjusted upward through 2050 to keep the average petroleum fraction approximately the same (35%).
2. Increased renewable natural gas to 100 million diesel-gallons-equivalent (Mdge) by 2020, and 450 Mdge in 2035 and thereafter (NPC, 2012b), which was equivalent to 0.7% biomass in 2020, increasing to ~3% in 2035 and then declining to 2.4% in 2050.
3. Increased renewable jet fuel to meet the United target of 5 million gallons per year (Gibbons, 2013), or 1% of demand, by 2015; this was maintained in future years.

See Table 60.

Table 60. Cleaner petroleum fuels, renewable natural gas and jet fuel (S3.8)

Year	Biomass fraction of fuels (input parameter, % by energy content)							
	Gaso-line	E-85	Diesel	Natural gas	Jet fuel	Avia-tion gaso-line, fuel oil	Average (petro-leum fuels)	Average (all)
	(input parameter)						(derived)	
2010	6.80%	85.00%	5.00%	0.00%	0.00%	0.00%	6.34%	3.03%
2015	14.54%	85.00%	12.00%	0.35%	1.00%	0.00%	13.73%	6.25%
2020	22.28%	85.00%	22.00%	0.70%	1.00%	0.00%	21.46%	10.55%
2022	27.00%	85.00%	27.00%	1.12%	1.00%	0.00%	25.92%	12.75%
2030	37.00%	85.00%	37.00%	2.80%	1.00%	0.00%	34.95%	17.17%
2050	41.00%	85.00%	41.00%	2.40%	1.00%	0.00%	35.32%	13.66%

The portion of advanced biofuels in gasoline, E-85 and diesel were also increased over what was used in S2, consistent with more aggressive pursuit of these biofuels:

Table 61. Advanced biofuel fraction of fuels (S3)

	Advanced biofuel fraction of fuel (%, input parameter)			Total biofuel GHG content (in-state portion only, kgCO_2e/MBtu, derived)		
Year	Gasoline, E-85	E-85	Diesel	Gasoline, E-85	E-85	Diesel
2010	0.00%	0.00%	0.00%	62.98	62.98	5.65
2015	0.00%	0.00%	0.00%	61.19	61.19	5.65
2020	10.00%	10.00%	10.00%	57.96	57.96	5.50
2022	18.00%	18.00%	18.00%	56.23	56.23	6.51
2030	50.00%	50.00%	50.00%	47.78	47.78	10.62
2050	100.00%	100.00%	100.00%	21.04	21.04	21.54

4.3.3 Buildings

4.3.3.1 Building electrification (S3.9) and commercial building/residential zero net energy retrofits (S3.10)

The impact of building electrification (residential and commercial) was simulated by a gradual phase-out of natural gas by 2050 (by increasing whole-building natural gas efficiency toward 100%, resulting in zero natural gas demand in 2050). This was based on work by a number of authors (ECF, 2010; CCST, 2011; Greenblatt et al., 2012; McCollum et al., 2012; Williams et al., 2012; Wei et al., 2012, 2013; Yang et al., 2014). There is a corresponding increase in electrical demand, facilitated by a decrease in efficiency. It was assumed that increasingly efficient electric heat pump space and water heating replaces equally increasingly efficient natural gas technology, such that the electrical-to-natural gas energy replacement ratio remains constant at 33% or 8.7 kWh $therm^{-1}$. While keeping this ratio fixed conveniently reduced the number of assumptions, there is reason to expect heat pump efficiencies to increase as the technology matures. See Table 62.

Table 62. Building electrification assumptions (S3.9)

Year	Assumed heating efficiency		Electricity increase per unit natural gas decrease		Replacement rates (residential & commercial)	
					New construction	Retrofits
	Natural gas	Electricity	%	kWh/therm	%	%
2010	65%	200%	33%	8.69	0%	0%
2020	70%	215%	33%	8.69	50%	20%
2030	80%	246%	33%	8.69	90%	50%
2040	90%	277%	33%	8.69	100%	90%
2050	90%	277%	33%	8.69	100%	100%

Table 63 through Table 66 show the assumptions for residential and commercial building efficiencies for new construction and retrofits that includes more efficient commercial retrofits (S3.10) to match the retrofit rates found in the residential sector in S2.7. These tables also reflect the efficiency changes due to building electrification (S3.9)

Table 63. Residential building efficiencies - new construction (S3.9)

Year	Annual rates* (input parameters)	Number of buildings* (derived)	Efficiency over 2010 (input parameters)		Efficiencies (derived)	
			Electricity	Natural gas	Electricity	Natural gas
	%/yr	10^6 hh/yr	%	%	kWh/hh	therms/hh
2010	2.85%	367.0	2.00%	0.00%	6,836	406.0
2011	0.55%	71.0	23.00%	23.00%	5,371	312.6
2015	0.88%	116.5	40.00%	40.00%	4,185	243.6
2020	1.15%	159.3	41.25%	76.50%	4,098	95.4
2025	1.15%	165.4	36.08%	85.90%	4,459	57.2
2030	1.15%	171.9	31.38%	95.30%	4,786	19.1
2040	1.15%	184.1	29.03%	100.00%	4,950	0.0
2050	1.15%	193.6	29.03%	100.00%	4,950	0.0

* Annual rates and number of buildings are identical for all scenarios

Table 64. Residential building efficiencies - retrofits (S3.9)

Year	Annual rates (input parameters)	Number of buildings (derived)	Efficiency over 2010 (input parameters)		Efficiencies (derived)	
			Electricity	Natural gas	Electricity	Natural gas
	%/yr	10^3 hh/yr	%	%	kWh/hh	therms/hh
2010	0.00%	-	0.00%	0.00%	6,975	406.0
2011	0.30%	38.81	9.08%	8.37%	6,342	372.0
2015	1.00%	132.55	20.00%	20.00%	5,580	324.8
2020	3.00%	416.27	34.00%	52.00%	4,604	194.9
2025	3.00%	432.20	29.20%	61.00%	4,939	158.3
2030	3.00%	449.30	25.00%	70.00%	5,232	121.8
2040	0.69%	110.68	12.40%	94.00%	6,110	24.4
2050	0.69%	116.40	12.40%	94.00%	6,110	24.4

Table 65. Commercial building efficiencies - new construction (S3.9)

Year	Annual rates[a] (input parameters)	Number of buildings[a] (derived)	Efficiency over 2010 (input parameters)		Efficiencies (derived)	
			Electricity	Natural gas	Electricity	Natural gas
	%/yr	10^6 sf/yr	%	%	kWh/sf	therms/sf
2010	1.32%	93.2	11.00%	17.00%	12.65	0.2324
2011	0.88%	62.5	9.91%	9.11%	12.81	0.2545
2015	1.90%	140.7	11.15%	14.52%	12.63	0.2393
2020	1.71%	133.5	4.22%	57.44%	13.61	0.1192
2025	1.66%	133.4	27.94%	81.23%	10.24	0.0525
2030	1.66%	137.3	54.00%	96.00%	6.54	0.0112
2040	1.66%	148.7	53.20%	100.00%	6.65	0.0000
2050	1.66%	166.1	53.20%	100.00%	6.65	0.0000

[a] Annual rates and number of buildings are identical for all scenarios

Table 66. Commercial building efficiencies - retrofits (S3.9 and S3.10)

Year	Annual rates (input parameters)	Number of buildings (derived)	Efficiency over 2010 (input parameters)		Efficiencies (derived)	
			Electricity	Natural gas	Electricity	Natural gas
	%/yr	10^6 sf/yr	%	%	kWh/sf	therms/sf
2010	0.00%	-	0.00%	0.00%	14.21	0.2800
2011	0.30%	21.26	9.91%	9.11%	12.81	0.2545
2015	1.00%	73.89	11.15%	14.52%	12.63	0.2393
2020	3.00%	233.86	8.66%	31.91%	12.98	0.1906
2025	3.00%	240.39	5.03%	45.87%	13.50	0.1516
2030	2.50%	206.18	3.23%	58.36%	13.75	0.1166
2040	0.00%	-	-2.14%	91.67%	14.52	0.0233
2050	0.00%	-	-2.14%	91.67%	14.52	0.0233

Zero net energy savings are also greater due to the inclusion of residential retrofits, more aggressive commercial new construction targets (100% by 2020 instead of 2030), and more building efficiency, which are also part of S3.10. See Table 67 and Table 68.

