UCDAVIS
POLICY INSTITUTE FOR ENERGY, ENVIRONMENT AND THE ECONOMY

UCDAVIS
SUSTAINABLE TRANSPORTATION ENERGY PATHWAYS
of the Institute of Transportation Studies

SUMMARY OF CALIFORNIA CLIMATE POLICY MODELING FORUM

DAVIS, CA, DECEMBER 16-17, 2013

Geoff Morrison
Anthony Eggert
Sonia Yeh
Raphael Isaac
Christina B. Zapata

February 2014

Electronic copy available at: http://ssrn.com/abstract=2401929

Contents

ACKNOWLEDGMENTS

The authors wish to sincerely thank the members of the Steering Committee of the California Climate Policy Modeling (CCPM) forum, including: Louise Bedsworth (California Governor's Office of Planning and Research), Jim Bushnell (University of California (UC), Davis), Steve Cliff (California Air Resources Board, CARB), Ashley Conrad-Saydah (California Environmental Protection Agency, Cal/EPA), Richard Corey (CARB), Joshua Cunningham (CARB), Nicole Dolney (CARB), Guido Franco (California Energy Commission, CEC), Karen Griffin (CEC), Bryan Hannegan (National Renewable Energy Laboratory, NREL), Daniel Kammen (UC Berkeley), Ryan McCarthy (CARB), Robin Newmark (NREL), Cliff Rechtschaffen (California Governor's Office), David Roland-Holst (UC Berkeley), John Weyant (Stanford), and Jim Williams (Energy + Environmental Economics, Inc., E3). We also appreciate the contributions, helpful insights and detailed modeling results provided by key modelers including Mark Delucchi (UC Davis), Jeffery Greenblatt (Lawrence Berkeley National Lab, LBNL), Mark Jacobson (Stanford), Mike Kleeman (UC Davis), Jimmy Nelson (UC Berkeley), Max Wei (LBNL), and Christopher Yang (UC Davis). Support for the modeling forum workshop was provided by Pacific Gas & Electric, Energy Foundation, and Environmental Defense Fund.

The CCPM is a joint project of the UC Davis Policy Institute for Energy, Environment and the Economy and the Sustainable Transportation Energy Pathways program of the Institute of Transportation Studies. While the content was significantly informed by the contributions of the above mentioned parties, any errors contained herein are strictly the responsibility of the authors.

For questions, please contact Anthony Eggert (areggert@ucdavis.edu) or Sonia Yeh (slyeh@ucdavis.edu).

Electronic copy available at: http://ssrn.com/abstract=2401929

Introduction

California is a leader in developing and implementing policies that reduce greenhouse gas (GHG) emissions, improve air quality, and encourage efficient use of energy and other resources. At the same time policymakers are often limited in their access to transparent and high-quality technical and economic models that can help them evaluate plausible future scenarios and assess environmental and economic impacts of current or proposed policy targets and policy instruments.

On December 16-17, the Policy Institute for Energy, Environment and the Economy and the Sustainable Transportation Energy Pathways (NextSTEPS), both of UC Davis, hosted a forum as part of the California Climate Policy Modeling (CCPM) project. The CCPM is an ongoing project to bring together policy makers, modeling groups, and key stakeholders in the state to:

- Improve the state of knowledge of plausible pathways/scenarios for future technology adoption, energy use, air quality, and GHG emissions.
- Identify plausible mid-point goals and/or targets for GHG emissions between 2020 and 2050.
- Discuss policy options needed for meeting the state's climate and air quality goals, identify policy gaps, and improve existing policies.
- Improve the state of modeling, including identifying ways to make the models and model findings more useful and accessible to policy-makers and other stakeholders.

This document is a brief summary of the primary model findings and insights discussed at the December 2013 forum.

Background

The CCPM forum included participation from six statewide energy models: ARB VISION (California Air Resources Board, CARB), Berkeley Energy and Resources (BEAR) macro-economic model (UC Berkeley), California TIMES (CA–TIMES) model (UC Davis), the California Greenhouse Gas Inventory Spreadsheet (GHGIS) (Lawrence Berkeley National Laboratory, LBNL), LEAP-SWITCH (UC Berkeley/LBNL), and PATHWAYS (Energy + Environmental Economics, E3). In addition to these six models a broader review of other California energy models and reports was conducted, including: Wind Water Solar (WWS) from Stanford University/UC Davis, California's Energy Future (CEF) Project from California Council on Science and Technology (CCST), Multi-Regional National – North American Electricity and Environment MRN-NEEN from EPRI/Charles River Associates, Environmental Revenue Dynamic Assessment Model (E-DRAM) from UC Berkeley/CARB, and the 2010 and 2013 (draft) AB32 Scoping Plan from CARB. Further information on these models, including model documentation and key publications and presentations, can be found at: policyinstitute.ucdavis.edu/initiatives/ccpm/. In addition to the modeling teams, several dozen experts, state officials, academics, and stakeholders participated in and contributed to the forum.

