Response to Editor and Referee Comments on

“Estimating Criteria Pollutant Emissions Using the California Regional Multisector Air Quality Emissions (CA-REMARQUE) Model v1.0” by Christina B. Zapata et al.

Response to Editor Comments

Comment 1.

In order to comply with GMD policy, your manuscript must include the name and version number of the model in its title, the model code must be made available, and the code availability should be described in your "Code and/or Data Availability" section. If the original model code has not been modified for this manuscript, I think it would still be appropriate to mention the availability of the version of the model you used.

Response 1.

We have added the model version number to the title as suggested.

Response to comments by Anonymous Referee #1

————- General comments: ————-

In this manuscript, the authors use the CA-REMARQUE method to develop 4km gridded emission inventories for the year 2050. Two inventories are generated: a baseline inventory and one in which GHG emissions are reduced by 80% relative to 1990 levels. The scenarios were developed using the CA-TIMES model. The authors describe their approach for translating the CA-TIMES projections into criteria pollutant values based on a variety of sector-specific procedures. The authors then examine the resulting 4 km inventories and highlight differences in scenario-, sector-, and pollutant-specific emission trends. Furthermore, they compare the changes in emissions to those of a more generalized, expert-driven approach and suggest that considering California specific conditions (e.g., regulatory environment, existing stock, renewable resources) yield very different changes in emissions than a more generalized approach found in the literature.

Scientific significance: This work tackles an important objective - developing emissions inventories that can be used to examine the air quality implications of specific energy system scenarios. While others have also tackled this problem, this work adds important detail. However, because the literature review is very limited, the authors are not able to explicitly identify how they advance the science. (see "Specific Comments" for suggestions about expanding the literature review)

Scientific quality: I believe that the scientific approach and methods are underlying the work presented here are valid.

Scientific reproducibility: The authors do an very good job of describing the process that they used to develop future-year inventories from energy system modeling results. While replicating the work for this or another state or geographic region would undoubtedly be a large and difficult task, that difficulty would not be due to lack of information on the method.

Presentation quality: In general, I feel as if this manuscript is well written and that the experimental design and results reinforce the arguments presented by the authors. Nonetheless, I think the presentation quality could be improved substantially if the graphics provided in the results section were revised. One particular area of improvement is in the graphics that map PM emissions for both scenarios. I believe the intent of these graphics was to illustrate (i) the ability to develop spatially explicit inventories, and (ii) the changes in these emissions from one scenario to another. By using different scales on each image, however, the differences are not readily apparent. I suggest using the same scale or perhaps showing a graphic for the business as usual case and another with deltas associated with the GHG mitigation case. The stacked bar graphs that showed pollutant specific changes were also confusing and it was not clear what stacking of percents was intended to indicate. Those data could be much more easily presented and compared using a table.

———– Specific comments: ———–

Comment 1:

I feel that the manuscript has several deficiencies, and that it could be improved substantially if these deficiencies are addressed. Please see the "Specific Comments" below. My main concern is related to the literature review which could be expanded. I suggest that the authors include addition studies that examine the emissions or air quality impacts of alternative policy scenarios. A few for the U.S. are listed below (although I do not think that all of these necessarily need to be referenced):

* Keshavarzmohammadian A, DK Henze, and JB Milford (2017). Emission impacts of electric vehicles in the US transportation sector following optimistic cost and efficiency projections. Envir. Sci. Technol., 51(12), 6665-6673.

* Loughlin DH, WG Benjey, CG Nolte (2011). ESP v1.0: methodology for exploring emission impacts of future scenarios in the United States. Geosci. Model Dev., 4, 287-297.

* Ran L, DH Loughlin, D Yang, Z Adelman, BH Baek, and CG Nolte (2015). ESP v2.0: enhanced method for exploring emission impacts of future scenarios in the United States - addressing spatial allocation. Geosci. Model Dev., 8, 1775-1787.

* Rudokas J, PJ Miller, MA Trail, and AG Armistead (2015). Regional air quality management aspects of climate change: Impact of climate mitigation options on regional air emissions. Environ. Sci. Technol., 49(8), 5170-5177.

* Trail MA, AP Tsimpidi, P Liu, K Tsigaridis, Y Hu, JR Rudokas, PJ Miller, A Nenes, and AG Russell (2015), Impacts of potential CO2-reduction policies on air quality in the United States. 49(8), 5133-5141.

Similar to this manuscript, the Loughlin et al. 2011 paper also illustrates the development of region-, sectoral- and pollutant-specific implications of a climate policy and discusses how an energy system model's emission projections can be used to develop inputs to air quality modeling. Ran et al. (2015) build on that by adding a land use change compontent to spatially re-allocate emissions for some sectors. This manuscript would benefit greatly by a comparison to the Loughlin et al. and Ran et al papers. In such a comparison, I feel that the work presented here has much to add. For example, it explicitly tackles a state's regulations, goes into much greater detail regarding specific sectors (e.g., nonroad and marine), tackles the siting of new biomass-related emission sources, examines speciated emissions changes from fuel switching (e.g., fossil to biofuels), incorporates consideration of the PM benefits of regenerative braking, and seeks to examine the impact of controls on particle size distribution. Described in the context of these advances, I think the merits of the work presented here are much clearer and point to areas where other analyses could be improved.

Response 1:

We agree that an expanded literature review describing the latest work and findings in field will strengthen the study and help put the results in context. We have provided a brief description of these studies and cited the references in the introduction section of the revised paper.

Comment 2:

I have an additional concern that is perhaps less critical. My concern is related to the presentation of the scenarios themselves. The first scenario is relatively easy to understand as it is just a baseline or business as usual scenario. Nonetheless, California has a very unique energy system, so the underlying trends and dynamics there may not be readily apparent to readers. The second scenario is a GHG reduction scenario, although how the GHG constraint is implemented is not completely clear. Since the authors only compare emissions between a base year, 2010, and a future year, 2050, they have chosen to show the CA-TIMES results only for those years. To convey the scenarios and underlying dynamics more fully, however, I believe the authors should show several model outputs for the period from 2010 *through* 2050, not just in 2010 and 2050. These outputs would include at a minimum, and for both scenarios: (i) CO2 emissions by sector, and (ii) electricity production by technology, and (iii) energy system fuel use. Additionally, displaying fuel used or technologies adopted in the transportation and transportation sub-sectors could be of interest but are not necessary. Stacked area plots would be one form of presenting these graphics. The sectoral GHG graphic would be particularly useful in understanding how the GHG policy is represented in the model. For example, is it a constraint represented only from 2050 onward as the text seems to imply? If so, how did the model respond to such a shock, and did it begin to make structural changes to the energy system with foresight or respond in more of a myopic way? These results wouldn't necessarily need to be in the main body of the manuscript, and instead could be in the supplemental information.

Response 2:

The three CA-TIMES predictions for CO2 emissions, electricity production and energy/fuel for each scenario are described in detail by Yang, Yeh et al. (2015), mainly Fig. 3, Fig. 8, and Fig. 10 or in the free version of the entire report (Yang, Yeh et al. 2014). An explicit reference to these publications is now provided on line 108 of the revised manuscript, and a summary figure for the intermediate year 2030 is now included in the SI. Fuel consumption/production was extracted from CA-TIMES results for 2050 and provided in the SI to assist in explaining the emission results.

The GHG-STEP is a step change in the emissions requirement, but because the model has perfect foresight and is optimizing (minimizing) the energy system cost over the entire modeling period from 2010 to 2050 (with a 4% discounting factor), it makes investment decisions that are necessary to ensure that the 2050 targets are met. Because technologies have finite lifetimes and cannot take over their respective markets instantaneously (in 2050), investments in low-GHG technologies start slowly and grow to reach the required market share needed to meet the targets. These points have been clarified on line 102 of the revised text.

<Actual enhanced description of the scenarios starts on line 88.>

Additional substantive comments are listed below, preceded by page number:

Comment 3:

55: The text refers to other modeling efforts as over-simplifying the California economy. This statement, I think, implies that CA-TIMES includes a much more detailed representation of the economy. I advise care with that description, however. I suspect that CA-TIMES respresents the "energy economy" only, which is only a portion of the larger economy, and may represent interactions with the rest of the economy via simple elasticities for energy demands or perhaps with a function that links to regional GDP. Many readers will assume that a model of the economy would take the form of a Computable General Equilibrium model, which would represent things like tradeoffs between labor and capital, employment, household income, etc.

Response 3:
We thank the reviewer for pointing out this over-generalization of our description for CA-TIMES, which models California's energy system, not the rest of the economy. We have modified the text on line 55 of the manuscript to clarify that CA-TIMES is not a CGE model and we specify demands for energy services exogenously, which are not affected by technology choices.

