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Modeling California policy impacts on greenhouse gas emissions

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HIGHLIGHTS

- Developed CALGAPS, a new California greenhouse gas (GHG) policy evaluation model.
- Three scenarios (plus counterfactual) developed, modeling 49 state/federal policies.
- All scenarios achieve 2020 target; GHG emissions through 2030 span a factor of two.
- No scenario achieves 2050 target, but cumulative emissions can be very low.
- GHG impact of each policy (plus combinations) quantified in sensitivity analysis.

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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 211–428 $MtCO_2e$ 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.

1. Introduction

California was the first state 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).[1] 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

Abbreviations: 2DS, IEA (2012) 2 °C Scenario; AB, California Assembly Bill; CALGAPS, *C*alifornia *LBNL GHG* (and criteria pollutant) *A*nalysis of *P*olicies *S*preadsheet; 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; NPC, National Petroleum Council; 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

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[1] 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.

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state is currently working to establish a mid-term (2030 era) GHG target to provide additional policy guidance (OPR, 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), predate 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 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 *Ca*lifornia *L*BNL *G*HG (and criteria pollutant) *A*nalysis of *P*olicies *S*preadsheet (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)[2] 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.

Fig. 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 is 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 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).

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

[2] 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).

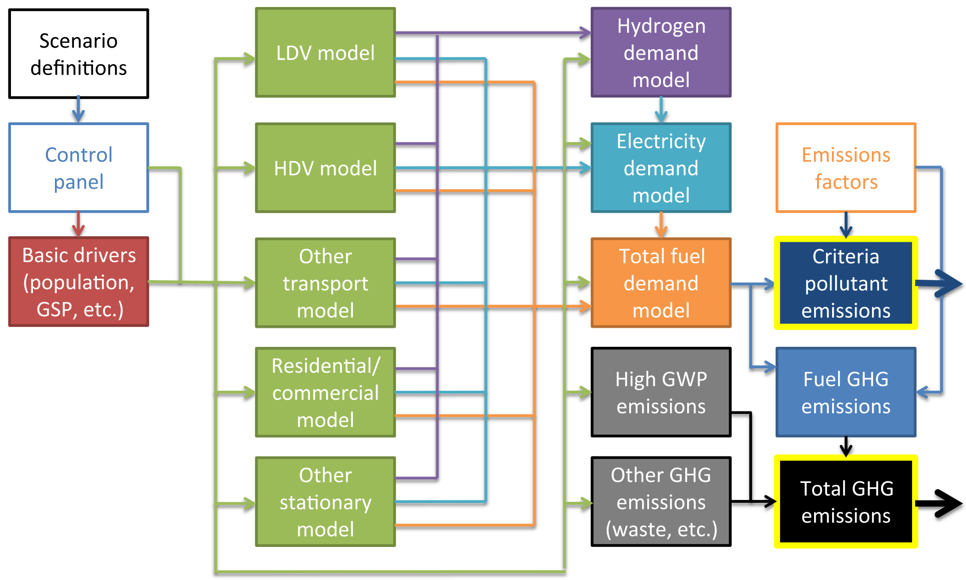

Fig. 1. CALGAPS model structure and sequence of calculations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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.[3] The impact of individual parameters on total GHG emissions was estimated, and a 1000-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.[4]

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 ± 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 $\pm 54\%\ yr^{-1}$ over 1983–2007 (EnergyAlmanac, 2014), presumably drives much of this variation,

[3] 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.

[4] 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.

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, personal communications, 2013) versus CARB inventory data (CARB, 2013b, 2014b).[5] For heavy-duty vehicles (HDVs), CALGAPS emissions were lower than the CARB inventory by $\sim$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 $\sim$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 $\le$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 $\sim$1% overall difference.

3.2. GHG emissions of scenarios

Fig. 2 displays total statewide GHG emissions between 2010 and 2050 for each scenario, along with historical emissions from 1990 to 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.

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

[5] 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, personal communications, 2014).