Table 67. Zero net energy building rates and energy savings (S3.10)

Year	Fraction of buildings affected				Total savings (GWh/yr equivalent)			
	Residential		Commercial		Residential		Commercial	
	New const.[a]	Retrofits	New const.	Retrofits	New const.	Retrofits	New const.	Retrofits
2010	0.0%	0.0%	0.0%	0.0%	-	-	-	-
2011	0.0%	0.0%	0.0%	0.0%	-	-	-	-
2015	50.0%	12.5%	50.0%	12.5%	712	90	552	54
2020	100.0%	25.0%	100.0%	25.0%	4,832	1,520	2,476	532
2025	100.0%	37.5%	100.0%	37.5%	9,420	5,670	5,418	1,656
2030	100.0%	50.0%	100.0%	50.0%	14,185	12,275	11,150	3,248
2040	100.0%	75.0%	100.0%	75.0%	24,267	26,976	25,556	6,259
2050	100.0%	100.0%	100.0%	100.0%	34,957	40,826	41,419	8,345

[a] New construction

Table 68. Zero net energy building energy savings breakdown (S3.10)

Year	Electricity savings (GWh/yr)				Natural gas savings (10^6 therms/yr)			
	Residential		Commercial		Residential		Commercial	
	New const.[a]	Retrofits	New const.	Retrofits	New const.	Retrofits	New const.	Retrofits
2010	-	-	-	-	-	-	-	-
2011	-	-	-	-	-	-	-	-
2015	478	60	455	45	26	3	11	1
2020	2,857	892	1,595	375	222	70	99	18
2025	5,024	3,071	3,344	972	493	292	233	77
2030	6,986	6,152	7,551	1,606	808	687	404	184
2040	10,737	11,941	18,450	2,535	1,519	1,688	798	418
2050	14,574	16,906	30,377	3,380	2,288	2,685	1,239	557

[a] New construction

4.3.4 Electricity

4.3.4.1 RPS 51% target (S3.11)

The RPS target was increased to 40% by 2020 and 51% by 2030, following the proposed target in AB 177 (CA LegInfo, 2013), though this bill never passed into law. It represents an increase of ~50% over the 2020 target in S1.8. See Table 69.

Table 69. RPS 51% target (S3.11)

Year	RPS target (input para-meter)	RPS genera-tion	RPS-eligible demand	Ineligible demand: Distributed solar PV not subject to RPS	Ineligible demand: Additional solar PV for zero net energy targets	Other self-generation	Gross demand
	% of eligible	TWh/yr (derived)					
2010	11.3%	32.5	286.4	-	-	12.4	298.8
2011	10.0%	28.4	284.3	2.5	-	12.6	299.4
2016	20.0%	53.5	267.6	15.0	-	13.4	296.0
2020	40.0%	100.5	251.3	25.0	-	13.5	289.8
2030	51.0%	121.0	237.3	25.0	15.9	20.9	299.1
2040	51.0%	105.7	207.3	25.0	58.1	24.8	315.2
2050	51.0%	95.8	187.8	25.0	100.5	28.5	341.9

Table 70 shows the breakdown by renewable generation type.

Table 70. Breakdown by renewable generation type (S3)

Year	Biomass	Geothermal	Small hydro	RPS-eligible solar (PV and concentrating thermal)	Wind	Other
	% of renewable generation (input parameters)					
2011	15.3%	33.5%	1.6%	2.8%	20.1%	26.7%
2016	16.3%	29.3%	1.4%	19.0%	24.2%	9.8%
2020	14.7%	18.2%	0.8%	37.0%	25.1%	4.3%
2030	15.1%	18.7%	0.9%	37.9%	25.7%	1.7%
2040	15.1%	18.7%	0.9%	37.9%	25.7%	1.7%
2050	15.1%	18.7%	0.9%	37.9%	25.7%	1.7%
	GW installed capacity (derived)					
2010	1.02	2.59	0.14	0.36	2.38	1.66
2011	1.02	1.89	0.14	0.36	2.39	1.56
2016	1.75	3.11	0.23	4.26	5.41	0.99
2020	2.45	3.62	0.27	13.33	10.54	0.54
2030	2.99	4.47	0.33	16.48	13.03	0.00
2040	2.61	3.90	0.29	14.40	11.38	0.00
2050	2.37	3.54	0.26	13.04	10.31	0.00

4.3.4.2 Reduced CHP (S3.12), SONGS nuclear power relicense/replacement (S3.13), build 8x CCS power (S3.14), and electricity storage 5x target (S3.15)

These policies are summarized in combination because they all affect low-carbon non-RPS generation. See Table 71. Details follow.

Table 71. Low-carbon non-RPS generation (S3.12-S3.15)

Year	Coal with CCS	Nuclear	Large hydro	Non-RPS solar PV	Other non-RPS	Exports	Im-ports	Storage
	% of gross demand (input parameters)							
2010	0.00%	14.95%	11.99%	0.84%	4.16%	-1.69%	33.67%	0.00%
2011	0.00%	14.75%	12.69%	0.84%	4.20%	-1.72%	32.07%	0.10%
2016	0.00%	7.73%	11.43%	5.07%	4.53%	-1.72%	22.13%	0.60%
2020	0.77%	13.40%	11.53%	8.63%	4.66%	-1.76%	13.97%	1.00%
2030	1.44%	12.12%	11.01%	13.66%	7.00%	-0.85%	0.84%	2.00%
2040	2.03%	11.50%	10.45%	26.35%	7.88%	-0.81%	0.00%	2.00%
2050	5.45%	0.00%	9.63%	36.72%	8.34%	-0.75%	0.00%	2.00%
	GW installed capacity (derived)							
2010	-	5.43	11.39	1.36	6.79	N/A	N/A	-
2011	-	5.37	12.08	1.37	6.89	N/A	N/A	0.34
2016	-	2.78	10.76	8.72	7.34	N/A	N/A	2.03
2020	0.30	4.72	10.63	18.18	7.39	N/A	N/A	3.31
2030	0.58	4.40	10.47	27.92	11.45	N/A	N/A	6.83
2040	0.86	4.40	10.47	50.30	13.59	N/A	N/A	7.20
2050	2.50	0.00	10.47	73.09	15.61	N/A	N/A	7.80

To accommodate additional non-fossil generation from the higher RPS, increased CCS and increased nuclear, the CHP target (S2.9) had to be completely removed, and the CHP capacity further reduced over time below that in S1 to keep NGCC capacity above zero (S3.12). Note that the CPUC has authorized the replacement of lost capacity from SONGS with a combination of natural gas generation and "preferred" resources such as energy efficiency, renewable generation and energy storage (CPUC, 2014a); in the model, NGCC provides whatever remaining generation capacity is required to meet demand.

In addition to relicensing Diablo Canyon nuclear plant through 2045, it was also assumed that the 2.2 GW SONGS nuclear plant (SONGS, 2013) is relicensed in 2020 (or a comparable amount of capacity is brought online elsewhere) instead of being decommissioned, and is allowed to run through 2045 (S3.13).

The CCS expansion policy (S3.14) assumes capacity in 2050 is 2.5 GW, about eight times the 2020 target in S2.13, so that it accounts for 5.5% of gross generation in that year.

S3.15 increased the amount of electricity storage to 1.0% of gross generation in 2020 (3.3 GW at 10% capacity factor) and 2.0% by 2030 (6.8 GW)—about five times the S2.11 level. The amount of load following NGSC was kept at 3% of gross generation, however, to balance the larger fractions of renewables assumed, but this capacity was varied in the uncertainty analysis. The CHP and NGSC following assumptions are summarized in Table 72.

Table 72. Fossil generation (S3.12-S3.15)

Year	Imported coal	Once-through cooling	CHP	NGSC	NGCC	Other coal	Other
	% of gross demand (input parameters)						
2010	9.91%	4.82%	14.14%	2.37%	13.05%	1.17%	13.43%
2011	9.89%	4.82%	14.14%	2.37%	15.16%	0.83%	12.54%
2016	7.87%	3.79%	12.19%	2.72%	19.33%	0.92%	8.06%
2020	6.05%	2.24%	10.31%	3.00%	2.01%	0.02%	4.47%
2030	0.84%	0.00%	9.99%	3.00%	1.33%	0.00%	0.00%
2040	0.00%	0.00%	5.53%	3.00%	0.53%	0.00%	0.00%
2050	0.00%	0.00%	2.18%	3.00%	7.40%	0.00%	0.00%
	GW installed capacity (derived)						
2010	3.89	15.57	8.50	26.95	10.74	0.40	7.25
2011	3.89	14.90	8.50	27.00	12.51	0.28	7.34
2016	3.34	11.47	7.25	30.64	15.77	0.31	7.67
2020	2.48	7.37	6.00	33.09	1.61	0.01	7.39
2030	0.37	-	6.00	34.14	1.10	-	11.45
2040	-	-	3.50	35.98	0.46	-	13.59
2050	-	-	1.50	39.02	6.97	-	15.61

4.3.5 Non-energy and other

4.3.5.1 Accelerated HFC phase-out (S3.16)

Compared to S2.16, the HFC phase-out schedule in S3.16 is more aggressive, reaching 70% of baseline by 2020 (consistent with SP H-7, with an estimated 5 $MtCO_2e\ yr^{-1}$ reduction; CARB, 2008) and 45% by 2030. Table 73 summarizes these assumptions.