<Actual enhanced description of CA-TIMES starts on line 74.>

Comment 4:

76: I suggest adding additional information to the description of CA-TIMES. For example, listing the sectors included would be helpful, as would listing the pollutants included in the model. Does it just represent CO2, or does it add other GHGs? What about air pollutants? Are demands fixed or elastic? How the model handles the rest of the country and the rest of the world? How trade with region(s) outside of CA is considered and constrained? Answers to some of these questions are alluded to later in the paper (as we see what CA-TIMES has produced and how it is used), but it would be very useful to have these types of questions answered explicitly when the model is introduced.

Response 4:
The CA-TIMES description has been enhanced starting on line 86 of the revised manuscript. Supply sectors are electricity and resources and fuel supply. Demand sectors are transportation, residential, commercial, industrial and agricultural. CA-TIMES includes emissions of CO2, methane and N2O, but not air pollutants (these are added in the current manuscript). Demands for energy services are fixed. Imports are allowed from out of state (e.g. oil and natural gas) with specified costs that are considered in the overall optimization scheme. Renewables and Biomass within the state and outside the state are handled separately with import levels once again chosen to optimize total costs.

<Actual enhanced description starts on line 74.>

Comment 5:

Fig 8: What is driving the reduction in commercial energy usage in 2050 GHG-Step? Is it elastic demands? More efficient technologies? Or is there commercial (on-site) solar power that isn't being shown?

Response 5:

The text on line 427 of the revised manuscript has been modified to state that commercial energy reduction is due to efficiency and electrification of end uses.

<Actual change is on line 407.>

Comment 6:

Fig 10: At first glance these look the same. It isn't until you examine the legend that it is clear that there has been a 2/3 reduction. I suggest having the scale the same on all the graphs. Alternatively, you could show the 2050 emissions and another graph showing deltas (e.g., where they increase or decrease). The latter approach may be more useful in conveying air pollutant emission co-benefits (or dis-benefits).

Response 6:

Figure 10 has been revised to show the BAU and the delta emissions as suggested by the reviewer.

Comment 7:

689 - Stacking percentages are difficult to interpret? Was a single % change then apportioned to components? If not, it may not be appropriate to stack these values. Perhaps you could show the actual quantities? I feel like a table would convey the information better.

Response 7:

The bar chart in Figure 17 was designed to indicate how each emission sector or source category is contributing to a percentage change in the nominal emissions. The text on line 700 of the revised manuscript has been added to better explain the figure.

Contributions below 0% indicate emissions reductions, while contributions above 0% indicate emissions increases. Each of these changes represents the statewide average for the sources within the indicated sector. Note that the changes within each sector may not be uniform across the entire state. The net change in total emissions is indicated by the black horizontal line for each species.

A table of the results summarized in Figure 17 has been added to SI.

<Actual change starts on line 680. Actual 3 tables added Table S36-38.>

———– Editorial comments and corrections: ———–

My other comments, which are more editorial in nature, are listed below. I hope that these are helpful in revising what I feel is a very interesting manuscript.

Line #: comment

Comment 8:

54: Editorial suggestion - Here and throughout, avoid using "/". Also, where you have "and/or" I suggest just using "or", which is not necessarily mutually exclusive.

Response 8:

Text throughout the manuscript changed to use "or" instead of "and/or".

Comment 9:

86: CAFE should be spelled without the accent mark on the E

Response 9:

Corrected.

Comment 10:

87: References to the regulations affecting CA would be helpful

Response 10:

References added.

Comment 11:

105: The statement is made that "vehicular emissions for the year 2050 were extrapoled", which left me wondering how. I see that you explain this later in the paper, but is there a way to reorganize so the reader doesn't ask this question, or, if they do, the answer if provided sooner? I had a similar concern with the text "vehicular activity and fuel consumption splits were applied..." in line 108.

Response 11:

The text in Section 2.1 of the revised manuscript has been revised to more clearly explain how emissions were extrapolated and fuels were split when this issue is first introduced.

<Actual changes made to section 2.2>

Comment 12:

Figure 2: The abbreviation EIC is used prior to being defined

Response 12:

Emissions Inventory Code (EIC) now defined in Figure 2.

Comment 13:

Figure 2: Minor suggestion: for the "2050 CA-TIMES Scenario on-road Emissions" box, I suggest renaming this "On-road emissions consistent with a 2050 CA-TIMES Scenario".

Response 13:

Figure 2 has been extensively revised in response to another reviewer comment. Text now reads "CA-TIMES 2050 Projections for vehicle miles traveled (VMT), fuel, and fleet composition statewide.

Comment 14:

128: A meteorological scaling factor is mentioned, but it isn't clear what is assumed about meteorology in the future.

Response 14:

Text on line 168 revised to clarify that temperature and relative humidity are downscaled to 4km resolution in 2054.

<Actual changes start on line 151.>

Comment 15:

128: It appears that the methodology does not explicitly consider expansion of existing roadways or the addition of new roadways. Similarly, I did not see a mention of the impact of land use change. If not, perhaps they could be mentioned in the discussion section as ways in which the analysis could be expanded?

Response 15:

The current analysis assumes that no new major highways will be built in California and population growth is accommodated partially through increased urban density such that traffic volumes increase uniformly across the transportation network. We recognize these assumptions are simplistic but a previous study of smartgrowth in the San Joaquin Valley indicated that more detailed accounting of population growth had minimal impact on air quality. These points are clarified in the updated discussion section of the paper as suggested by the Reviewer.

Comment 16:

145: There are two equations listed as (1). I suggest making each its own.

Response 16:

Corrected.

Comment 17:

155: Please provide definitions for the vehicle sub-categories

Response 17:

Clarified on line 191 of the revised manuscript, with an explicit reference to Table S2.

Comment 18:

209: Replace "_" with "approximately"?

Response 18:

Corrected.

Comment 19:

223: "Fueled" misspelled?

Response 19:

Corrected.

Comment 20:

345: Perhaps a better way to state "CA-TIMES finds that it is too expensive to adopt biomass-based fuels for ships in the GHG-Step scenario in 2050" is that the model identifies other approaches for meeting the GHG target more cost-effectively?

Response 20:

Revised as suggested.

Comment 21:

376: awkward

Response 21:

Reworded.

Comment 22:

388: Were wood and distillate held constant, or were they allowed to compete in CATIMES... but just not allowed to increase?

Response 22:

Clarified on line 426. These sources were allowed to compete in CA-TIMES subject to the constraint that they could not increase above 2010 levels in order to maintain compliance with current air quality regulations.

Comment 23:

Fig 9: Too many significant figures are shown in the table. Perhaps limit to 3 for each value shown?

Response 23:

Significant figures reduced to 3 as suggested.

Comment 24:

431: CA-GREET1.8b is argued to have the highest accuracy. But it isn't clear what that means or to what it is being compared to evaluate accuracy.

Response 24:

Text on line 480 revised to clarify

An inter-comparison study between GREET1.8, GREET 2014, and CA-GREET2.0 showed that theCA-GREET1.8b model had the best agreement with emissions rates from approximately 30 biomass plants operating on wood residue in California. (California Air Resources Board 2011, US Environmental Protection Agency 2014).

Comment 25:

447: Replace "predicted" with "determined"? CA-TIMES and similar models aren't typically referred to as predictive models. Instead, they are used to evaluate how technology and fuel choices play out under particular scenarios and assumptions.

Response 25:

Revised as suggested.

Comment 26:

450: Do you know the amount of reduced usage vs. switching to imports?

Response 26:

Based on purely the crude oil supply numbers shown in Figure S6, crude oil supply reduces by 44% (2,400PJ down from 4300PJ in 2010) in the GHG-Step scenario. We're not switching to imports as

much as eliminating crude extraction within California (0PJ in 2050 GHG-Step versus 1500 in 2010). This is likely due to carbon constraint and costs of extraction determined in CA-TIMES relative to importing. Imports would also drop slightly by 14% (down to 2400PJ relative to 2800PJ in 2010) for this scenario. Additional information added on line 497.

Comment 27:

453: Where "Assumed to increase" is used, I think the authors are referring to a model result, not an assumption. Perhaps reword to clarify.

Response 27:

Corrected.

Comment 28:

711: The legend for Fig 18a should include at least one more significant digit to be more comparable with the other graphics.

Response 28:

Fig. 18 revised.

Comment 29:

744: You should probably be clear that the CA-TIMES model "code" isn’t part of this package (assuming that it is not).

Response 29:

Clarified.

Comment 30:

734: "does not have significant impact on criteria..." I understand the point, but this is worded awkwardly.

Response 30:

Revised.