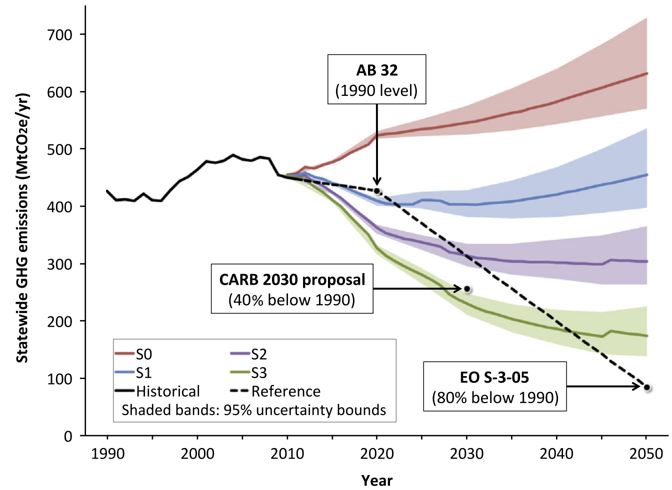

Fig. 2. GHG emissions by scenario, with historical emissions and straight-line reference pathway between 2020 and 2050 GHG policy targets. Uncertainty bounds (95% confidence intervals) for each scenario are shown as shaded bands.

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} $MtCO_2e\,yr^{-1}$ (S3) or 41^{+12}_{-8}% of the 1990 level. S2 remains essentially flat between 2030 and 2050 at $\sim$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).

Fig. 3 shows cumulative GHG emissions for each scenario, along with the reference and scaled 2DS emissions pathways for the U.S.

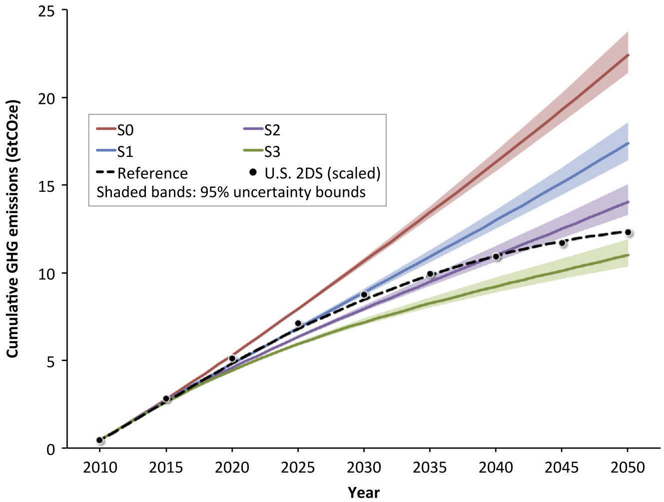

Fig. 3. Cumulative GHG emissions for each scenario. Reference and scaled U.S. 2DS cumulative emissions pathways are also shown. Uncertainty bounds (95% confidence intervals) for each scenario are shown as shaded bands.

(IEA, 2012).[6] 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.

3.4. *GHG emission sensitivities of uncertain parameters*

Figs. 2 and 3 show the sensitivity of GHG emissions due to the combined uncertainty in all 10 parameters discussed in Section 2.3. Fig. 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.

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? Fig. 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.

[6] 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.

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.

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, personal communications, 2014).[7] Removing S1.1 increases GHG emissions by 22 $MtCO_2e\ yr^{-1}$ in 2020,[8] 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 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.[9] 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 $MtCO_2e\ yr^{-1}$

[7] 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, personal communications, 2014).

[8] 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.

[9] 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.

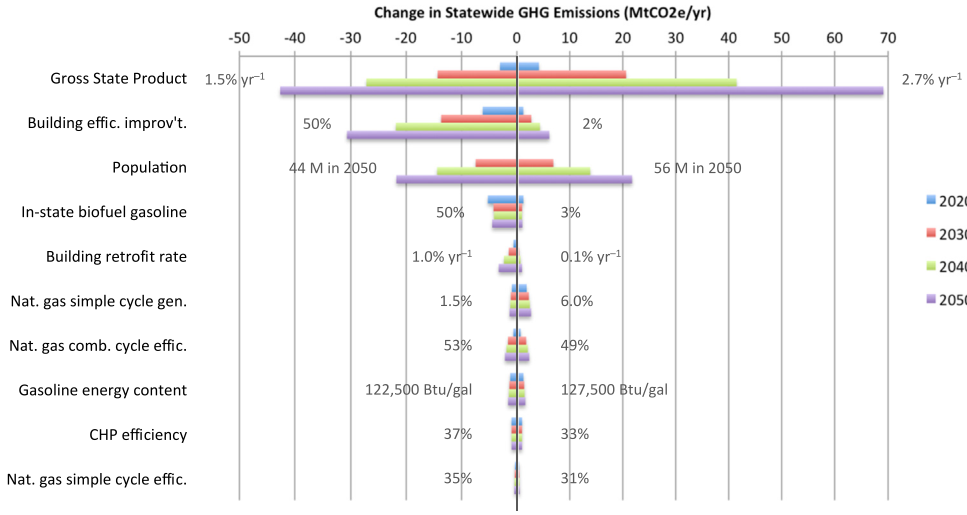

Fig. 4. "Tornado" diagram showing sensitivity of statewide GHG emissions to each uncertain parameter varied in the analysis, by decade from 2020 to 2050.