Table 73. HFC phase-out (S3.16)

Year	HFC emissions (% of baseline, input parameter)	Residen-tial	Commer-cial	Industrial	LDV	HDV	Other transport	Total
		$MtCO_2e\ yr^{-1}$ (derived)						
2010	100%	2.89	5.81	0.77	2.48	1.00	0.27	13.23
2020	70%	4.71	6.08	0.65	1.31	0.94	0.23	13.91
2030	45%	4.17	4.76	0.45	0.49	0.78	0.15	10.81
2040	20%	1.99	2.20	0.21	0.14	0.44	0.07	5.05
2050	0%	-	-	-	-	-	-	-

4.3.5.2 Re-convert pasture to forests (S3.17)

S3.17 expands on S1.13 to save an additional 15 $MtCO_2e\ yr^{-1}$ by 2050. The basis of this expansion is afforestation, or the re-conversion of California grazing lands that were once forests back to their native state; a study by Brown et al. (2004) estimates that up to 112 $MtCO_2e\ yr^{-1}$ could be sequestered after 40 years on 18 million acres. It was conservatively assumed that a small fraction of this land would be afforested in phases, beginning in 2015. Specifically, it was assumed that 0.8 million acres would be afforested beginning in 2015, sequestering 5 $MtCO_2e\ yr^{-1}$ in 2035 and 10 $MtCO_2e\ yr^{-1}$ in 2050. Another 0.8 million acres would be afforested beginning in 2030, reaching 5 $MtCO_2e\ yr^{-1}$ in 2050. In total, about 9% of the 17.8 million acres available for sequestration would be used. These savings from afforestation are comparable as a percentage of 1990 emissions to estimates for the European Union in 2050 (ECF, 2010). Table 74 summarizes these assumptions.

Table 74. Re-convert pasture to forest (S1.17)

Year	Forest emissions reductions ($MtCO_2e\ yr^{-1}$)
2010	3.76
2020	5.00
2030	8.33
2035	10.00
2040	15.00
2050	20.00

4.3.5.3 Double local actions (S3.18)

S3.18 assumes that local actions to reduce GHG emissions are twice as effective by 2030, enabling an additional 8.2 $MtCO_2e\ yr^{-1}$ savings by that year (R. McCarthy, pers. commun., 2013). Unlike S2.17, however, additional renewable electricity generation was not assumed due to increased local actions, because the statewide RPS 51% target (S3. 10) is already considerably higher than in S2. Table 75 summarizes the assumed GHG reduction schedule.

Table 75. Double local actions (S3.18)

Year	Additional GHG offsets ($MtCO_2e\ yr^{-1}$)
2010	0.00
2015	2.34
2020	8.20
2030	16.40
2040	16.40
2050	16.40

4.4 Counterfactual scenario (S0)

S0 was generated by removing all policies from S1. The purpose was to create a counterfactual baseline against which policies in S1 could be compared to determine their collective effectiveness at reducing GHGs and criteria pollutants. The notation "–S1.*x*" was adopted here for each policy to denote the removal of policy *x* from S1.

4.4.1 Transportation

4.4.1.1 No Pavley LDV efficiency/GHG standards (-S1.1)

The "Pavley" (AB 1493) standards are actually divided into "Pavley I" and "Pavley II," covering vehicle model years 2009-2016 and 2017-2025, respectively. As the 2014 vehicle fleet already strongly reflects the impact of Pavley I, for modeling purposes, disabling S1.1 only assumes that the effects of Pavley II are removed. Therefore, fuel efficiencies of new vehicles would still rise through 2016 due to Pavley I standards. CARB (2014a) provided estimates of LDV efficiencies in the absence of Pavley II, indicating that new LDV adjusted, on-road efficiencies would flatten at ~26 mpg after 2015 (the average of passenger car and light truck efficiencies was used). Using an estimated average LDV lifetime of ~15 years, the impact of these terminal LDV efficiencies was delayed to 2030 (B. Chen, pers. commun., 2014). Any changes in efficiency were due to market share shifts among conventional ICEVs, HEVs and PHEVs. See Table 76.

Table 76. No LDV efficiency improvements (-S1.1)

Year	Fuel efficiency (mi/gal)			
	Average gasoline (input parameter)	Gasoline ICEV (derived)	Gasoline HEV (derived)	Gasoline PHEV (derived)
2010	19.32	19.32	29.06	30.08
2013	21.09	21.08	35.71	34.37
2021	22.00	21.89	38.77	35.40
2025	23.11	22.95	39.88	35.04
2030	24.50	24.32	40.17	34.22
2040	25.70	25.39	41.13	40.93
2050	25.70	25.40	40.74	42.25

4.4.1.2 Less LDV ZEVs (-S1.2)

ZEVs were assumed fixed at the market share reached in 2013. See Table 77.

Table 77. ZEV fraction of LDVs (-S1.2)

Year	ZEV fraction of LDV stock (input parameter)	Number of ZEVs (derived, thousands)
2010	0.03%	7
2013	0.44%	97
2020	0.44%	102
2025	0.44%	106
2035	0.44%	114
2050	0.44%	124

4.4.1.3 No LDV VMT reductions (-S1.3)

Effects on VMT represented by S1.3 (SB 375) were included in baseline input data. CARB estimated that removing these effects results in higher VMT by 8.2% in 2020, increasing to 13.6% in 2035 (CA LegInfo, 2008; J. Cunningham, pers. commun., 2013). The change in VMT was kept fixed at this latter value through 2050, which keeps VMT per vehicle approximately constant also. See Table 78.

Table 78. VMT scenario (-S1.3)

Year	Change in VMT per vehicle (input parameter)	VMT per vehicle (derived, mi/yr)	Total VMT (derived, 10^9 mi/yr)	Change in total VMT relative to 2010 (derived)
2010	0.00%	12,406	272.36	0.00%
2020	8.20%	13,241	309.59	13.67%
2035	13.60%	12,576	326.83	20.00%
2040	13.60%	12,613	339.37	24.60%
2050	13.60%	12,553	357.03	31.09%

4.4.1.4 No HDV efficiency standards (-S1.4)

The effects of HDV efficiency standards due to EPA and NHTSA regulations (EPA, 2011; J. Cunningham, pers. commun., 2013) in S1.4 were also included in the S1 baseline, so they were removed by keeping fuel efficiencies nearly constant at 2010 levels. See Table 79. Note that because the same efficiency parameter was used for all fuel types within a vehicle class (e.g., in-state HHD), the fuel efficiency for each fuel type was not necessarily constant. This was especially pronounced in the case of in-state HHD natural gas vehicles; however, as no natural gas vehicles appear in S0, this had no impact on results.

Table 79. No HDV efficiency standards (-S1.4)

Year	Change relative to baseline (input parameters)			Fuel efficiency (mi/gge) (derived)				
				In-state HHD		OOS HHD	MHD	
	In-state HHD	OOS HHD	MHD	Diesel	Natural gas	Diesel	Gasoline	Diesel
2010	0.00%	0.00%	0.00%	5.67	3.81	5.59	9.84	12.51
2020	-23.50%	-22.60%	-14.20%	5.67	4.11	5.59	9.61	12.80
2030	-24.00%	-22.60%	-13.60%	5.67	5.20	5.59	9.77	12.59
2050	-24.00%	-22.60%	-13.60%	5.66	5.55	5.58	9.90	12.38

4.4.2 Fuels

4.4.2.1 No LCFS target (-S1.5)

The use of biofuel was phased out in all fuels but E-85 by 2020, resulting in an average for petroleum fuels falling to virtually zero by 2020. The in-state fraction of the small amount of biofuel ethanol retained in the scenario was kept at 12% throughout. No advanced biofuels were assumed. See Table 80 through Table 82.

Table 80. Biomass fraction of fuels (-S1.5)

Year	Biomass fraction of fuels (% by energy content)							
	Gaso-line	E-85	Diesel	Natural gas	Jet fuel	Avia-tion gaso-line, fuel oil	Average (petro-leum fuels)	Average (all)
	(input parameter)						(derived)	
2010	6.80%	85.00%	5.00%	0.00%	0.00%	0.00%	6.34%	3.02%
2015	6.80%	85.00%	5.00%	0.00%	0.00%	0.00%	6.43%	3.03%
2020	0.00%	85.00%	0.00%	0.00%	0.00%	0.00%	0.31%	0.15%
2022	0.00%	85.00%	0.00%	0.00%	0.00%	0.00%	0.34%	0.17%
2030	0.00%	85.00%	0.00%	0.00%	0.00%	0.00%	0.37%	0.18%
2050	0.00%	85.00%	0.00%	0.00%	0.00%	0.00%	0.39%	0.19%

Table 81. In-state fraction of biofuels (S0)

Year	In-state fraction of biofuels (%)					
	Gasoline, aviation gasoline	E-85	Diesel, fuel oil	Natural gas	Jet fuel	Weighted average (derived)
	(input parameter)					
2010	12%	12%	100%	100%	100%	23%
2012	12%	12%	100%	100%	100%	24%
2020	12%	12%	100%	100%	100%	12%
2030	12%	12%	100%	100%	100%	12%
2040	12%	12%	100%	100%	100%	12%
2050	12%	12%	100%	100%	100%	12%

Table 82. Advanced biofuel fraction of fuels (S0)

Year	Advanced biofuel fraction of fuel (%, input parameter)			Total biofuel GHG intensity (in-state portion, $kgCO_2e/MBtu$, derived)		
	Gasoline, E-85	E-85	Diesel	Gasoline, E-85	E-85	Diesel
2010	0.00%	0.00%	0.00%	62.98	62.98	5.65
2015	0.00%	0.00%	0.00%	62.98	62.98	5.65
2020	0.00%	0.00%	0.00%	62.98	62.98	5.65
2022	0.00%	0.00%	0.00%	62.98	62.98	5.65
2030	0.00%	0.00%	0.00%	62.98	62.98	5.65
2050	0.00%	0.00%	0.00%	62.98	62.98	5.65

4.4.3 Buildings

4.4.3.1 No Integrated Energy Policy Report efficiency savings (-S1.6)

As efficiency savings of the residential and commercial building stock were built into the S1 baseline (C. Kavalec, pers. commun., 2013), these savings were removed by keeping per unit efficiencies fixed at 2010 values. See Table 83.