Response to comments by Anonymous Referee #2

The authors present an ambitious modeling effort to project air pollutant emissions from multiple sectors under differing climate policies at high resolution across California. In doing so, this study carries out a significant effort to simulate changes to technology, fuels and human activity for varying sources based on multiple models, datasets and careful assumptions. The paper describes a methodology that goes beyond prior attempts to project pollutant emissions changes associated with GHG mitigation strategies. The methodology and model developed will be a valuable contribution to the air quality and climate modeling communities. Additionally, the manuscript is well written. I believe the paper should be considered for publication in GMD. However, I have some concerns with the manuscript in its current form. These issues must be addressed before I can recommend publication. My comments are described below:

Comment 1:

- My largest concern relates to the presentation of results under section 3 Results and Discussion. Although the authors describe the model's results and discuss some interesting findings, the section (particularly the plots and visualizations) should be improved to better communicate the study's results. Figures 10-15 are not informative. Figures 16 and 18 are unclear. The quality of all figures with maps in the section could be improved. Some specific comments are provided below. I encourage the authors to improve the manuscript's overall discussion of results.

Response 1:

Figures 10-15 were revised to show the spatial detail and location of various emission sources as well as indicate changes between scenarios. Figures 16 and 18 captions and scaling are clarified. The legend scaling for all these figures have been updated to improve clarity and ease of scenario comparison.

Comment 2:

-Although the study focuses on California, and the depth with which the authors model projected emissions within the state is a strength, the manuscript would benefit from including a discussion of the potential benefits and challenges associated with applying the emissions modeling methods used to other regions beyond California or at a national scale. Given the specificity of the analysis, it is difficult to identify which elements may be extended to other locations or to Policy/GHG/Energy projections developed with other models beyond CA-TIMES.

Response 2:

The basic calculations demonstrated in the current manuscript to estimate criteria pollutant emissions that are consistent with energy policies can be extended outside California, but the tools and data sources needed for the analysis would need to be modified as appropriate for each new region. Within the United States, the mobile sector analysis would need to use the MOVES model created by US EPA rather than the EMFAC model created by the California Air Resources Board (CARB). The spatially-resolved based inventory would be produced from the National Emissions Inventory (NEI) rather than the inventory maintained by CARB.

The input data needed for other sectors may be more difficult to obtain outside of California. Changes to off-road emissions would need to be estimated following procedures similar to those employed in

the CARB off-road VISION model. Effort would be needed to estimate how changes to marine fuel sources would influence emissions at major ports. Studies would need to be conducted describing potential locations for new facilities producing low-carbon fuels and the resulting emissions from those facilities. All of these studies have could be carried out for regions outside of California given sufficient time and resources.

Comment 3:

- Line 17: Change “play” to “plays”

Response 3:

Revised.

Comment 4:

- Cite references to strengthen the statements in lines 38-40, 40-41 and 42-44.

Response 4:

Section removed since verbose (Comment 5).

Comment 5:

- The paragraphs from line 38 to 48 felt a bit verbose and off the point.

Response 5:

Removed.

Comment 6:

- Line 49: “Most previous attempts: : : focused on developing countries: : :” This is not correct; many studies have focused on the US.

Response 6:

Revised to discuss US studies more thoroughly.

Comment 7:

- Line 53-55: Consider the study, by Zhang et al.; doi: 10.5194/acp-16-9533-2016

Response 7:

Added.

Comment 8:

- Line 68: remove “previous”

Response 8:

Removed.

Comment 9:

- Line 81: define AB32

Response 9:

Defined AB32 as California Assembly Bill 32, the Global Warming Solutions Act on line 97.

Comment 10:

- Line 82: Better explain “step function constraint”

Response 10:

Text revised to explain step function more clearly on line 99.

In the GHG-Step scenario a “step” GHG emissions function constraint is applied in which a constant 2020 cap is held until 2050, and then an 80% reduction is applied from 2050 onward. This allows the model to adopt strategies that lower GHG emissions prior to 2049 if those strategies minimize costs. This 2050 GHG constraint does not shock the energy system because the CA-TIMES model has perfect foresight and optimally minimizes the energy system cost (with a 4% discount factor) over the entire period from 2010 to 2050 making investment decisions to meet targets. Also, CA-TIMES investments in low-GHG technologies start slowly and grow to reach the required market share to meet the targets since technologies have finite lifetimes and cannot take over respective markets instantaneously.

Comment 11:

- Line 88-89: How do projected energy consumption and population compare to current levels?

Response 11:

Text on line 115 revised to read

CA-TIMES predicts total annual energy consumption in California for the year 2050 to be 8,763 PJ in the BAU scenario and 7,679 PJ in the GHG-Step scenario (reference value for 2010 is approximately 7,500 PJ).

Text on line 647 revised to read

Population growth from approximately 37.4 million in 2010 to approximately 50.4 million in 2050 was assumed to be identical under the BAU and GHG-Step scenarios yielding virtually identical spatial distributions for both scenarios.

Comment 12:

- Line 93: Change to “overview”

Response 12:

Fixed.

Comment 13:

- Define acronyms upon first mention, e.g. EMFAC on line 105

Response 13:

EMissions FACtor now defined on line 133 of the revised manuscript.

Comment 14:

- Line 117: Define VMT

Response 14:

Vehicle Miles Traveled (VMT) defined on line 138 of the revised manuscript.

Comment 15:

- I found figure 2 hard to follow and not very informative. In the figure, I do not see where the 4 km2 resolution is achieved or the 2010 emissions inventory is used. I would recommend simplifying this figure into a version that better conveys the overall process, without showing every step included in the algorithm.

Response 15:

As requested, Figure 2 has been revised to provide an overview of the mobile source process that should be easier to follow.

Comment 16:

- Line 129: Is there a reference for the 2010 inventory?

Response 16:

No published reference is available but the inventory can be provided upon request by the staff at the California Air Resources Board.

Comment 17:

- Line 136: Is 2050 meteorology being used? If so, what is the source of this data?

Response 17:

Yes, 2050 meteorology is being used as described on line 167 of the revised manuscript.

Comment 18:

- Line 148: This appears to be a second scaling factor, beyond that just described in equations 1 and 2. This can be made clearer in the sentence.

Response 18:

Clarified.

Comment 19:

- Lines 148-151: It seems that there are 2 projections being used, (1) the projection from EMFAC (which also accounts for policy) and (2) the CA-TIMES projection. Are both projections fully compatible?

Response 19:

EMFAC accounts for population growth and emissions changes that are required by existing air quality rules and regulations through 2050. CA-TIMES accounts for additional changes that will be required to comply with state GHG targets but which have not yet been placed into emissions rules and regulations. The two projections are compatible since we have not double-counted any emissions reductions. This has been clarified on line 186 of the revised text.

Comment 20:

- Line 280: change 2050 to 2010

Response 20:

Thank you. Corrected.

Comment 21:

- Line 318: Define ROGs

Response 21:

Reactive Organic Gases (ROGs) defined on line 169.

Comment 22:

- Figure 10: This figure should use the same scale on all panels to adequately contrast the emissions projected under the BAU and GHG-Step scenarios. It would also be useful to map the difference between both scenarios, as well as the difference between each and the 2010 emissions inventory. In its current form, the figure is not very informative.

Response 22:

Figure revised as suggested.

Comment 23:

- The same observations mentioned above apply to figures 11-15.

Response 23:

Figures revised as suggested.

Comment 24:

- Lines 572-573: I'm not sure if this is clear; improving the figures would help.

Response 24:

Revised figures illustrate the trend more clearly.

Comment 25:

- Figure 16: What are the units on the color scale?

Response 25:

They are PM2.5 mass emissions in μg m^{-2} min $^{-1}$ of production at each facility. Clarified.

Comment 26:

- Lines 646-649: These sentences are unclear. Which are minor and major pollutants? this is not a typical classification.

Response 26:

Text clarified on lines 703-708.

Comment 27:

- Lines 656-657: Cite literature supporting this.

Response 27:

Added.

Comment 28:

- Lines 659-660: What is the rational for this statement? PM0.1 is a component of PM2.5, how are the health benefits amplified?

Response 28:

The text on line 716 has been clarified to read

Recent epidemiology results indicate that PM0.1 is associated with mortality in the California Teachers Study (Ostro, Hu et al. 2015). Enhanced PM0.1 emissions reductions could amplify the potential health benefits of the future GHG-Step scenario beyond the level expected from reductions in PM2.5 emissions reductions.

Comment 29:

- Figure 17: The net total marker could be made clearer.

Response 29:

Done.

Comment 30:

- Figure 18: The quality of this figure should be greatly improved. Label the panels, make the scale coloring uniform among them. What units are being used for NOx? This shows the change with respect to BAU or 2010?

Response 30:

Figure modified as requested.

Comment 31:

- Line 706-707: This sentence is unclear. How is the effect immediate?

Response 31:

Revised text to indicate the changing emissions patterns will have a direct effect on population exposure.

Comment 32:

- Line 11: What is meant by “second or higher rounds of emissions controls”?

Response 32:

Text at line 768 revised to state more clearly

Similar efforts will be required to analyze the effects of GHG mitigation strategies on criteria pollutants in other highly-populated regions that have already moved beyond simple emissions regulations banning obvious sources of air pollution.