Key Forum Insights[1]

1. **Models demonstrate a wide range of GHG emissions in 2030 on path to GHG goal in 2050[2]**
   - Of the models that include statewide emissions scenarios to 2050, five (CA-TIMES, CCST, LEAP-SWITCH, MRN-NEEM, PATHWAYS) include one or more pathways that achieve an 80% reduction in *annual* emissions by 2050 relative to 1990 levels[3]. GHGIS includes a scenario that, while not achieving the 2050 goal, nonetheless achieves lower *cumulative* emissions reductions by 2050 compared to a straight-line reduction from the 2020 to 2050 GHG goal. Both sets of modeled scenarios will be referred to within this report as "Deep GHG reduction" scenarios.
   - Annual emissions in 2030 in deep GHG reduction scenarios range from **208-396 million metric tonnes** (MMT) of CO_2e per year, or an 8-52% reduction from 1990 levels (Figure 1, left).
   - Cumulative emissions in deep GHG reduction scenarios range from **6,492-9,205 MMT in 2030** and **10,357-14,394 MMT in 2050** (Figure 1, right). These large ranges highlight the significance of early action on emission reductions: the scenario with the earliest reduction also has the lowest cumulative emissions (GHGIS Case 3 in Appendix, Figure 2).

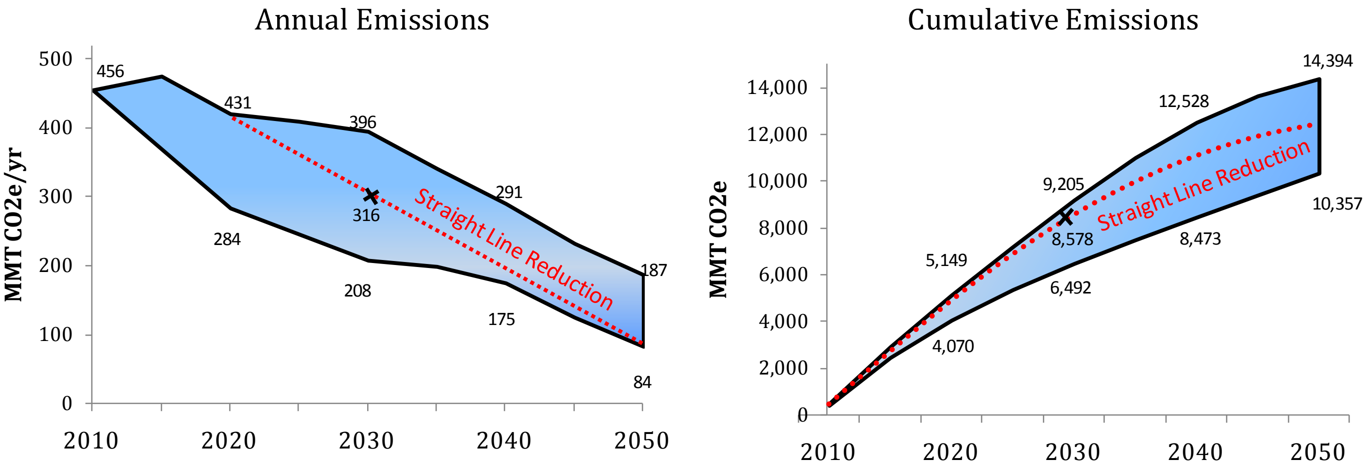


Figure 1: Annual (left) and cumulative (right) emissions in scenarios that achieve deep GHG emissions reductions by 2050.[4]

   - In jurisdictions where climate policy has established GHG emissions targets, they are typically set at a particular emissions rate (GHG/year) by a certain year (e.g. 2020). However, due to the long residence time of many GHGs in the atmosphere, the radiative forcing impact of a scenario is associated with the timing of the emissions as well as the cumulative emissions, not just the rate

---

[1] Where the findings or insights are associated with a specific model, the model is indicated in (parenthesis).

[2] An 80% reduction in 2050 implies an emissions rate of 86 $MMTCO_2e$/year in 2050.

[3] It may be possible to achieve reductions below the 2050 target. For example, sensitivity studies in LEAP-SWITCH achieve as low as 63 MMT CO2e in 2050.