Table 83. Stock building efficiency (-S1.6)

Year	Number of units (same for all scenarios)		Unit efficiency of remaining stock			
			Residential		Commercial	
	Residential	Commercial	Electricity	Natural gas	Electricity	Natural gas
	10^6 hh*	10^6 sf*	kWh/hh	therms/hh	kWh/sf	therms/sf
2010	12.87	7,059	6,976	406.1	14.24	0.2806
2011	12.94	7,086	6,976	406.1	14.24	0.2806
2015	13.25	7,389	6,976	406.1	14.24	0.2806
2020	13.88	7,795	6,976	406.1	14.24	0.2806
2025	14.41	8,013	6,976	406.1	14.24	0.2806
2030	14.98	8,247	6,976	406.1	14.24	0.2806
2040	16.04	8,935	6,976	406.1	14.24	0.2806
2050	16.87	9,976	6,976	406.1	14.24	0.2806

* hh = households; sf = square feet

4.4.3.2 No Title 24 new construction, no efficient retrofits (-S1.7)

The efficiencies of new construction for both residential and commercial buildings were assumed fixed after 2010, and there were zero efficiency retrofits. See Table 84 through Table 87.

Table 84. Residential building efficiencies - new construction (-S1.7)

Year	Annual rates[a] (input parameters)	Number of buildings[a] (derived)	Efficiency over 2010 (input parameters)		Efficiencies (derived)	
			Electricity	Natural gas	Electricity	Natural gas
	%/yr	10^6 hh/yr	%	%	kWh/hh	therms/hh
2010	2.85%	367.0	2.00%	0.00%	6,836	406.0
2011	0.55%	71.0	2.00%	0.00%	6,836	406.0
2015	0.88%	116.5	2.00%	0.00%	6,836	406.0
2020	1.15%	159.3	2.00%	0.00%	6,836	406.0
2025	1.15%	165.4	2.00%	0.00%	6,836	406.0
2030	1.15%	171.9	2.00%	0.00%	6,836	406.0
2040	1.15%	184.1	2.00%	0.00%	6,836	406.0
2050	1.15%	193.6	2.00%	0.00%	6,836	406.0

[a] Annual rates and number of buildings are identical for all scenarios

Table 85. Residential building efficiencies - retrofits (-S1.7)

Year	Annual rates (input parameters)	Number of buildings (derived)	Efficiency over 2010 (input parameters)		Efficiencies (derived)	
			Electricity	Natural gas	Electricity	Natural gas
	%/yr	10^3 hh/yr	%	%	kWh/hh	therms/hh
2010	0.00%	-	0.00%	0.00%	6,975	406.0
2011	0.00%	-	0.00%	0.00%	6,975	406.0
2015	0.00%	-	0.00%	0.00%	6,975	406.0
2020	0.00%	-	0.00%	0.00%	6,975	406.0
2025	0.00%	-	0.00%	0.00%	6,975	406.0
2030	0.00%	-	0.00%	0.00%	6,975	406.0
2040	0.00%	-	0.00%	0.00%	6,975	406.0
2050	0.00%	-	0.00%	0.00%	6,975	406.0

Table 86. Commercial building efficiencies - new construction (-S1.7)

Year	Annual rates[a] (input parameters)	Number of buildings[a] (derived)	Efficiency over 2010 (input parameters)		Efficiencies (derived)	
			Electricity	Natural gas	Electricity	Natural gas
	%/yr	10^6 sf/yr	%	%	kWh/sf	therms/sf
2010	1.32%	93.2	11.00%	17.00%	12.65	0.2324
2011	0.88%	62.5	11.00%	17.00%	12.65	0.2324
2015	1.90%	140.7	11.00%	17.00%	12.65	0.2324
2020	1.71%	133.5	11.00%	17.00%	12.65	0.2324
2025	1.66%	133.4	11.00%	17.00%	12.65	0.2324
2030	1.66%	137.3	11.00%	17.00%	12.65	0.2324
2040	1.66%	148.7	11.00%	17.00%	12.65	0.2324
2050	1.66%	166.1	11.00%	17.00%	12.65	0.2324

[a] Annual rates and number of buildings are identical for all scenarios

Table 87. Commercial building efficiencies - retrofits (-S1.7)

Year	Annual rates (input parameters)	Number of buildings (derived)	Efficiency over 2010 (input parameters)		Efficiencies (derived)	
			Electricity	Natural gas	Electricity	Natural gas
	%/yr	10^6 sf/yr	%	%	kWh/sf	therms/sf
2010	0.00%	-	0.00%	0.00%	14.21	0.2800
2011	0.00%	-	0.00%	0.00%	14.21	0.2800
2015	0.00%	-	0.00%	0.00%	14.21	0.2800
2020	0.00%	-	0.00%	0.00%	14.21	0.2800
2025	0.00%	-	0.00%	0.00%	14.21	0.2800
2030	0.00%	-	0.00%	0.00%	14.21	0.2800
2040	0.00%	-	0.00%	0.00%	14.21	0.2800
2050	0.00%	-	0.00%	0.00%	14.21	0.2800

4.4.4 Electricity

4.4.4.1 No RPS 33% target (-S1.8)

The amount of renewable capacity was kept fixed starting in 2016 at the 2012 actual RPS-eligible fraction (20% or ~60 TWh/yr; CPUC, 2014b). The amount of non-RPS distributed solar PV was small (~2 TWh/yr after 2020) so this was left unchanged. Overall electricity demand was a bit lower than in S1 due to fewer ZEVs. The fractions of renewable generation types were fixed at 2016 values. See Table 88 and Table 89.

Table 88. RPS target (-S1.8)

Year	RPS target (input para-meter)	RPS genera-tion	RPS-eligible demand	Ineligible demand			Gross demand
				Distributed solar PV not subject to RPS	Additional solar PV for zero net energy targets	Other self-generation	
	% of eligible	TWh/yr (derived)					
2010	11.3%	32.5	286.4	-	-	12.4	298.8
2011	10.0%	28.7	287.2	0.2	-	12.6	300.0
2016	20.0%	58.9	294.4	1.1	-	13.4	308.9
2020	20.0%	60.0	299.8	1.8	-	13.5	315.1
2030	19.0%	59.5	313.4	2.2	-	15.2	330.8
2040	17.5%	58.7	335.5	2.2	-	17.9	355.6
2050	16.0%	58.3	364.3	2.2	-	21.2	387.7

Table 89. Breakdown by renewable generation type (S0)

Year	Biomass	Geothermal	Small hydro	RPS-eligible solar (PV and concentrating thermal)	Wind	Other
	% of renewable generation (input parameters)					
2011	15.1%	33.2%	1.5%	2.8%	19.9%	27.4%
2016	16.0%	28.7%	1.3%	18.6%	23.7%	11.7%
2020	16.4%	29.4%	1.4%	19.1%	24.2%	9.6%
2030	16.8%	30.2%	1.4%	19.6%	24.9%	7.2%
2040	16.7%	30.0%	1.4%	19.4%	24.7%	7.7%
2050	16.6%	29.8%	1.4%	19.3%	24.6%	8.4%
	GW installed capacity (derived)					
2010	1.02	2.59	0.14	0.36	2.38	1.66
2011	1.02	1.89	0.14	0.36	2.39	1.61
2016	1.90	3.34	0.25	4.58	5.83	1.32
2020	1.96	3.49	0.26	4.78	6.08	1.08
2030	1.99	3.56	0.27	4.88	6.20	0.77
2040	1.95	3.49	0.26	4.78	6.07	0.83
2050	1.93	3.43	0.26	4.71	5.99	0.91

4.4.4.2 No imported coal power phase-out (-S1.9) and no once-through cooling power plant phase-out (-S1.10)

Both OOS coal and once-through cooling power plants were kept running through 2050 (CCEF, 2011, 2012). Other low-carbon resources were roughly the same as in S1. See Table 90 and Table 91.