References

California Air Resources Board. (2011, May 28, 2015). "Facility Search Engine Tool." Retrieved 6/5/2015, 2015, from www.arb.ca.gov/app/emsinv/facinfo/facinfo.php.

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Yang, C., S. Yeh, S. Zakerinia, K. Ramea and D. McCollum (2015). "Achieving California's 80% greenhouse gas reduction target in 2050: Technology, policy and scenario analysis using CA-TIMES energy economic systems model." Energy Policy **77**: 118-130.

Estimating Criteria Pollutant Emissions Using the California Regional Multisector Air Quality Emissions (CA-REMARQUE) Model v1.0

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Abstract. The California REgional Multisector AiR QUality Emissions (CA-REMARQUE) model is developed to predict changes to criteria pollutant emissions inventories in California in response to sophisticated programs implemented to achieve deep Green House Gas (GHG) emissions reductions. Two scenarios for the year 2050 act as the starting point for calculations: a Business as Usual (BAU) scenario and an aggressive GHG reduction (GHG-Step) scenario. Each of these scenarios was developed with an energy economic model to optimize costs across the entire California economy and so they necessarily include changes in activity, fuels, and technology. Separate algorithms are developed to estimate emissions of criteria pollutants (or their precursors) that are consistent with the future GHG scenarios for the following economic sectors: (i) on-road, (ii) rail and off-road, (iii) marine and aviation, (iv) residential and commercial, (v) electricity generation, and (vi) biorefineries. Properly accounting for new technologies involving electrification, bio-fuels, and hydrogen plays a central role in these calculations. Critically, criteria pollutant emissions do not decrease uniformly across all sectors of the economy. Emissions of certain criteria pollutants (or their precursors) increase in some sectors as part of the overall optimization within each of the scenarios. This produces non-uniform changes to criteria pollutant emissions in close proximity to heavily populated regions when viewed at 4km spatial resolution, with obvious implications for exposure to air pollution for those populations. As a further complication, changing fuels and technology also modify the composition of reactive organic gas emissions and the size and composition of particulate matter emissions. This manifests most notably through a comparison of emissions reductions for different size fractions of primary particulate matter. Primary PM2.5 emissions decrease by 4% in the GHG-Step scenario vs. the BAU scenario while corresponding primary PM0.1 emissions decrease by a factor of 36%. Ultrafine particles (PM0.1) are an emerging pollutant of concern expected to impact public health in future scenarios. The complexity of this situation illustrates the need for realistic treatment of criteria pollutant emissions inventories linked to GHG emissions policies designed for fully developed countries and states with strict existing environmental regulations.

1 Introduction

The United States, along with many developing countries, is debating optimal strategies to mitigate threats to long-term prosperity including (among other things) climate change and threats to public health. These specific issues are at least partially linked through regional air quality. Realistic mitigation plans for Green House Gas (GHG) emissions (CO_2, CH_4, N_2O, etc) usually include measures encouraging reduced energy consumption ~~and/~~or changes to energy sources leading to reduced GHG emissions. These measures also impact emissions of criteria pollutants or their precursors (PM, NOx, SOx, VOCs, NH_3, etc) that influence regional air quality. Air quality influences public health through impacts on mortality (primarily related to $PM_{2.5}$) and morbidity (primarily related to $PM_{2.5}$ and O_3).

~~The relationship between climate change, air quality, and public health within the United States is being explored vigorously by California since this state has already adopted comprehensive environmental laws out of necessity to protect public health. Air quality in California's largest city, Los Angeles, was notoriously poor in the middle of the 20th century. The formation of the California Air Resources Board (CARB) to address this problem pre-dates the formation of the United States Environmental Protection Agency (US EPA). California has been a leading global voice in developing science to support environmental policies since that time, with many of the policies developed by California later adopted by the rest of the United States and the world.~~

~~California's most recent environmental efforts seek to reduce Green House Gas (GHG) emissions to sustainable levels while simultaneously improving air quality. This "win-win" approach attempts to demonstrate that responsible GHG policies can be adopted while still encouraging economic growth and prosperity. The debate around such policies is vigorous and clear science is needed to support the selection of optimal strategies moving forward.~~

~~Most~~ Many previous attempts to characterize the impact of ~~how~~ climate policies on criteria pollutant ~~will impact~~ emissions ~~of criteria pollutants~~, air quality, and public health have ~~focused on~~often ~~developing~~ emphasized countries where potential health savings are largest. These previous studies have also usually performed calculations for large geographic areas without resolving details at regional scales appropriate for California (Bollen, van der Zwaan et al. 2009, van Aardenne, Dentener et al. 2010, Rafaj, Schöpp et al. 2012, Shindell, Kuylenstierna et al. 2012, West, Smith et al. 2013, Garcia-Menendez, Saari et al. 2015). These studies represent California with only a small number of grid cells ~~and/~~or they uses simplistic representations of California's energy economy. ~~As a result, further work is needed to support the desired level of detailed analysis for the intersection of air, climate, and energy choices in California.~~

~~There have been growing US~~More recent studies addressing interactions between ~~future~~ climate policies, ~~on~~ emissions, and air quality in the US ~~(Keshavarzmohammadian, Henze et al. 2017)that include~~ (Loughlin, Benjey et al. 2011, Ran, Loughlin et al. 2015, Rudokas, Miller et al. 2015, Trail, Tsimpidi et al. 2015, Zhang, Bowden et al. 2016, Keshavarzmohammadian, Henze et al. 2017) have allocated future emissions using ~~. Although many of these studies also include~~ enhanced population surrogates ~~for emission allocation~~ (Ran, Loughlin et al. 2015) and federal climate policies (Trail, Tsimpidi et al. 2015). The current ~~this~~ study builds on this previous work to explicitly account for ~~advances further in determining emissions based on arguably environmentally aggressive~~ California's ambitious climate regulations broken out by detailed sectors including realistic siting of biofuel facilities. ~~, detailed sector changes, new biofuel facility siting,~~The current study also considers the effects of regenerative braking, and exhaust particulate size and speciation changes from the heavy use of alternative and renewable fuels across multiple economic sectors. These enhancements ~~As a result, further work is needed to~~ support the desired level of detailed analysis for the intersection of air, climate, and energy choices in California.

The purpose of this paper is to describe the California REgional Multisector AiR QUality Emissions (CA-REMARQUE) model that can translate complex GHG mitigation scenarios to criteria pollutant emissions inventories with sufficient detail to support fine-scale air quality models and public health analysis. Here we emphasizes solutions that optimize state-wide total GHG emissions across the entire California economy, with potential tradeoffs between different source types to achieve this objective. The complex optimization problem requires an energy economic model, and so we focus on scenarios predicted by the CA-TIMES energy economic model as the starting point for the analysis. The detailed algorithms within the CA-REMARQUE model are then developed to translate predicted changes in GHG emissions associated with source activity, fuels, and technology to criteria pollutant emissions that are spatially-resolved (4 km) for each sector of the California economy. Changing emissions profiles caused by fuel substitutions are also accounted for. Final results are compared to an expert-analysis method developed for a previous global analysis to illustrate why the complex methods described in this study are needed when analysing developed regions like California that have major diversified economies and a long history of ~~previous~~ environmental regulations.

2 Methodology

Energy scenarios are translated to criteria pollutant emissions inventories by the CA-REMARQUE model in a multi-step process with unique algorithms developed for each major sector of the economy that emits air pollution precursors. All calculations start with energy scenarios developed by the energy economic model CA-TIMES. The details needed to produce criteria pollutant emissions inventories are discussed in the following sections.

2.1 CA-TIMES Energy Model and Energy Scenarios

CA-TIMES (McCollum, Yang et al. 2012, Yang, Yeh et al. 2014, Yang, Yeh et al. 2015) is a bottom-up energy-economic model originally based on the MARKAL TIMES model (Loulou, Goldstein et al. 2016). CA-TIMES is a cost-minimization optimization model that balances energy supply and demand system-wide from all economic sectors of the energy economy. Demand sectors include transportation, industrial, residential, commercial, and agricultural. Fuel and electricity supply includes electric, biofuel, hydrogen production plants and biofuel and petroleum refineries. Demand was assumed fixed for the scenarios considered (Yang, Yeh et al. 2014, Yang, Yeh et al. 2015)~~.~~. CA-TIMES allows imports from out of state, such as oil, natural gas, and electricity. Renewables and Biomass are handled separately and modelled explicitly as located in or out of state and imports are determined on a cost basis. CA-TIMES contains capital and operation costs for each technology, diverse fuel and energy carriers, and calculates GHG emissions for CO_2, CH_4, and N_2O ~~emissions~~.