[4] Red dashed line represents a straight line reduction in annual emissions from 2020 to 2050 GHG goals. Note that the system boundaries of these models vary slightly: For example, LEAP-SWITCH and PATHWAYS track emissions from CARB emissions inventory, while CA-TIMES includes out-of-state aviation/marine emissions, out-of-state electric generation that meets CA demand, and omits non-energy emissions. See appendix for further detail.

achieved in the end year. Therefore a better understanding of the implications of different scenarios and policies as they relate to cumulative emissions is needed.

- With the exception of GHGIS and one scenario in CA-TIMES (GHG-Line), the models included in Figure 1 focus on achieving the long-term, annual emissions target in 2050, potentially leaving additional emissions reductions on the table between today and 2030. More modeling effort is needed to determine the potential and costs of early and aggressive climate change action.

2. **De-carbonizing energy generation and 'end-use' energy including transportation and heating is essential to meeting the long-term GHG goals.**
    - De-carbonizing end-use energy consumption, including transportation and residential and commercial heating, are key compliance pathways to meet the 2050 goals across all models. If pursued primarily through electrification, total electricity generation for the state (i.e. in-state + imported generation) will rise dramatically from today's level of 323 TWh to the following levels in 2050: 710 TWh (CA-TIMES, High Renewables Case), 510 TWh (CCST, Eff. & Electrification Case), 617 TWh (LEAP-SWITCH, Aggressive Electrification Case), 619 TWh (PATHWAYS, High Renewables Case), and 1375 (WWS, 100% WWS Case).[5] Other deep reduction scenarios have slightly lower total electricity generation in 2050 ranging from 436-703 TWh (CA-TIMES), 531-572 TWh (LEAP-SWITCH), and 611-614 TWh (PATHWAYS).
    - The rapid de-carbonization of power generation (electricity) is essential in all scenarios that achieve the 2050 goal; however, the precise composition of power generation types and the magnitude of this change vary across the models.
    - Wide-scale deployment of renewable energy, especially wind and solar, are key elements in a decarbonized electricity grid. Non-CCS coal generation is phased out by 2030 in every deep reduction scenario (CA-TIMES, CCST, LEAP-SWITCH, PATHWAYS, WWS).
    - Results from deep reduction scenarios suggest a renewable generation range in 2030 of: 38-55% (CA-TIMES), 51% (GHGIS, Case 3), 30-45% (LEAP-SWITCH), and 33-39% (PATHWAYS).[6] By 2050, the range of renewable penetration is: 42-94% (CA-TIMES), 38-74% (LEAP-SWITCH), 44-81% (GHGIS), and 38-81% (PATHWAYS). Values on the lower end of these ranges tend to deploy large amounts of carbon capture and sequestration (CCS) technology and/or nuclear power plants by 2050, while values on the upper end tend to deploy mostly renewable energy. The above renewable generation values imply a build-out rate of new renewable capacity (mostly solar and wind) of between 0.2-4.2 GW per year from 2013 until 2030, with an average of 0.83 GW per year. The

---

[5] WWS was estimated from available documentation and is much larger than others because it: (1) shifts to 100% renewable by 2050 and (2) over-sizes generation capacity to help solve the renewable intermittency problem.

[6] The ranges reported here were adjusted to be similar to the formula used for the Renewable Portfolio Standard (RPS) calculation. As such, the percentages are based on estimated retail electricity sales rather than generation (assuming a 7% transmission and distribution loss) and exclude electricity from large hydroelectric plants. Solar PV is included in the reported percentages, but because utility-scale solar PV and rooftop solar PV are not differentiated in all models, these ranges may overestimate the generation that would count towards RPS obligations. Except for GHGIS, the models reviewed focused on achieving 2050 emission target, therefore higher fractions of renewables by 2030 may be possible if different objectives (e.g. cumulative emission targets) are specified.

renewable build-out rate increases to between 1.5-10.4 GW per year from 2030 until 2050, with an average of 3.9 GW per year.

- The WWS plan calls for a 63% RPS by 2030 and 100% by 2050. The implied build-out rate of new renewables is 17 GW of nameplate capacity per year from 2013 to 2050 to reach 652 GW of total renewable capacity by 2050.
- The need for new electricity transmission, demand response, and energy storage to balance intermittent renewable generation becomes much greater after 2030 (CA-TIMES, CCST, LEAP-SWITCH, PATHWAYS, WWS).
- Across all sectors, natural gas for power generation plays an important role in the short- to medium-term (2030). However, natural gas will not be sufficiently low-carbon enough to play a significant role by 2050 without carbon-capture and sequestration (CCS) with very high capture rates and near zero storage losses. The capacity factor of natural gas plants that do not use CCS drops precipitously by 2050 (CA-TIMES, LEAP-SWITCH). Natural gas CCS with high capture rates could be a key enabling low-carbon technology (CA-TIMES, LEAP-SWITCH, PATHWAYS); however, the need for natural gas CCS may be offset by a strong, cost-effective demand response program (LEAP-SWITCH).
- California remains a net electricity importer, with imports potentially ranging from 17-24% of total generation in 2030 to 19-60% in 2050 (LEAP-SWITCH). Coordination with other states will become increasingly important for the cost-effective deployment of low-carbon electricity.