Table 90. Fossil generation (-S1.9 and –S1.10)

Year	Imported coal	Once-through cooling	CHP	NGSC	NGCC	Other coal	Other
	% of gross demand (input parameters)						
2010	9.91%	5.12%	14.11%	2.37%	13.56%	1.17%	13.43%
2011	9.87%	5.12%	14.11%	2.37%	15.23%	0.82%	12.92%
2016	9.59%	4.97%	13.70%	2.72%	16.88%	0.74%	10.32%
2020	9.40%	4.87%	13.43%	3.00%	25.56%	0.83%	8.24%
2030	8.95%	4.64%	12.79%	3.00%	31.19%	0.00%	5.65%
2040	8.33%	4.32%	11.90%	3.00%	34.78%	0.00%	5.65%
2050	7.64%	3.96%	10.92%	3.00%	38.60%	0.00%	5.65%
	GW installed capacity (derived)						
2010	3.89	15.57	8.50	26.95	11.17	0.40	7.25
2011	3.89	15.57	8.50	27.06	12.59	0.28	7.34
2016	3.89	15.57	8.50	31.97	14.37	0.26	7.62
2020	3.89	15.57	8.50	35.97	22.19	0.30	7.39
2030	3.89	15.57	8.50	37.76	28.43	-	8.32
2040	3.89	15.57	8.50	40.59	34.08	-	9.77
2050	3.89	15.57	8.50	44.25	41.24	-	11.59

Table 91. Low-carbon non-RPS generation (S0)

Year	Coal with CCS	Nuclear	Large hydro	Non-RPS solar PV	Other non-RPS	Exports	Im-ports	Storage
	% of gross demand (input parameters)							
2010	0.00%	14.95%	11.99%	0.06%	4.16%	-1.69%	33.67%	0.00%
2011	0.00%	14.80%	12.68%	0.06%	4.20%	-1.72%	32.71%	0.00%
2016	0.00%	7.93%	11.05%	0.35%	4.34%	-1.65%	27.84%	0.00%
2020	0.00%	1.65%	10.76%	0.57%	4.29%	-1.62%	23.98%	0.00%
2030	0.00%	1.13%	10.17%	0.65%	4.60%	-0.77%	18.95%	0.00%
2040	0.00%	1.13%	9.47%	0.61%	5.02%	-0.72%	18.33%	0.00%
2050	0.00%	1.13%	8.71%	0.56%	5.47%	-0.66%	17.64%	0.00%
	GW installed capacity (derived)							
2010	-	5.43	11.39	0.10	6.79	N/A	N/A	-
2011	-	5.40	12.10	0.10	6.89	N/A	N/A	-
2016	-	2.98	10.85	1.14	7.34	N/A	N/A	-
2020	-	0.63	10.78	1.56	7.39	N/A	N/A	-
2030	-	0.45	10.70	1.76	8.32	N/A	N/A	-
2040	-	0.49	10.71	1.75	9.77	N/A	N/A	-
2050	-	0.53	10.74	1.74	11.59	N/A	N/A	-

4.4.5 Non-energy and other

4.4.5.1 No 20x20 water conservation (-S1.11)

No SB X7-7 water conservation (DWR, 2014) was implemented, resulting in the same unit water consumption as today; see Table 28.

4.4.5.2 No landfill methane capture (-S1.12)

SP RW-1 (CARB, 2008) was ignored, resulting in the same share of biogenic landfill waste through 2050 and increasing per capita and total net landfill emissions. See Table 92.

Table 92. Reduction in emissions from landfills (-S1.12)

	Gross emissions	Biogenic share of total	Net emissions
Year	**$kgCO_2$ $person^{-1}$ yr^{-1}**	**%**	**$MtCO_2e$ yr^{-1}**
2010	372	50.3%	6.90
2020	397	50.3%	8.02
2030	424	50.3%	9.32
2040	452	50.3%	10.71
2050	482	50.3%	12.07

4.4.5.3 No sustainable forests (-S1.13)

The sustainable forest policy (SP F-1; CARB, 2008) was eliminated, resulting in no net reductions from forests after 2020. See Table 93.

Table 93. Forest GHG emissions (-S1.13)

Year	Forest emissions reductions ($MtCO_2e$ yr^{-1})
2010	3.76
2020	0.00
2030	0.00
2040	0.00
2050	0.00

4.4.5.4 No Scoping Plan high GWP measures (-S1.14)

In S1, Scoping Plan measures to reduce GWP emissions (H-1 through H-5 and some H-6; CARB, 2008) were included in the baseline data provided by CARB (G. Gallagher, pers. commun., 2013). To remove these, the HFC level was raised relative to this baseline to 150% in 2020 to match the CARB (2008) estimate of 10 $MtCO_2e$ yr^{-1} savings due to these measures. The relative HFC level was fixed in subsequent year; due to population and GSP growth, HFC emissions rose slightly through 2050; see Table 94.

Table 94. No Scoping Plan high GWP measures (-S1.14)

Year	HFC emissions (% of baseline, input parameter)	Residen-tial	Commer-cial	Industrial	LDV	HDV	Other transport	Total
		$MtCO_2e\ yr^{-1}$ (derived)						
2010	100%	2.89	5.81	0.77	2.48	1.00	0.27	13.23
2020	150%	10.09	13.03	1.39	2.81	2.00	0.48	29.81
2030	150%	13.91	15.87	1.51	1.63	2.61	0.50	36.03
2040	150%	14.93	16.54	1.57	1.05	3.30	0.51	37.90
2050	150%	15.20	17.33	1.61	0.76	4.21	0.54	39.65

5 Other GHG sensitivities

5.1.1 Other policies

Figure 6 shows the effect of certain parameters on statewide GHGs relative to S1; these are discussed below.

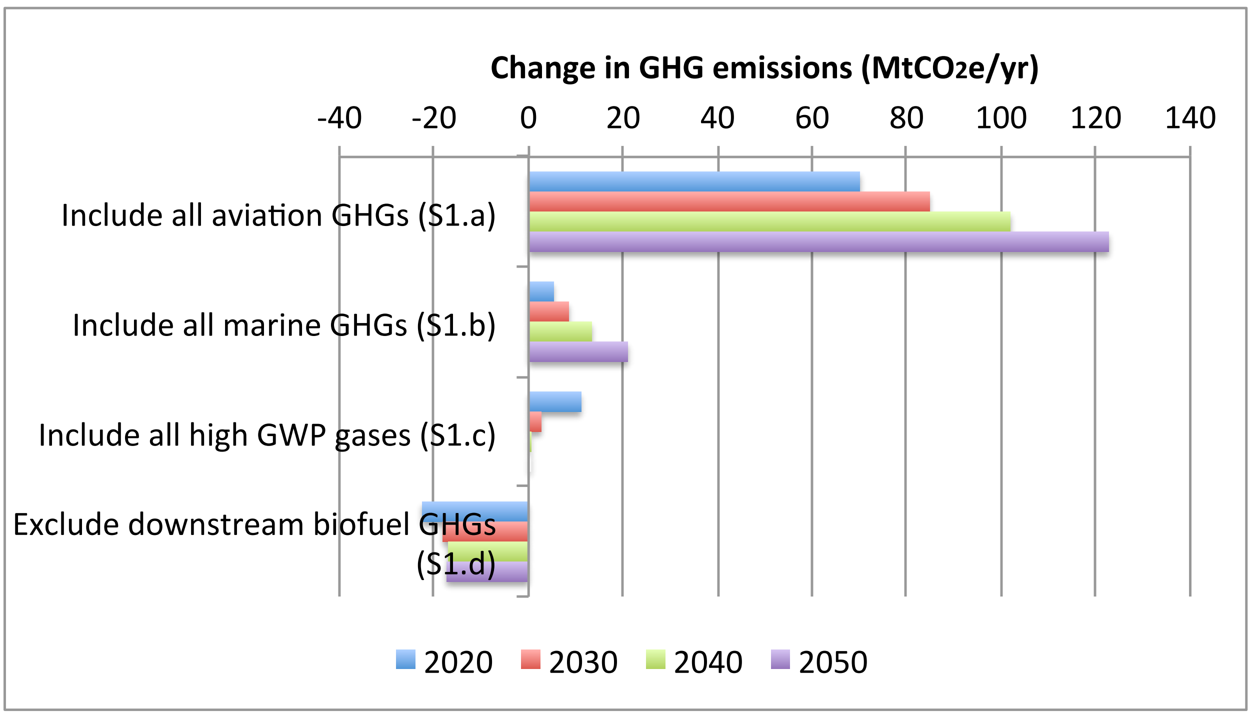

Figure 6. Statewide GHG emission sensitivities (relative to S1) for other parameters not included in S1

5.1.1.1 Inclusion of aviation and marine emissions (S1.a, S1.b)

While the vast majority of emissions from aviation (92%) and marine transport (75%) occur outside state borders (J. Cunningham, pers. commun., 2013), these emissions still occur and contribute to global GHG concentrations. From total fuel consumption associated with these transportation modes having one endpoint in California, it was estimate that these omitted emissions account for an additional 70 $MtCO_2e$ yr^{-1} in 2020 from aviation, and 5 $MtCO_2e$ yr^{-1} from marine transport, increasing to, respectively, 85 and 9 $MtCO_2e$ yr^{-1} in 2030, and 123 and 22 $MtCO_2e$ yr^{-1} in 2050. Long-term policy must account for these emissions through some mechanism, since they vastly outweigh the in-state emissions.