The case studies considered in the present study focus on two CA-TIMES scenarios in 2050: (i) a Business as Usual (BAU) scenario that achieves the goals outlined in California Assembly Bill 32 (AB32), the Global Warming Solutions Act of 2006 and (ii) a climate friendly GHG-Step scenario that achieves an 80% reduction (relative to 1990 levels) in GHG emissions by 2050. In the GHG-Step scenario ~~applying~~ a "step" GHG emissions ~~function~~ constraint is applied in which a constant 2020 cap is held until 2050, and then an 80% reduction ~~in 2049~~is applied from 2050 onward. This

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allows t~~. T~~he model ~~is~~ freedom to adopt strategies that lower GHG emissions prior to 2049 if those strategies minimize costs~~, but the step constraint ensures compliance with the final targets in 2050~~. This 2050 GHG constraint does ~~is~~ not ~~applied like a sudden~~ shock to the energy system because the CA-TIMES model has perfect foresight and optimally minimizes the energy system cost (with a 4% discount factor) over the entire period from 2010 to 2050 making investment decisions to meet targets. Also, CA-TIMES investments in low-GHG technologies start slowly and grow to reach the required market share to meet the targets since technologies have finite lifetimes and cannot take over respective markets instantaneously. The criteria pollutant emissions between 2010 and 2049 were not analysed in the current study but a summary of CA-TIMES results for intermediate years is provided by (Yang, Yeh et al. 2015). Both BAU and GHG-Step scenarios include current and sunset GHG regulations in California (Corporate Average Fuel Economy (~~CAFÉ~~CAFE) Standards (California Air Resources Board 2005, California Air Resources Board 2009, California Air Resources Board 2010), Zero Emission Vehicle (ZEV) Mandate (California Air Resources Board 2012, California Air Resources Board 2012, California Air Resources Board 2012, California Air Resources Board 2012, California Air Resources Board 2012), Low Carbon Fuel Standard (LCFS) (California Air Resources Board 2009, California Air Resources Board 2011), Cap-and-Trade Program (California Air Resources Board 2011, California Air Resources Board 2017)~~)~~ and federal and state incentives (tax credits and subsidies). CA-TIMES predicts total annual energy consumption in California for the year 2050 to be 8,763 PJ in the BAU scenario and 7,679 PJ in the GHG-Step scenario (reference value for 2010 is approximately 7,500 PJ) (Yang, Yeh et al. 2015).

The methods to estimate criteria emissions for different sources developed in the current paper take advantage of the best available information describing future energy and emissions as a function of location. The quality of this information varied considerably for each major source category and so the details of the methodology also varied. Figure 1~~Figure 1~~ illustrates an over~~-~~view of the general procedure. The changes in energy consumption and GHG emissions produced by CA-TIMES for each energy sector in the year 2050 were translated to changes in criteria pollutant emissions by accounting for changing energy activity levels ~~and /~~ or fuel switching. Literature searches were conducted to identify any previous studies describing spatial locations of future emissions within California. Altered emissions for the year 2050 were then projected from a 2010 emissions inventory with 4 km spatial resolution provided by the California Air Resources Board (CARB). Additional details for each major source type are discussed below.

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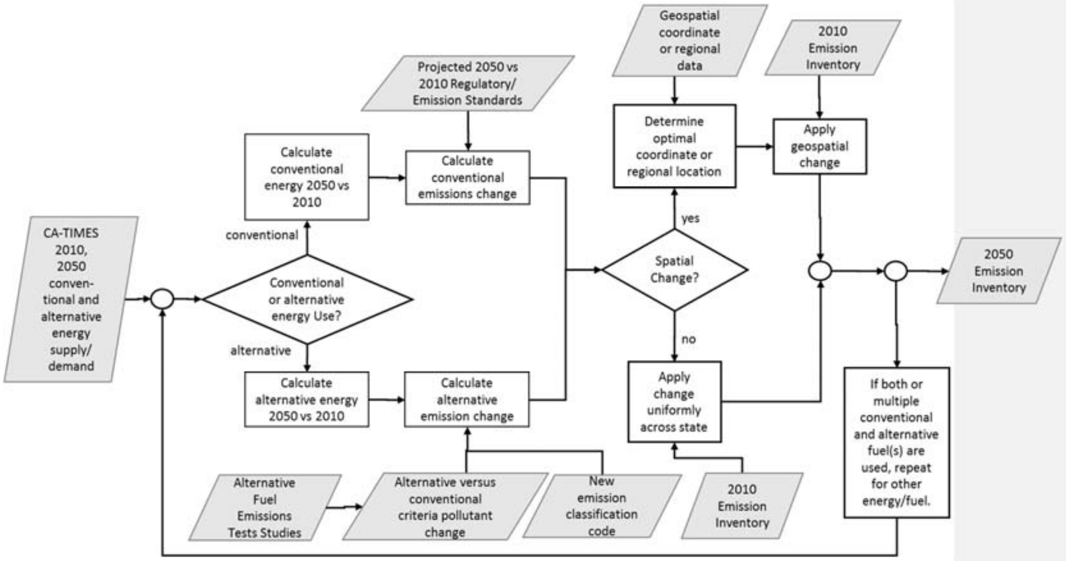

Figure 1: Process diagram of emission inventory generation for each sector or mode.

2.2 CA-REMARQUE On-road Mobile Algorithms

On-road mobile sources include passenger cars, light duty trucks (LDT), medium duty trucks (MDT), heavy duty trucks (HDT), buses, motorcycles, and motor homes. On-road emissions were generated in a multi-step process summarized in Fig. 2. In the first step, ~~vehicular emissions for the year 2050 were extrapolated using~~2010-2035 emission projection trends from the EMission FACtor (EMFAC) 2011 model (California Air Resources Board 2011) were used to extrapolate further to 2050. ~~EMFAC 2011.~~ In the second step, an intermediate 4km vehicular emissions inventory was generated by combining EMFAC 2050 projections with 2010 4km emission inventory as a spatial surrogate. In the third step, the 2050 fossil fuel vehicular emission rates that were projected from EMFAC as well as new emission rates gathered from alternative fuel emission literature were used to scale the 4km intermediate mobile emission inventory based on the vehicle miles travelled (VMT), trips, and vehicle class and (conventional and alternative) fuel consumption output produced for each CA-TIMES scenario~~vehicular activity and fuel consumption splits were applied to the 2050 inventory using current fossil fuel emission rates and alternative fuel emissions literature~~.

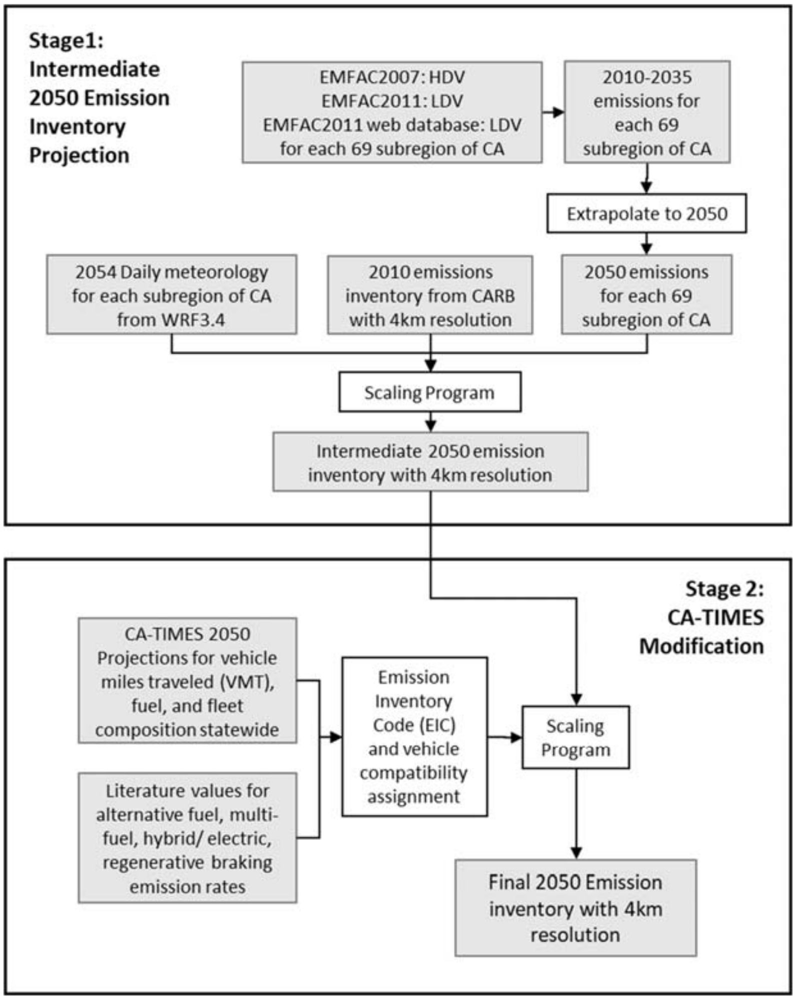

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Figure 2: Simplified sequence of algorithms, calculations, and inputs used in developing the CA-TIMES alternative fuel on-road mobile emissions inventory per scenario. EIC is emission inventory code.