3. **Significant de-carbonizing of transportation sector including both passenger vehicles and freight is necessary by 2050.**
    - Across deep reduction scenarios that achieve the 80 percent reduction target in 2050, transportation achieves the largest magnitude of GHG reductions of any sector from 2010 to 2050[7], while at the same time remaining the highest contributor to overall emissions of any sector in 2050. The transportation sector's share of statewide emissions in 2050 is estimated at:
        - ~30 MMT/yr or 36% of statewide emissions (LEAP-SWITCH-Base);
        - 45 MMT/yr or about 54% of statewide emissions (PATHWAYS-Mitigation);
        - 105 MMT/yr or 62% of statewide emissions (CA-TIMES-STEP)[8];
    - The ARB VISION model demonstrate the potential for a ~50% reduction in transportation GHG emissions below 2010 levels by 2030[9].
    - In deep GHG reduction scenarios, by 2050 the light-duty-vehicle (LDV) fleet has moved primarily to battery electric (BEV), plug-in hybrid electric (PHEV), and hydrogen fuel cell vehicles (FCV), although the exact composition and magnitude of change varies between scenarios. For example, in CA-TIMES the combination of battery electric and hydrogen fuel cell vehicles makes up between 50% and 96% of the LDV fleet in 2050. In the ARB VISION model's mitigation scenario, these same technologies comprise over 80% of the LDV fleet in 2050. Regardless of the exact fleet

---

[7] The one exception is the electric sector in PATHWAYS which achieves equal reductions as transportation

[8] This is higher than others due to inclusion of out-of-state marine and aviation emissions and all emissions associated with electricity use regardless of in-state or imports generation.

[9] The VISION model focuses on the transportation sector and associated upstream energy and is not included in Figure 1.

composition, hydrogen and electricity with near-zero life-cycle GHGs (e.g. from wind, solar, biomass, NG with CCS) is needed to power virtually all of the LDV fleet by 2050.

- Goods movement, or freight transportation, which includes medium and heavy-duty trucks, rail, marine, and aviation, is the fastest growing source of GHGs in the transportation sector and faces unique challenges toward low-carbon solutions due to the large variation in products, duty-cycles, and industry composition. Goods movement overall is also the largest source of local criteria pollutants, including NOx, and contributes to local air quality issues (ARB VISION). For those scenarios that are also designed to consider national ambient air quality goals for ozone, zero and near zero-emission goods movement solutions are needed much earlier, especially in the South Coast (includes Los Angeles) and San Joaquin Valley Air Basins, with significant sales fractions of these technologies occurring by 2030 (ARB VISION). Low-carbon biofuels are one of the more promising fuel strategies to achieve near-term GHG emissions reductions, especially for heavier long-haul modes, by 2030, while electrification and hydrogen play increasingly important roles between 2030 and 2050 (CA-TIMES, GHGIS, PATHWAYS).
- Among deep GHG reduction scenarios that include a strong role for biomass[10], that biomass is used almost exclusively for transportation. Due to feedstock limitations, maximum penetration of biofuels in the transportation energy mix is ~40% across all modes in 2050 (CA-TIMES, GHGIS, PATHWAYS). Including both in-state and imports, between 5.5-10.3 billion gallons of gasoline equivalent are assumed in 2050 across models (ARB VISION, CA-TIMES, CCST, GHGIS, LEAP-SWITCH, PATHWAYS)[11]. This range is based on biomass supply curves of advanced feedstocks, such as energy crops grown on marginal land, forest and agriculture residue, waste products, and, in some models, algae. Biofuel plants that use biomass with CCS and co-generate electricity, if viable, can provide large carbon reductions with 'negative-carbon' fuels and small amounts of electricity (CA-TIMES, LEAP-SWITCH). More research on biomass pathways is needed to ensure long-term feedstock sustainability and there remains a high degree of uncertainty concerning the carbon intensity of many bioenergy pathways, especially those non-waste-based biofuels that require significant amounts of land per unit of energy produced.