5.1.1.2 Inclusion of all high GWP gases (S1.c)

Official CARB inventory policy excludes emissions from CFCs and HCFCs because these substances, which also destroy stratospheric ozone, face a worldwide moratorium (G. Gallagher, pers. commun., 2013). However, while no longer being produced in California, they are still emitted via product use and leakage. Including them was estimated to increase the state inventory emissions by 11 $MtCO_2e$ yr^{-1} in 2020, decreasing to 3 $MtCO_2e$ yr^{-1} in 2030 and less than 0.5 $MtCO_2e$ yr^{-1} in 2040, so they are not a long-term concern.

5.1.1.3 Downstream biofuel emissions (S1.d)

As discussed in section 2.1 in the main text, CARB inventory accounting rules require inclusion of downstream GHG emissions from all fuels including biofuels. This approach is valid, because CO_2 absorption during biomass growth balances emissions during biofuel combustion, and this growth resulting in a decrease of GHG emissions is included in the agricultural sector. However, this is only the case for in-state emissions; OOS biofuels are "penalized" in the current inventory approach by including their GHG emissions during combustion, but not subtracting their CO_2 absorption (the LCFS accounts for biofuel emissions differently, however, by including CO_2 absorption regardless of where it occurs). For S1, only 12% of ethanol (which replaces 22% of gasoline in 2020 and is used in E-85 fuel) is produced in-state. (Note that 100% of diesel is assumed to be produced in-state). If the combustion emissions from biofuels were excluded, statewide GHG emissions would be 24 $MtCO_2e$ yr^{-1} lower in 2020, and 19-20 $MtCO_2e$ yr^{-1} lower in 2030 and beyond. This disparity will grow with larger amounts of biofuels in S2.4 and S3.8, but is tempered by the higher in-state biofuel targets in S2.5.

6 Model validation

While CALGAPS was initialized using much data produced by state agencies, it was still important to compare GHG emissions from CALGAPS with the official CARB inventory (CARB, 2013b). The starting year of the model was 2010, whereas the CARB inventory data extended from 1990 to 2011; therefore, there were two overlapping years (2010 and 2011) that was used to compare GHG emissions at the sector level. S1 was used to do the comparisons, as this scenario most closely reflected recent reality.

To maintain consistency with the CARB inventory, several items within certain sectors in the CALGAPS inventory were moved to other sectors, as the CALGAPS categorization method differed somewhat from CARB's. Results are shown in Figure 7 and Table 95.

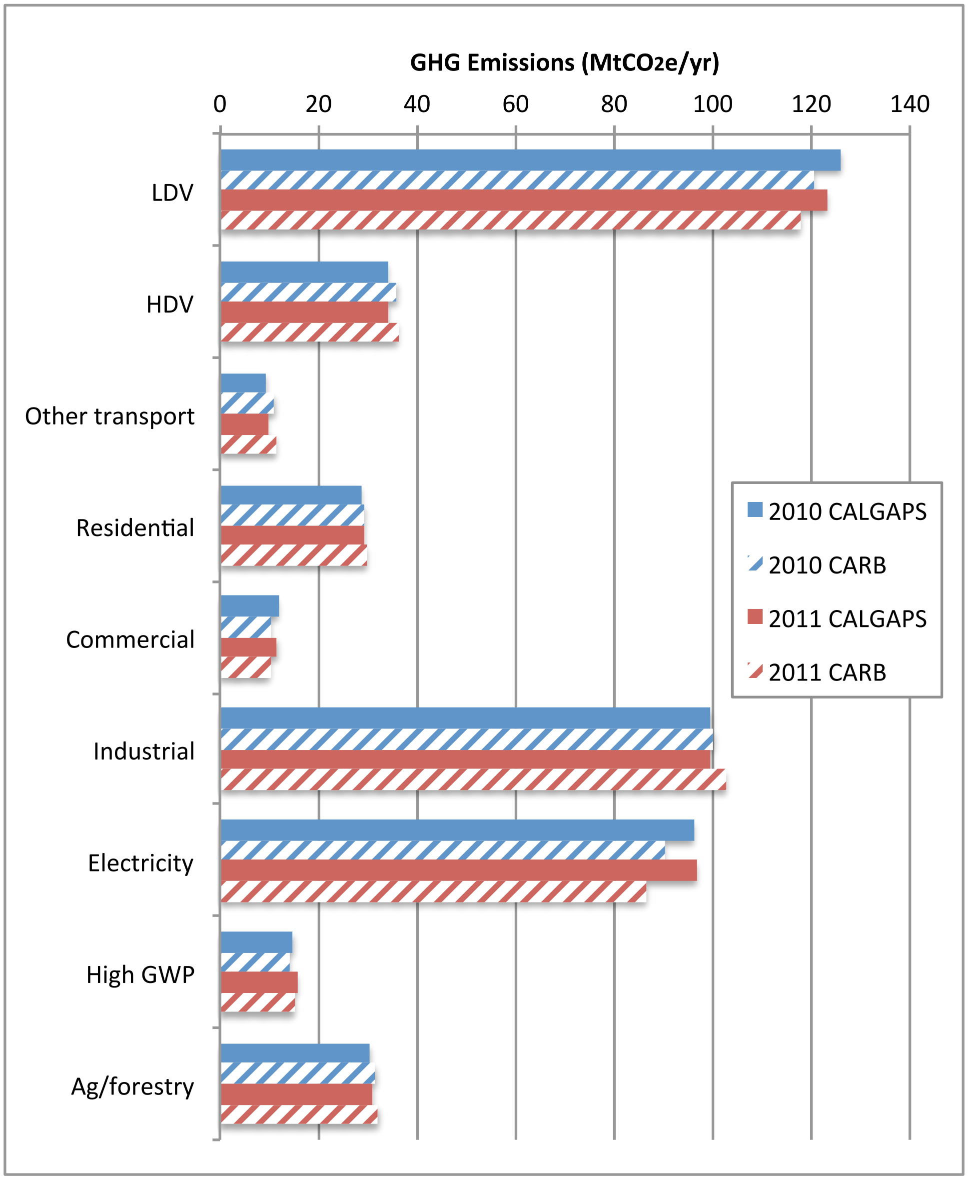

Figure 7. Comparison of CALGAPS and CARB statewide GHG emissions by sector for 2010-2011

Table 95. Comparison of statewide GHG emissions between CALGAPS S1 and CARB inventories for 2010-2011

Sector	2010				2011			
	CALGAPS	CARB	Difference		CALGAPS	CARB	Difference	
	$MtCO_2e\ yr^{-1}$			%	$MtCO_2e\ yr^{-1}$			%
LDV[a]	126.03	120.38	+5.65	+4.7	123.09	117.77	+5.32	+4.5
HDV[b]	34.07	36.02	-1.95	-5.4	34.13	36.08	-1.95	-5.4
Other transport[c]	9.40	11.17	-1.77	-15.9	9.66	11.47	-1.81	-15.8
Transport subtotal[d]	169.49	169.45	+0.04	+0.0	166.88	167.28	-0.40	-0.2
Residential[e]	28.71	29.38	-0.67	-2.3	29.29	29.85	-0.56	-1.9
Commercial[f]	11.78	10.29	+1.49	+14.5	11.73	10.15	+1.58	+15.5
Industrial[g]	99.59	100.20	-0.61	-0.6	99.51	102.68	-3.17	-3.1
Electricity[h]	96.08	90.09	+5.99	+6.6	96.66	86.57	+10.09	+11.7
High GWP[i]	14.95	14.15	+0.80	+5.7	15.74	15.17	+0.57	+3.7
Agriculture & forestry[j]	30.54	31.68	-1.14	-3.6	30.97	32.24	-1.27	-3.9
Total	**454.23**	**449.59**	**+4.64**	**+1.0**	**453.79**	**448.11**	**+5.68**	**+1.3**

Notes:
[a]Excludes motorcycles (CALGAPS did not model this category, which amounts to 0.4 $MtCO_2e\ yr^{-1}$)
[b]ARB includes buses & motorhomes, which were separated out; CALGAPS did not model these categories
[c]Includes air, marine, rail, and off-road transportation. Some additional categories included in CARB may not be captured by CALGAPS.
[d]Does not include ~4 $MtCO_2e\ yr^{-1}$ transportation emissions due to F gases (included in high GWP category)
[e]Excludes ~2.5 $MtCO_2e\ yr^{-1}$ "not specified" from CARB inventory
[f]Excludes ~11 $MtCO_2e\ yr^{-1}$ "not specified" from CARB inventory; includes commercial CHP heat
[g]Includes industrial processes, cement, landfills, waste, industrial CHP heat and upstream emissions from other categories
[h]Includes both in-state and OOS emissions, and electricity portions of CHP
[i]Excludes CFCs and HFCs which are not part of CARB inventory
[j]GHGIS "other sectors" minus cement, landfills and waste

Differences in most sectors are minor, with the largest absolute differences between CALGAPS and CARB in the electricity sector (+6.0 $MtCO_2e\ yr^{-1}$ in 2010 and +10.1 $MtCO_2e\ yr^{-1}$ in 2011). Uncertainty analysis suggests an overall confidence level of approximately ±1.6 $MtCO_2e\ yr^{-1}$ in the electricity sector for these years. A 3.5 $MtCO_2e\ yr^{-1}$ decrease in electricity sector GHG emissions in the CARB inventory between 2010 and 2011, not captured by CALGAPS (which indicated a slight increase of 0.6 $MtCO_2e\ yr^{-1}$), is mostly due to a large decrease in the amount of natural gas used in the CARB inventory (-8.4 $MtCO_2e\ yr^{-1}$), whereas CALGAPS assumed a more consistent use of natural gas, resulting in a 2.0 $MtCO_2e\ yr^{-1}$ increase. As discussed in the main text, an analysis of the year-to-year variation in electricity GHG emissions since 1990, after correcting for long-term secular trends, amounts to ±6 $MtCO_2e\ yr^{-1}$ (1 sigma); see Figure 8.