2.2.1 EMFAC Emissions and Activity Projections

Criteria pollutant emissions for on-road mobile sources in future years were forecast using the ~~EMission FACtor~~ ~~(~~EMFAC~~)~~ 2011 model developed by the California Air Resources Board (CARB) (California Air Resources Board 2011). EMFAC 2011 accounts for annual ~~vehicle miles travelled (~~VMT~~)~~ trends and vehicle fleet composition turnover using Department of Motor Vehicle (DMV) data. EMFAC incorporates the latest on-road mobile policies including the Low Emission Vehicle emission standards, Low Carbon Fuel Standard (LCFS), Pavley Clean Car Standard, and the Truck and Bus ruling (California Air Resources Board, 2011). EMFAC 2011 predicts past, present, and future year (up to 2035 or 2040) emissions including anticipated future emissions standards and regulations specific to California. EMFAC predicts emissions and energy activity (VMT, trips, vehicles, gallons fuels) for 69 Geographical Area Indexes (GAIs) which represent the intersection of air basins and counties (listed in Table S1).

In the current study, EMFAC was run for each calendar year from 2020–2035 to infer the emissions trends that could then be extrapolated to 2050. A simple linear regression model was used to represent VMT over the period 2020-2035, while a logarithmic regression model was fit to pollutant emissions for each vehicle type over the same time period. Future studies will use EMFAC 2014 which directly predicts emissions in 2050 making this step unnecessary.

2.2.2 Spatial Allocation of Mobile Source Emissions in an Intermediate 2050 Inventory

An existing on-road mobile emissions inventory for the year 2010 with 4 km spatial resolution served as the starting point for the projection of an intermediate emissions inventory in 2050. Scaling factors to account for VMT growth and adoption of existing policies were first calculated as the ratios between EMFAC emissions from 2010 and (extrapolated) 2050 within each of the 69 GAI regions. Separate scaling factors were developed for each pollutant emitted from different vehicle classes and control technologies as represented by unique emission inventory codes (EICs). The combined intermediate emissions (em) scaling factor $SF_{act + met}$ defined in equation~~s (1) and~~ (~~2~~3) reflects independent changes in activity (act) (Eq. 1) and meteorology (met) (Eq. 2). ~~Daily f~~Future 2054 ~~meteorological~~ temperature and relative humidity generated at 4km resolution with ~~from previous~~ WRF3.2 ~~projections~~ (Zhang, Chen et al. 2014) were averaged to GAI regions used ~~read~~ by EMFAC to produce hour-specific ~~diurnal and season dependent~~ reactive organic gas (ROG) emission rates that vary from the annual average emission rates. Activity is either defined as vehicle miles travelled (VMT) or vehicle trips, depending on the emission process. For example, ~~Activity~~ activity equals ~~vehicle miles travelled (VMT)~~VMT for tailpipe emission rates (e.g. grams NO~~/~~ mile^{-1}) or tire and brake wear emissions (grams PM ~~/~~mile^{-1}). Otherwise, ~~Activity~~ activity equals the number of vehicles within each type/fuel/aftertreatment category ~~for~~ such as for evaporative emissions of non-methane hydrocarbons (grams NMHC~~/~~ vehicle^{-1}) from the fuel system (non-tailpipe emissions). ~~Meteorology that affects emissions includes temperature and relative humidity.~~ Emission rates are highly dependent on the emission process (evaporative, exhaust, tire or brake wear), fuel (gasoline or~~/~~ diesel) and the aftertreatment device (catalytic or ~~/~~non-catalytic).

Emissions within each 4km grid cell of the 2010 inventory are multiplied by the 2050 to 2010 scaling factor $SF_{act+met}$ to estimate the “intermediate” 2050 emissions that will be further modified according to various additional policy choices represented in CA-TIMES.

$$SF_{act} = \frac{em(act_{2050}, met_{2010})}{em(act_{2010}, met_{2010})} \qquad (1)$$

$$SF_{met} = \frac{em(act_{2010}, met_{2050})}{em(act_{2010}, met_{2010})} \qquad (2)$$

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$$\mathrm{SF}_{\mathrm{act+met}} = \mathrm{SF}_{\mathrm{act}} \cdot \mathrm{SF}_{\mathrm{met}} \qquad (~~2~~3)$$

~~(Hixson, Mahmud et al. 2010)~~

2.2.3 CA-TIMES Modification of Intermediate 2050 On-Road Mobile Emissions

State-wide CA-TIMES scaling factors were applied uniformly at all locations to the 2050 intermediate emissions inventory described in the previous section to produce the final 2050 emissions inventory. EMFAC accounts for population growth and emissions changes that are required by existing air quality rules and regulations through 2050. CA-TIMES accounts for additional changes that will be required to comply with state GHG targets but which have not yet been placed into emissions rules and regulations. The final inventory retains the spatial and temporal features inherent in the intermediate emissions inventory but incorporates updated information about new fuels, technologies, and emissions rates based on state-wide predictions from CA-TIMES (Fig. 3).

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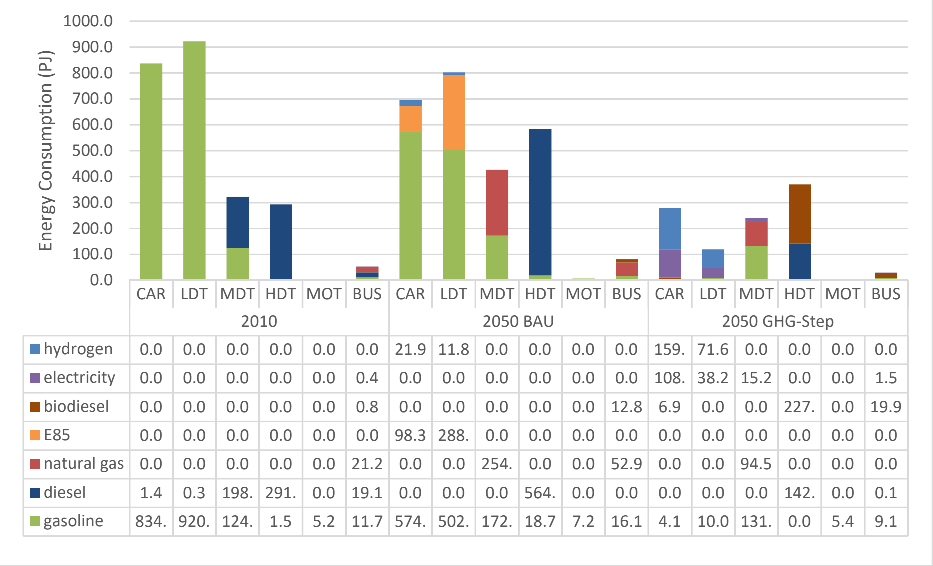
EMFAC vehicles classes expressed as EIC codes were mapped to compatible vehicle classes used by CA-TIMES as described in Table S2. Spark ignition (gasoline) vehicles in CA-TIMES were further classified as catalyst-equipped or non-catalyst-equipped to match EMFAC categories. EMFAC resolves non-catalyst-equipped and catalyst-equipped gasoline vehicles into several sub-categories (light-heavy duty truck (LHDT) and heavy-heavy duty truck (HHDT) (see Table S2 for complete description of vehicle classes~~)~~) while CA-TIMES does not include this level of resolution.



	CAR	LDT	MDT	HDT	MOT	BUS	CAR	LDT	MDT	HDT	MOT	BUS	CAR	LDT	MDT	HDT	MOT	BUS
	2010						2050 BAU						2050 GHG-Step					
hydrogen	0.0	0.0	0.0	0.0	0.0	0.0	21.9	11.8	0.0	0.0	0.0	0.0	159.	71.6	0.0	0.0	0.0	0.0
electricity	0.0	0.0	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	0.0	108.	38.2	15.2	0.0	0.0	1.5
biodiesel	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.0	0.0	12.8	6.9	0.0	0.0	227.	0.0	19.9
E85	0.0	0.0	0.0	0.0	0.0	0.0	98.3	288.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
natural gas	0.0	0.0	0.0	0.0	0.0	21.2	0.0	0.0	254.	0.0	0.0	52.9	0.0	0.0	94.5	0.0	0.0	0.0
diesel	1.4	0.3	198.	291.	0.0	19.1	0.0	0.0	0.0	564.	0.0	0.0	0.0	0.0	0.0	142.	0.0	0.1
gasoline	834.	920.	124.	1.5	5.2	11.7	574.	502.	172.	18.7	7.2	16.1	4.1	10.0	131.	0.0	5.4	9.1

Figure 3: CA-TIMES' energy consumption by vehicle weight class, fuel, and scenario for on-road sources. Vehicle categories include car, light duty truck (LDT), medium duty truck (MDT), heavy duty truck (HDT), motocycles (MOT), and bus.