4. Non-energy GHGs become increasingly important

The relative contribution of non-energy and High Global Warming Potential (HGWP) GHGs to overall emissions levels is likely to increase in the coming decades. Absent further policy, non-energy related emissions could exceed the 2050 emission goal even if all other emissions are zero (GHGIS, LEAP-SWITCH).

5. Scenario costs and economics vary greatly. Including net-savings and co-benefits has the potential to offset most, if not all, of the increased technology costs.

For those models that include an estimate of technology costs (BEAR, CA-TIMES, LEAP-SWITCH, PATHWAYS, WWS), the results varied based on assumptions, such as the composition of technologies

---

[10] One model (WWS) does not require biomass to achieve 2050 goals.

[11] This range reflects an assumption that biofuels in 2050 will be made from "low carbon" pathways including energy crops grown on marginal lands, agriculture and forest residues, and MSW.

included in the scenarios, initial costs, learning curves, discount rate, and policy mechanisms. The BEAR model also included an estimate of macro-economic impacts to 2020. The results presented or discussed at the forum include:

- Estimates of average carbon mitigation cost ($/tCO$_2$e, converted to 2013 dollars) vary between models, across sectors and time periods. Additionally, not all models use the same reporting conventions. CA-TIMES reports the average mitigation costs across the time period from 2010-2050 across 22 scenarios range from -$110 (savings, including from demand reduction and efficiency improvement) to +$220/tCO2e. Similarly, in PATHWAYS the average mitigation cost from 2010-2050 is $109/tCO2e with the average in 2050 equal to $97/tCO2e. Policies that reduce GHG emissions, in addition to reducing the impacts from climate change, may also yield a number of other valuable co-benefits (e.g. ecosystem services, improved air quality, health benefits, etc.) which are not captured in many of these estimates.[12]
- In deep GHG reduction scenarios, LEAP-SWITCH estimates electricity rates, in real dollars, do not increase in 2030 relative to current rates and do not vary significantly from "Business As Usual" (BAU). Electricity rates do, however, rise relative to BAU after 2030 to meet the 2050 goal, with estimates of an increase of 21-88% relative to BAU to meet a 2050 GHG emission target of 86% below 1990 levels for the entire Western Electricity Coordinating Council (LEAP-SWITCH) [13].
- While initial technology and energy infrastructure investment costs are expected to increase in some sectors, the statewide investment in efficiency is expected to provide financial savings that can be invested back into the state economy, providing overall economic benefits (BEAR, PATHWAYS). For models that include macro-economic feedback (BEAR), calculate net savings (PATHWAYS), or include full accounting of social costs (WWS), these savings have the potential to offset most or all of the increased technology costs.

6. **A more comprehensive comparison of modeling uncertainty with regard to input assumptions is needed in future work.**

   For example, PATHWAYS finds that under certain high oil price assumptions, the deep GHG reduction scenarios are cheaper than the BAU scenario (i.e. cost savings). CA-TIMES finds that the mitigation costs (and technology adoptions) are most sensitive to the costs and availability of critical technology options or breakthroughs such as advanced bio-liquids, nuclear and CCS, and assumptions about energy demand growth.

7. **Climate policies should complement and integrate with other air quality goals**

   There is a need to pursue strategies that contribute to both climate and air quality goals, especially in the central valley and south coast regions of California. This implies that:

   - Strategies are needed that simultaneously reduce GHG emissions, particulate matter (PM), oxides of nitrogen (NOx), and/or reactive organic gases (ROG) related to ozone pollution consistent with

---

[12] For example the WWS model calculates the full social cost and benefit of reduced GHG and criteria pollutant emissions and finds that the external benefits of a system powered by 100% WWS pays back the installation and operating costs of the low-carbon energy system in approximately 6 years.

[13] Note that rates do not reflect savings that might accrue from energy efficiency improvements, therefore the effect on consumer bills could be lower.

both the near-term 2023 and midterm 2032 national ambient air quality standards (NAAQS) and long-term 2050 GHG targets.

- Under some scenarios, compliance with AB32 reduces population exposure to PM2.5 by 6% during extreme air pollution episodes and 8% over annual averages. The potential co-benefits of improved air quality associated with AB32 have an estimated monetary value of $5.4B in 2030 from avoided premature deaths from PM2.5 exposure[14]. WWS estimates that a 100% renewable energy system would eliminate approximately 16,000 state air pollution deaths per year and avoid $131 billion per year in health care costs.
- Aggressive pursuit of zero- and near-zero-emission transportation technologies has the potential to achieve NAAQS of 75ppb ozone (O_3) and relevant targets in the South Coast Air Basin and many parts of the San Joaquin Valley. Accomplishing this by the 2032 legally binding deadline will be very challenging due to assumed vehicle turn-over rates and higher initial technology costs, suggesting the need for additional strategies, early action items, and more rapid development and adoption of zero-emission technologies, especially for freight applications (ARB VISION).
- A better understanding and specification of spatial and temporal NOx and ROG emissions is needed to guide air quality policy including the response to and relationship with GHG reduction goals and strategies. The strong relationship between proximity of emission sources to population and health impacts makes high resolution and geospatial information necessary for accurate assessment of pollution exposure impacts (heath and fiscal benefits and costs).