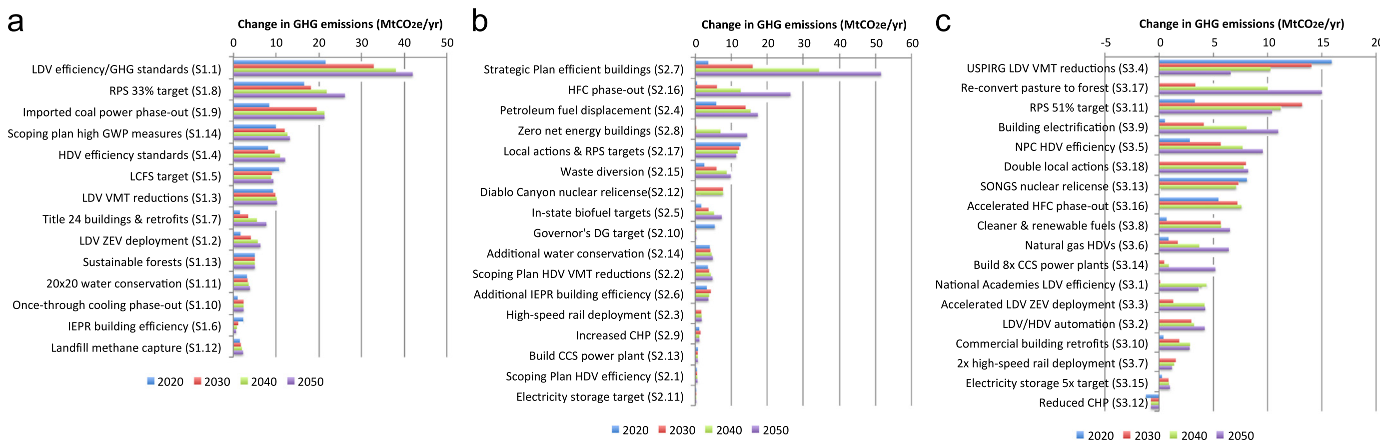

Fig. 5. Changes in GHG emissions by decade (2020–2050) in the absence of each policy in scenario (a) S1, (b) S2 and (c) S3. For each scenario, policies are sorted in order from largest to smallest GHG impact in any decade.

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, 2014).

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.[10] 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 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.[11] If this phase-out were not pursued, emissions in

[10] 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, (*footnote continued*) 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.

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

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

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.

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,[12] 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.

[12] 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, personal communications, 2013).

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
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

Table 2 (*continued*)

Policy description	Policy code	Increase in GHG emissions if policy not pursued ($MtCO_2e\ yr^{-1}$)			
		2020	2030	2040	2050
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					
20 × 20 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).

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

[13] 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).

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

Water and waste. SB X7-7 (“20 × 20”) 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, personal communications, 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 Fig. 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, personal communications, 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) $MtCO_2e\ yr^{-1}$, 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

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, personal communications, 2013; J. Cunningham, personal communications, 2013). Section 2.1 in the main text describes the sequence of calculations depicted in Fig. 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 1000 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 Supplementary 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, personal communications, 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, personal communications, 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, personal communications, 2014) to estimate penetrations and airplane/LDV displacements.

A.3. Stationary

The preliminary IEPR (C. Kavalec, personal communications, 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, personal communications, 2013) provided additional demand savings estimates. Residential and commercial water savings estimates were included (CEC, 2005; D.P. Waters, personal communications, 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, personal communications, 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, personal communications, 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, personal communications, 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 to 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

State and federal policies included in scenarios S1–S3 are shown in Tables B1–B3, respectively.

Appendix C. Supplementary information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.enpol.2014.12.024.

Table B1
Policies included in Committed Policies scenario (S1).

Sector	Policy name	Code	Quantitative targets and references
Transportation	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, personal communications, 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, personal communications, 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 (personal communications, 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, personal communications, 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	20 × 20 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, personal communications, 2013)

[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 B2
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 Myr^{-1} by 2030 (M. Cederoth, personal communications, 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, personal communications, 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, 2013)
	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, personal communications, 2013)

[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 B3
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 and 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 8 × CCS power	2.5 GW capacity by 2050 (author estimate)
	S3.15	Electricity storage 5 × 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)

[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.

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