The use of new fuels in the on-road fleet required special consideration during preparation of the 2050 emissions inventory. As a starting point, emission rates from EICs representing conventionally-fuelled vehicles were calculated from 2050 EMFAC output by dividing each pollutant emission by the respective vehicle activity indicator (either VMT, vehicle number, or fuel consumption) to serve as a baseline for CA-TIMES scenario adjustments. Next, the 181 combinations of alternative fuels and electric hybrid, dedicated or single/multi-fuelled applications and vehicles weight classes were mapped to EMFAC by vehicle class and reference fuel (see Table S2 and S3). CA-TIMES predicts the amount of alternative fuel consumed, not the VMT associated with that alternative fuel. The VMT associated with each alternative fuel was therefore estimated as the VMT associated with the conventional fuel divided by the energy content of the consumed conventional fuel (E_v) multiplied by the energy content of the alternative fuel ($E_{v,f}$) output by CA-TIMES. This calculation assumes that vehicle weight and aerodynamics do not change significantly as alternative fuels are adopted. Finally, the emissions rate for each alternative fuel was estimated based on a literature review of emissions factors for conventional vs. alternative fuelled vehicles. Reference emission rates ($er_{v,ref}$) and "alternative to conventional" scaling factors ($er_{v,f}$ / $er_{v,ref}$) for the vehicle fuels of interest are listed in Table 1.

Table 1: Emission rate changes for alternative fuels in on-road vehicles. Alternative fuels include 85% ethanol 15% gasoline mixture (E85), biodiesel (B100), and compressed natural gas. Conventional fuels include gasoline, diesel, or ultra low sulfur diesel (USLD). After treatment devices include three way catalyst (TWC), diesel oxidation catalyst (DOC), diesel particle filter (DPF), exhaust gas recirculation (EGR), and selective catalytic reduction (SCR).

Alternative Fuel	Reference Conventional Fuel	After-treatment	Pollutant	Alt/ Conv Ratio	Conv % Change	Data Source
E85	Gasoline	same (TWC)	CO	1.00	0.0%	Graham, Belisle et al. (2008)
			NOx	0.55	-45%	Graham, Belisle et al. (2008)
			SOx	1.00	0.0%	Assumed
			ROG	1.00	0.0%	Graham, Belisle et al. (2008)
			PM	0.25	-75%	Hays, Preston et al. (2013)
B100	Diesel or ULSD	DOC+ DPF+ EGR+ SCR	CO	0.03	-97%	Alleman, Eudy et al. (2004), Alleman, Barnitt et al. (2005), Hasegawa, Sakurai et al. (2007)
			NOx	0.85	-15%	Alleman, Eudy et al. (2004), Alleman, Barnitt et al. (2005), Tsujimura, Goto et al. (2007)
			SOx	1.00	0.0%	Assumed
			ROG	0.03	-97%	Alleman, Eudy et al. (2004), Alleman, Barnitt et al. (2005), Hasegawa, Sakurai et al. (2007)
			PM	0.03	-97%	Alleman, Eudy et al. (2004), Alleman, Barnitt et al. (2005), Hasegawa, Sakurai et al. (2007), Rounce, Tsolakis et al. (2012)
CNG	Diesel or ULSD	TWC	CO	0.67	-33%	Cooper, Arioli et al. (2012)
			NOx	0.19	-81%	Cooper, Arioli et al. (2012)
			SOx	1.00	0.0%	Assumed
			ROG	0.34	-66%	Cooper, Arioli et al. (2012)
			PM	0.08	-92%	Cooper, Arioli et al. (2012)

Equation (~~3~~4) illustrates how the total emissions (em_v) were calculated for a given vehicle class (subscript v) by summing the product of the emission rate and VMT for each fuel (subscript f) for the number of different fuels (n) consumed by that vehicle as defined by each CA-TIMES scenario.

$$em_v = \sum_f^n \underbrace{er_{v,ref} \cdot \frac{er_{v,f}}{er_{v,ref}}}_{\text{Alternative fuel/energy emission rate}} \cdot \underbrace{act_v \cdot \frac{E_{v,f}}{E_v}}_{\text{Proportion of activity by fuel/ energy for vehicle}} \qquad (\cancel{3}4)$$

where

v = vehicle type by weight
f = unconventional or alternative fuel type from f1, f2, f3…n
ref = reference (conventional) fuel, typically gasoline or diesel.
em_v = emissions for a give vehicle type per pollutant. Where pollutant is ROGs, CO, NOx, PM10, SOx [tons pollutant].
$er_{v,ref}$ = pollutant emission rate for a vehicle using the reference (conventional) fuel based from EMFAC [tons pollutant ~~/~~VMT^{-1} or tons pollutant~~/~~ vehicle^{-1}]
$er_{v,f}$ = pollutant emission rate for a vehicle using an alternative fuel based from EMFAC [tons pollutant~~/~~ VMT^{-1} or tons pollutant ~~/~~vehicle^{-1}]
act_v = total vehicular activity (not divided by fuel) [VMT or vehicles]
$e_{v,f}$ = energy consumption for a given fuel by vehicle given by CA-TIMES scenario [PJ]
e_v = total energy consumed for vehicle for all fuels by CA-TIMES scenario [PJ]

Alternative fuels considered by CA-TIMES include 95% volume blend methanol (M95), 85% volume blend ethanol (E85), compressed natural gas (CNG), liquid petroleum gas (LPG), biodiesel, compressed or liquid hydrogen, and electric drivetrains. Electric vehicles (EVs) include hybrid, (HEV), plug-in hybrid (PHEV), and plug-in or battery (PEV or BEV). CA-TIMES often predicted the use of multiple technologies and fuels within the same vehicle weight class (see Table S4 through Table S12 for complete lists). For example, in the case of a hybrid diesel electric vehicle which runs on 3 energy sources, diesel, biodiesel, and electricity, (e.g. a biodiesel PHEV MDT), 3 sets of emission rates (1 for each fuel) were estimated to replace the single emissions rate for the traditional CI engine for this vehicle class (diesel MDT).

Only approximately ~~~~~10% of the possible vehicle type/fuel/engine combinations considered by CA-TIMES (see Table S4 to Table S12) were actually used in the 2050 BAU and GHG-Step scenarios as the model optimized for low cost and low-carbon solutions. The main alternative liquid~~/~~ or gaseous fuels projected by CA-TIMES were E85, biodiesel, and CNG. CA-TIMES predicted that E85 would displace gasoline while biodiesel and CNG would displace diesel based on the dominant fuel consumed for the same vehicle weight class counterpart. This fuel substitution alters emissions rates for criteria pollutants as shown in Table 1. For battery electric or fuel cell vehicles, the conventional fuel displaced was based on the dominant fuel for that vehicle class, e.g. gasoline for LDVs.

2.2.4 On-Road Mobile PM and Gas Speciation and Size Profile Changes

Tailpipe exhaust, fuel tank evaporative, and brake wear emissions were adjusted when the vehicle fuel~~/~~ or technology was changed. This requires new source profiles to be defined for E85, biodiesel, and CNG fuel~~l~~ed vehicles to describe their emissions of speciated volatile organic compounds (VOCs) and size ~~/~~& composition-resolved particulate matter. New emissions inventory codes (EICs) were created (summarized in Table S13) and associated with new VOC and PM emissions profiles (summarized in Tables S14 – S16) for this purpose.

Multiple measurements are available in the literature for the composition of exhaust from ethanol-fuel~~l~~led vehicles. In the present study, the average VOC profiles measured using the Federal Test Procedure (FTP), Unified Cycle (UC), and US06 high speed drive cycles were used for the hot running E85 VOC exhaust (Haskew and Liberty 2011). The FTP phase 1 profile was applied for the cold-start E85 VOC emissions (Haskew and Liberty 2011). E85 PM size distributions are summarized in Table S15 (Szybist, Youngquist et al. 2011), while PM composition information is summarized in Table S16 (Ferreira da Silva, Vicente de Assuncao et al. 2010, Hays, Preston et al. 2013). Figure 4 illustrates the size and composition distribution of particulate matter emitted from catalyst-equipped gasoline vehicles and catalyst-equipped vehicles fuel~~l~~ed by 85% ethanol and 15% gasoline (E85) as an example.