8. Better communication needed between modelers and policymakers

More dialogue between modelers and policymakers is needed to guide decision-making and policy design, and to improve the value of future modeling efforts. Several opportunities for improvement were discussed at the forum, including:

- Policymakers would like to see more modeling of explicit policies in order to better understand the effects of existing and proposed regulations as well as the interactive effects of policies.
- Modelers seek more up-to-date information about upcoming policies and more access to the latest state-collected data to improve model calibration/validation and detailed analysis of existing and future policies.
- Policymakers seek further information regarding scenario impacts on water, land-use, and air quality; on how best to sequence and prioritize policies and technologies; and on the costs and benefits of policies. Some modelers cautioned that incorporating other (non-GHG) environmental effects into economy-wide energy models can be difficult and may be better understood if modeled separately.
- Greater use of uncertainty ranges in model assumptions and outputs can help policymakers design better policies. Modelers emphasized that policy can be designed to be more robust to uncertainty by incorporating flexible policy mechanisms (e.g. market mechanisms such as trading, banking, and borrowing) and regular review.

---

[14] Zapata, C.; Muller, N.; Kleeman, M., PM2.5 co-benefits of climate change legislation part 1: California's AB 32. *Climatic Change* **2013,** *117* (1-2), 377-397.

- Policymakers asked the modelers to provide more results in the form of policy metrics in order to improve their relevance, ease their interpretation, and help guide the development of policy targets. Examples discussed include performance metrics such as gCO_2e/mile for vehicles, gCO_2e/MJ for fuels, $kgCO_2$/KWh for electricity, % renewables by year; and economic metrics such as $/metric ton CO_2e, % change of household expenditure on energy, lifecycle costs of travel ($/vehicle miles traveled), etc.[15]