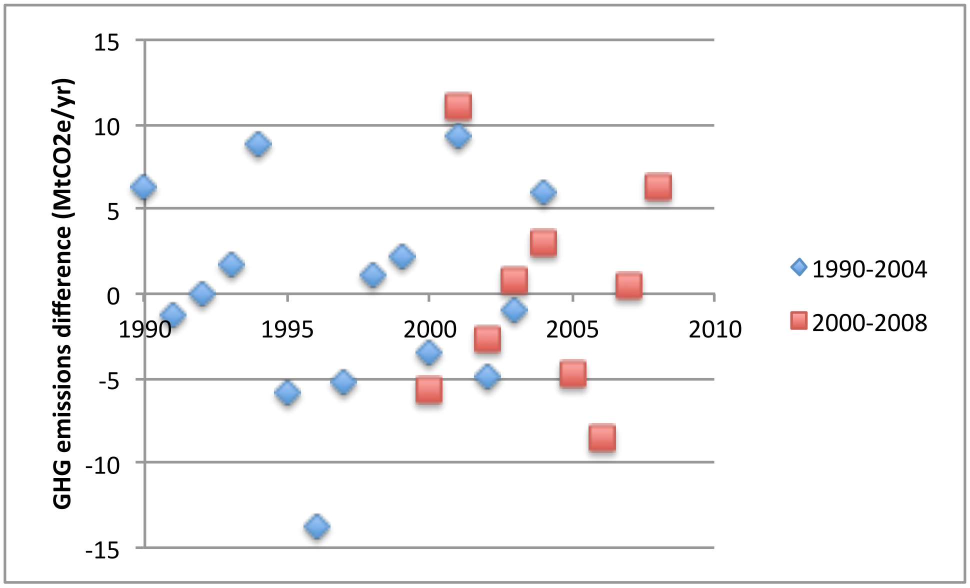

Figure 8. Difference in electricity sector GHG emissions versus long-term linear trend
Sources: Data from 1990-2004 from CARB (2007); data from 2000-2008 from CARB (2013b) (note that 2009-2011 data was omitted due to sharp departure in total electricity demand trend relative to previous years).

Hydro capacity, which varied by ±27% yr^{-1} (1 sigma) between 1983 and 2007 (CA Energy Almanac, 2014; see Figure 9), presumably drives much of this variation, assuming that natural gas generation mainly fills in when hydro falls short. CALGAPS, which was designed to model changes to the energy system over several decades, assumed a long-term average value for hydro capacity in all years. Therefore, differences in emissions in the electricity sector in 2010-2011 are attributed to year-to-year variation in the actual generation mix (dominated by changes in hydro capacity and the resulting natural gas consumed) that is not captured by the model.

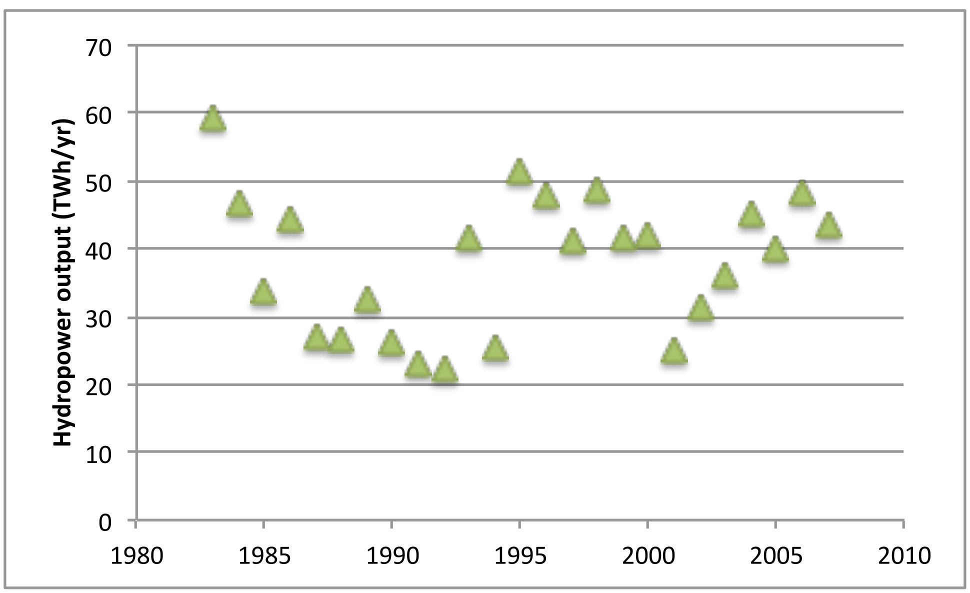

Figure 9. Annual California hydroelectric generation (both in-state and imported)
Source: CA Energy Almanac (2014)

The next largest categorical difference was in the LDV transportation sub-sector, with 5-6 $MtCO_2e$ yr^{-1} higher emissions in CALGAPS than in CARB in 2010-2011. The cause of this difference is slightly higher assumed fuel consumption from data supplied by CARB (J. Cunningham, pers. commun., 2013) versus official inventory data (CARB, 2014b). CARB oversees various mobile and stationary inventory efforts, some of which use inconsistent methodologies, a result of varying program goals. For example, CARB's EMFAC model (the output of which CALGAPS used) estimates vehicle GHG emissions through vehicle fleet populations, vehicle miles traveled (VMT) by vehicle classification, and corresponding vehicle GHG and fuel efficiency parameters; by contrast, the CARB inventory uses fuel sales records to estimate GHG emissions from vehicles, and can arrive at slightly different GHG estimates. Additionally, EMFAC used data from 2009 and 2010, whereas inventory data used more recent fuel records (J. Cunningham, pers. commun., 2014).

For the heavy-duty vehicle (HDV) sector, CALGAPS emissions were lower than the CARB inventory by ~2 $MtCO_2e$ yr^{-1} but CALGAPS did not include buses or motorhomes, which were an inseparable part of HDVs in the CARB inventory. For other parts of the transportation sector—rail, marine, airplanes and off-road—fuel consumption data supplied by CARB again differed slightly from data in the official CARB inventory (lower for rail and marine, higher for airplanes), amounting to ~2 $MtCO_2e$ yr^{-1} lower emissions for CALGAPS than CARB for this subsector as well. For the transportation sector as a whole, net differences between CALGAPS and CARB are $\leq$0.4 $MtCO_2e$ yr^{-1}.

Other sectors indicate small differences on the order of 1-3 $MtCO_2e$ yr^{-1}. For the total state inventory, CALGAPS emissions are higher than those of CARB by 5-6 $MtCO_2e$ yr^{-1}, amounting to a ~1% overall difference.

7 Summary of previous studies

Roland-Holst (2008) developed the BEAR model, a computable general equilibrium macroeconomic model of the California economy. It models energy supply and consumption, GHG and other emissions, and economic activity, and can be used to assess GHG mitigation costs as well as indirect economic impacts.

The California Council on Science and Technology (CCST, 2011; Greenblatt and Long, 2012) modeled GHG emissions of the California energy system by developing a set of ~80 "portraits" of the California energy system in 2050, many of which met or exceeded the 2050 GHG reduction target. Various combinations of technologies encompassing a wide range of technical maturities were examined.

The CA-TIMES model (McCollum et al., 2012; Yang et al., 2014) is an integrated energy-engineering-environmental-economic model of the California energy system based on the International Energy Agency's TIMES model framework (IEA, 2011). It contains both bottom-up, technological assumptions about the energy economy, and an economic optimization to select the most promising GHG emissions reduction options. Several scenarios were developed that achieve the 2050 target.