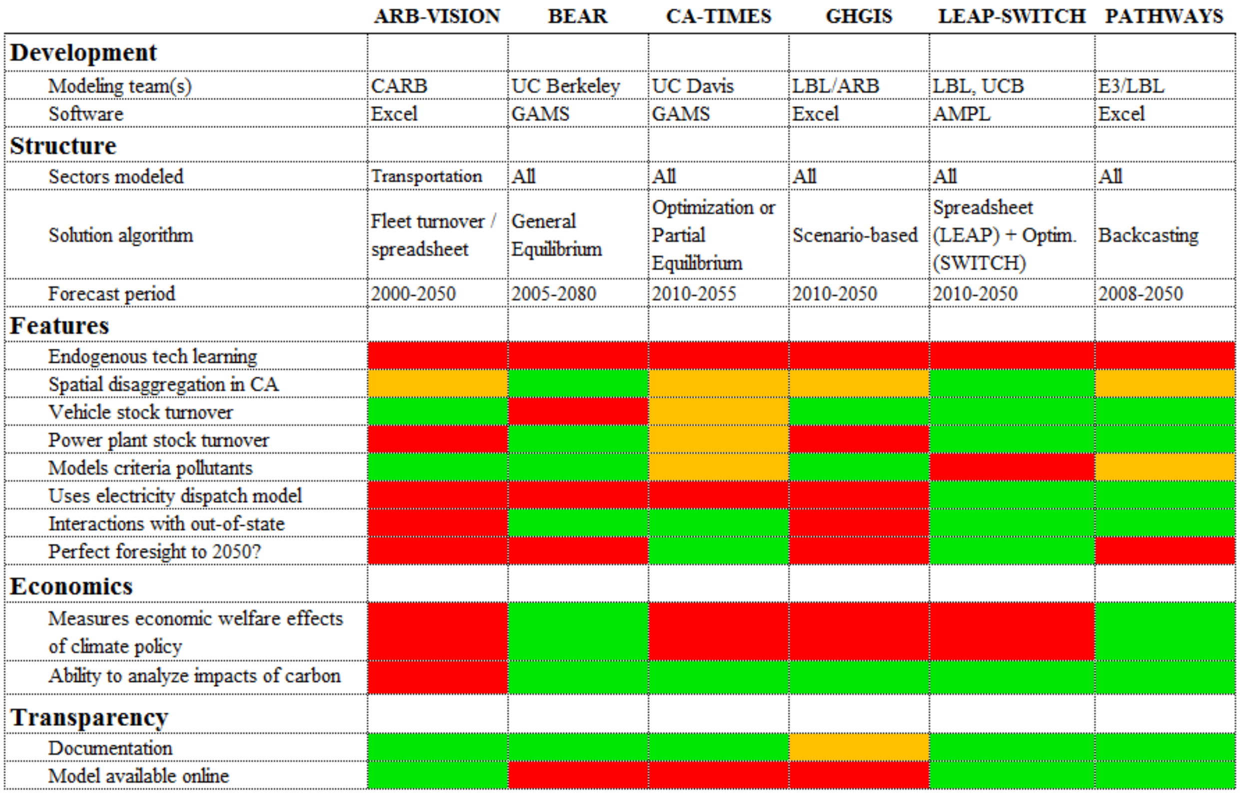
---

[15] Cost metrics using $ per delivered energy (e.g. $/gallon and $/MJ) do not capture changes in end-use efficiencies over time (e.g. improvements in miles traveled per gallon and improvements of cooling technology efficiency) and could be misleading. Depending on the purpose of the cost metric, modelers should consider reporting lifecycle cost (e.g. $/mile) to reflect the consumer costs of energy consumption.

Appendix: Model Summaries and Illustrations

The selected models participating in the first CCPM forum cover a range of modeling techniques (e.g. optimization vs. scenario based vs. general equilibrium), which are designed to answer different policy questions, and, as such, incorporate different system boundaries, time periods, and geographic scales.

Table 1 highlights key differences in model structure, system boundaries, and other key attributes that can have significant impacts on the results. More detailed descriptions of each model can be found at the program website (policyinstitute.ucdavis.edu/initiatives/ccpm/), and an upcoming companion white paper will discuss in greater detail these and other differences and the impacts on the results.



	ARB-VISION	BEAR	CA-TIMES	GHGIS	LEAP-SWITCH	PATHWAYS
Development						
Modeling team(s)	CARB	UC Berkeley	UC Davis	LBL/ARB	LBL, UCB	E3/LBL
Software	Excel	GAMS	GAMS	Excel	AMPL	Excel
Structure						
Sectors modeled	Transportation	All	All	All	All	All
Solution algorithm	Fleet turnover / spreadsheet	General Equilibrium	Optimization or Partial Equilibrium	Scenario-based	Spreadsheet (LEAP) + Optim. (SWITCH)	Backcasting
Forecast period	2000-2050	2005-2080	2010-2055	2010-2050	2010-2050	2008-2050
Features						
Endogenous tech learning	🟥	🟥	🟥	🟥	🟥	🟥
Spatial disaggregation in CA	🟨	🟩	🟨	🟨	🟩	🟨
Vehicle stock turnover	🟩	🟥	🟨	🟩	🟩	🟩
Power plant stock turnover	🟥	🟩	🟨	🟥	🟩	🟩
Models criteria pollutants	🟩	🟩	🟨	🟩	🟥	🟨
Uses electricity dispatch model	🟥	🟥	🟥	🟥	🟩	🟩
Interactions with out-of-state	🟥	🟩	🟩	🟥	🟩	🟩
Perfect foresight to 2050?	🟥	🟥	🟩	🟥	🟩	🟥
Economics						
Measures economic welfare effects of climate policy	🟥	🟩	🟥	🟥	🟥	🟩
Ability to analyze impacts of carbon	🟥	🟩	🟩	🟩	🟩	🟩
Transparency						
Documentation	🟩	🟩	🟩	🟨	🟩	🟩
Model available online	🟩	🟥	🟥	🟥	🟩	🟩

Note: Green: yes/represented; Yellow: limited; Red: none/not represented.

TABLE 1: QUALITATIVE COMPARISON OF MODELS

Table 2 compares the criteria pollutant emissions and pollutant concentrations tracked in energy models. Each model is at various stages in progress or ongoing inclusion of criteria pollutant emissions. The ARB VISION, BEAR, and GHGIS models currently have either the relevant capability or have updated NOx, ROG, and PM2.5 emissions inventories. The PATHWAYS model is adding Air Quality Management District resolved NOx emissions, and the CA-TIMES group is adding a module to begin estimating changes to criteria pollutant emissions to conduct PM2.5 and ozone air quality simulations.

	Tracked Pollutant Emissions						Pollutant Concentrations	
Model	**NOx**	**ROG**	**PM2.5**	**CO**	**SOx**	**NH3**	**PM2.5**	**O3**
ARB VISION	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥
CA-TIMES	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
BEAR	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥
GHGIS	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥
PATHWAYS	🟨	🟥	🟥	🟥	🟥	🟥	🟥	🟥
LEAP-SWITCH	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥

Note: Green: yes/represented; Yellow: limited; Red: none/not represented. The Yellow for CA-TIMES represents an add-on feature (ex-post analysis) as opposed to being part of the integrated model.

TABLE 2: NON GHG EMISSIONS TRACKED BY EACH MODEL

Figure 2 compares GHG emissions scenarios that achieve the 80% reduction goal by 2050. Figure 2 also includes scenarios that achieve cumulative GHG reductions equivalent to those scenarios, but do not achieve the 80 percent emissions reduction target in 2050 (GHGIS). The models use different approaches for meeting the target (e.g. cost minimization/optimization, bounded technology scenarios, etc.), different system boundaries, and include several other differences (see Table 1). As a result, the range of projected emissions levels in 2030 (as shown in Figure 2) varies between 208-396 MMTCO$_2$e (8% to 52% below 1990). GHGIS (also shown in Figure 2) takes a unique approach whereby, instead of trying to meet the 2050 target, it assumes continuing and strengthening existing and future policies. While all three GHGIS-modeled scenarios did not meet the annual GHG reduction target in 2050, two of the three achieve similar or more stringent cumulative emissions reductions compared to a straight-line emissions reduction between 2020 and 2050.

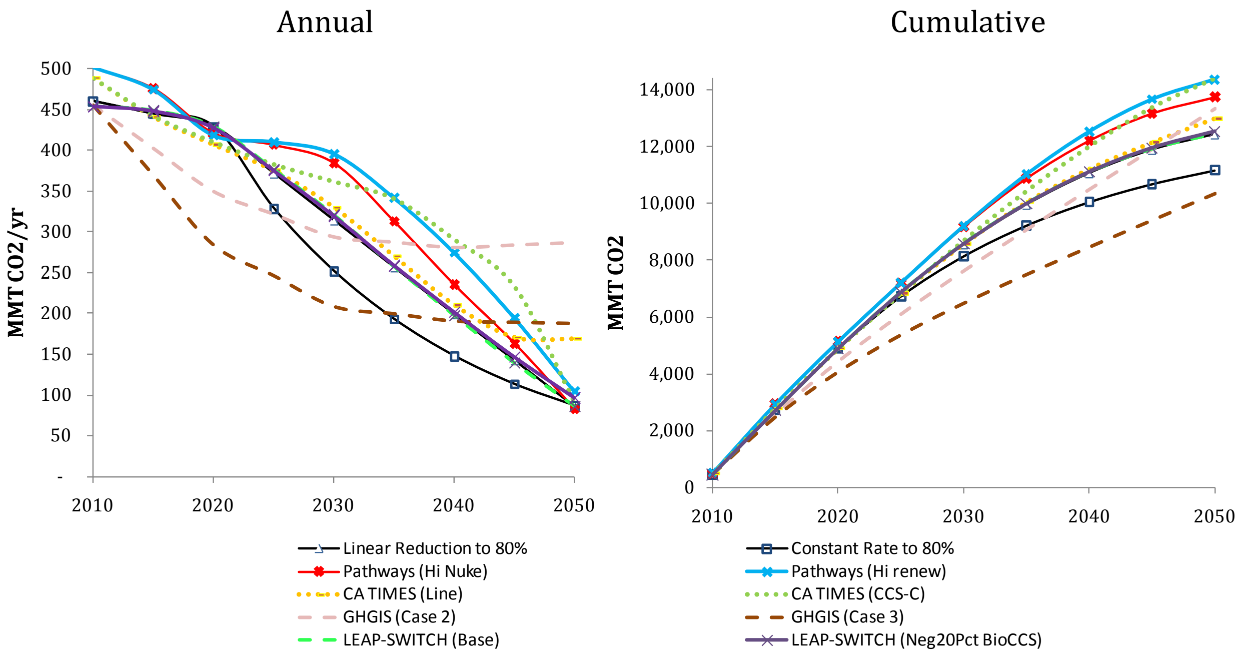


FIGURE 2: SELECT GHG ANNUAL (RIGHT) AND CUMULATIVE (LEFT) EMISSIONS SCENARIOS[16].

---

[16] "Constant Rate to 80%" is an emissions trajectory of constant rate of emissions reduction between 2020 and 2050 while meeting the 80% emissions reduction level by 2050. Figure 2 is similar to figure 1 but shows individual model/scenarios.