Williams et al. (2012) developed PATHWAYS, an economic assessment model producing several scenarios that achieve the 2050 GHG reduction target. The model simulates all California energy sectors, plus non-energy GHG emissions, implementing near-term state policy as well as long-term trends based on technological progress and rates of introduction. Results emphasized the pivotal role of electricity as a potentially low-carbon energy sector and as an energy carrier to replace fuel combustion.

Wei et al. (2012, 2013) and Nelson et al. (2013) reported on an economically-driven electricity sector model (SWITCH-WECC) coupled with a scenario-based, non-economic model of other sectors, including non-energy emissions. The electricity model optimizes generation and transmission capacity over multi-decadal timescales with hourly resolution, subject to GHG and/or other constraints. The studies reported on several scenarios through 2050, some of which met the GHG target.

Jacobson et al. (2013) reported on the technical and economic feasibility of repowering California for all purposes with wind, water and sunlight by 2050. The model contains a detailed electricity sector dispatch capability, and notably achieves a 100% renewable electricity system and eliminates all hydrocarbon fuels, both fossil- and biomass-based, by 2050.

Greenblatt (2013) reported on preliminary results using GHGIS, an older, non-validated version of the model reported on here, with fewer modeled policies and without quantifying GHG sensitivities of individual policies. The current study builds substantially upon this work.

ECF (2010) looked at an 80% GHG emissions reduction relative to the 1990 level in 2050 in the 27 European Union countries. The study shared many of the same approaches as the California studies, and reached similar conclusions that substantial changes will be needed both inside and outside the energy system in order to meet the 2050 target.

8 Criteria pollutant emission results

The state is required to comply with National Ambient Air Quality Standards set by the EPA, which targets ozone and fine (≤2.5 μm) particulate matter (PM2.5) (EPA, 2008, 2013b). This will require the state to achieve ambitious reductions in reactive organic gas (ROG) and nitrogen oxide (NO_x) criteria pollutants, which act as ozone precursors, and PM2.5, between 2014 and 2032.

Figure 10 shows statewide criteria pollutant emissions (ROG, NOx and PM2.5) relative to 2010 levels for each scenario. For NOx, a target emissions line was also included, based on 2023 and 2032 ozone targets. The model calculated emissions by state sub-region (San Joaquin Valley, South Coast Air Basin and the rest of California) but as results are very similar, only statewide results are shown.

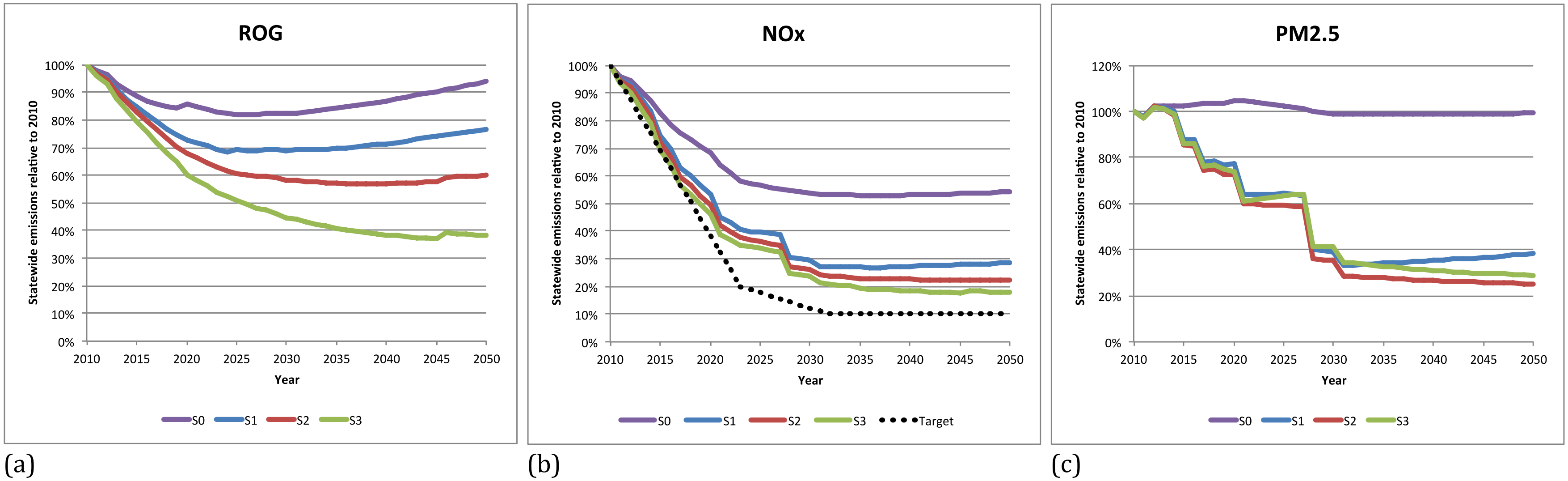

Figure 10. Statewide criteria pollutant emissions relative to 2010 levels for each scenario: (a) ROG, (b) NOx, and (c) PM2.5.

While emissions typically fall in all years as one moves from S0 to S1 to S2 to S3, NOx emissions fall the most by 2023, reaching roughly 40% of the 2010 level in S1-S3, and by 2032 emissions are between 21% and 27%, only changing slightly in later years. Even the S0 scenario falls to 58% by 2023 and 53% by 2032. PM2.5 follows a similar pathway, falling to roughly 60% of the 2010 level in all three scenarios in 2023, and to between 28% and 34% by 2032; however, the S0 scenario remains almost flat at the 2010 level. The "stair step" pattern observed in S1-S3 is a result of successive iterations between 2014 and 2031 of the "truck and bus" rule, requiring new trucks to emit lower levels of PM2.5, and existing trucks to install filters to reduce PM2.5 emissions. These changes were modeled in the data CARB provided.

ROG follows a different pattern with respect to time and Scenario. There is more differentiation among scenarios, qualitatively more similar to the statewide GHG emissions curves shown in Figure 2 in the main paper. S1 produces about twice the reductions in 2023 as S0, and S3 produces roughly three times those reductions, with S2 falling halfway in between S1 and S3. In later years, these ratios become more pronounced as emissions in S0 and S1 begin to increase, while S2 emissions approximately level off and those in S3 continue to fall.

In summary:

- For ROG and NOx, emissions fall even in the S0 scenario (though ROG emissions increase again after 2025), implying a certain amount of reductions "baked in" to existing trends from previous policy measures and technology development not captured here. However, for PM2.5, this is not the case, with S0 emissions holding roughly steady through 2050.
- Measures present in S1 are largely responsible for decreases in NOx and PM2.5, with relatively little additional reductions from policies in S2 or S3. This is particularly pronounced for PM2.5, where S1 achieves reductions of 66% by 2034, while S2 and S3 reductions are only slightly lower. In fact, S2 emissions are the lowest of all.
- Policies in S2 and S3 provide important additional reductions in ROG, with S3 reducing statewide ROG twice as much as S1 by 2036.
- None of the scenarios are able to achieve the statewide NOx reduction targets of 80% below 2010 levels in 2023 and 90% in 2032; the best scenario (S3) achieves roughly double these levels. Additional policies will be required to achieve these goals.

9 Abbreviations used

2DS, IEA (2012) 2°C Scenario;
AB, California Assembly Bill;
CALGAPS, California LBNL GHG (and criteria pollutant) Analysis of Policies Spreadsheet;
CARB, California Air Resources Board;
CEC, California Energy Commission;
CHP, combined heat and power;
CPUC, California Public Utilities Commission;
CCS, CO_2 capture and sequestration;
EPA, U.S. Environmental Protection Agency;
EO, California Executive Order;
GHG, greenhouse gas;
GSP, gross state product;
$GtCO_2e$, billion metric tons CO_2 equivalent;
GWP, global warming potential;
HDV, heavy-duty vehicle;
HEV, hybrid electric vehicle;

HFC, hydrofluorocarbon;
HHD, heavy heavy-duty;
HHV, higher heating value;
ICEV, internal combustion engine vehicle;
LBNL, Lawrence Berkeley National Laboratory;
LCFS, Low Carbon Fuel Standard (EO S-01-07);
LDV, light-duty vehicle;
LHV, lower heating value;
MHD, medium heavy-duty;
mpg, miles per gallon (equivalent to 0.425 km per liter);
mpgge, miles per gallon gasoline equivalent (0.425 km per liter gasoline equivalent);
$MtCO_2e$, million metric tons CO_2 equivalent;
NGCC, natural gas combined cycle;
NGSC, natural gas simple cycle (also known as combustion turbine or gas turbine);
NHTSA, National Highway Transportation Safety Administration;
NOx, nitrogen oxides;
OOS, out-of-state;
PHEV, plug-in hybrid electric vehicle;
PM2.5, fine (≤2.5 μm) particulate matter;
PV, solar photovoltaic;
ROG, reactive organic gases;
RPS, Renewable Portfolio Standard (SB 1078 and amendments);
SB, California Senate Bill;
SONGS, San Onofre Nuclear Generating Station;
SP, CARB (2008) Scoping Plan measure;
VMT, vehicle miles traveled (equivalent to 1.609 vehicle km traveled);
ZEV, zero-emission vehicle;

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