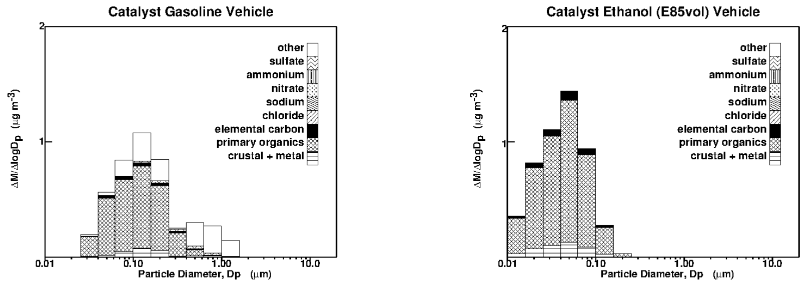


Figure 4: Particle emissions size and composition distribution for catalyst equipped gasoline vehicles (left panel) and catalyst equipped ethanol (E85) vehicles (right panel).

Aftertreatment devices were found to be more influential on biofuel exhaust rates (Alleman, Eudy et al. 2004, Alleman, Barnitt et al. 2005, Frank, Tang et al. 2007, Hasegawa, Sakurai et al. 2007, Tsujimura, Goto et al. 2007, Rounce, Tsolakis et al. 2012) than changes to fuel properties and feedstock origin (Graboski, McCormick et al. 2003, Durbin, Cocker et al. 2007). Diesel particulate filters (DPF), exhaust gas recirculation (EGR), selective catalytic reduction (SCR), and oxidation catalyst (OC) were assumed to be deployed on diesel and biodiesel powered vehicles by 2050. PM size distributions for DPF-equipped vehicles were obtained from (Rounce, Tsolakis et al. 2012) (Table S15), and trace element, carbonaceous and inorganic ion fractions of PM distributions were obtained from (Cheung, Polidori et al. 2009, Cheung, Ntziachristos et al. 2010) (see Table S16). Gas-phase VOC emissions profiles for biodiesel were not updated from fossil diesel profiles in the current study, but this change will be considered in future work.

The CNG VOC profile and PM size distribution was constructed based on (Gautam 2011) (Tables S14 and S15). PM emissions of carbonaceous compounds, metals, and ions were measured from CNG vehicles running on the UDDS driving cycle (Yoon, Hu et al. 2014) (see Table S16). Figure 5 illustrates the size and composition distribution of particulate matter emitted from diesel vehicles, bio-diesel vehicles equipped with a diesel particle filter and exhaust gas recirculation, and catalyst-equipped CNG vehicles.

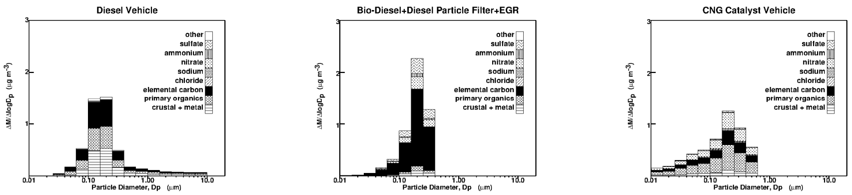


Figure 5: Particle emissions size and composition distribution for diesel vehicles (left panel), bio-diesel vehicles (center panel), and CNG catalyst equipped vehicles (right panel).

All fully electric vehicles, such as battery electric vehicles (BEVs) and H2 fuel cell vehicles, were assumed to have zero tailpipe exhaust and evaporative emission rates. Brake wear emission rates were reduced by 59% (Antanaitis 2010) for all partial or fully electric vehicles equipped with regenerative breaking, such as hybrid, electric battery or fuel cell vehicles. Tire wear emissions were assumed to be independent of fuel~~/~~ or technology type.

2.3 CA-REMARQUE Aviation, Rail, and Off-Road Algorithms

Aviation sources include commercial, civil, agricultural, or military use and primarily run on jet fuel or aviation gasoline. The rail emission sources include passenger, commuter, switching and hauling trains which currently run primarily on diesel fue~~l~~led generators powering an electric drivetrain. Off-road equipment includes industrial, agricultural, and construction equipment, port and rail operations, as well as lawn and garden equipment. The list of aviation, rail, and off-road emission source categorizations are based on the EICs listed in Table S17 (including new EICs created to represent sources operating on alternative fuels previously not in the CARB inventory).

2.3.1 VISION Model

Future 2050 emissions for aviation, rail, and off-road equipment were assumed to follow the 2010 versus 2050 growth projected by the CARB VISION model (California Air Resources Board 2012), an off-road expansion of Argonne's on-road VISION model (Argonne National Laboratory Transportation Technology R&D Center 2012). CARB's off-road VISION model uses historical trends to project to the year 2050 while incorporating some future standards for criteria pollutant emission rates. These include the implementation of Tier 4 130-560 kW compression-ignition diesel engine emission standards for PM, CO, and NMHC+NOx (California Air Resources Board 2010) leading to 90% reduction in PM emissions rates and an 85% reduction in NMHC and NOx emissions rates.

Aviation, rail, and off-road 2010 emissions at 4 km resolution ($em^{2010}_{cell,I}$) were scaled to produce an “intermediate” estimate prior to CA-TIMES adjustments using Eq. (~~4~~5).

$$em^{2050}_{cell,i,intermediate} = \underbrace{\left(\frac{em_i^{2050}}{em_i^{2010}}\right)}_{\text{State-wide emission growth scaling from 2010 to 2050}} \cdot em^{2010}_{cell,i}$$

(~~4~~5)

where

$em^{2050}_{cell,i,intermediate}$ = intermediate grid cell 2050 emissions for a transport source (aviation, rail, off-road) consuming a reference or conventional fuel~~/~~ or energy [kg~~/~~ hr^{-1}]

em_i^{2050} = state-wide 2050 emissions of a transport source [kg ~~/~~hr^{-1} or tons ~~/~~day^{-1}]

em_i^{2010} = state-wide ~~2050~~ 2010 emissions of a transport source [kg ~~/~~hr^{-1} or tons~~/~~ day^{-1}]

$em^{2010}_{cell,i}$ = grid cell 2010 emissions of a transport source [kg~~/~~ hr^{-1}]

2.3.2 CA-TIMES Modification of Intermediate 2050 Off-Road Mobile Emissions

The portion of energy consumed for each fuel (Ei,f/Σf Ei,f) as projected by CA−TIMES was applied to the intermediate 2050 emissions inventory for each transport mode (f) and source type (i) using Eq. (~~5~~6). The consumption of different fuels relative to total fuel consumption for a given mode is shown in Fig. S1-S3 for rail, off−road, and aviation modes respectively. Alternative to conventional scaling factors were applied to account for adoption of alternative fuels as summarized in Table 2. Eq. (~~5~~6) also includes an after treatment ~~and/~~or control device factor (1−η) where appropriate.

$$SFi,f = \underbrace{\left(\frac{E_{i,f}}{\Sigma_f E_{i,f}}\right)}_{\text{Portion of alternative fuel energy consumption}} \cdot \underbrace{\left(\frac{em_{i,f}{}^{2050}}{em_{i,intermediate}{}^{2050}}\right)}_{\text{Alternative fuel emission scaling relative to conventional}} \cdot \underbrace{(1-\eta_i)}_{\text{Fraction of pollutant not removed by aftertreatment device}}$$

(~~5~~6)

where

$SF_{i,f}$ = emission scaling factor for a given new/alternative or non-conventional/non-reference fuel for a transport source [dimensonless]

$E_{i,f}$= new/alternative fuel/energy consumed by a transport source (e.g. biodiesel for commuter rail) [PJ]

$\sum_f E_{i,f}$= total fuel/energy consumed by a transport source (e.g. biodiesel + diesel for commuter rail) [PJ]

$em_{i,f}^{2050}$ = state-wide 2050 emissions of a transport source consuming a new/alternative fuel [kg~~/~~ hr^{-1} or tons~~/~~ day^{-1}]

$em_{i,intermediate}^{2050}$= state-wide 2050 intermediate emissions of a transport source consuming a new/alternative fuel. [kg~~/~~ hr^{-1} or tons~~/~~ day^{-1}]

η_i = efficiency of removal from a control or aftertreatment device [fraction from 0.00-1.00]

Table 2: Emission rate changes for alternative fuels in off-road vehicles.

Transport Mode	Alternative Fuel	Reference Conven-tional Fuel	Pollutant	Alt/ Conv Ratio	Conv % Change	Citations
Rail	Biodiesel	Diesel	CO	0.655	-34.5%	Osborne, Fritz et al. (2010)
			NOx	1.13	13%	Osborne, Fritz et al. (2010)
			SOx	0.0005	-99.95%	Assumed (see text)
			ROG	0.775	-22.5%	Osborne, Fritz et al. (2010)
			PM	0.805	-19.5%	Osborne, Fritz et al. (2010)
Off-road/ Agricultural	Biodiesel	Diesel	CO	1	0%	Durbin, Cocker et al. (2007)
			NOx	1.08	8%	Durbin, Cocker et al. (2007)
			SOx	1	0%	Durbin, Cocker et al. (2007)
			ROG	0.39	-61%	Assumed (see text)
			PM	1.13	13%	Durbin, Cocker et al. (2007)
	Compressed natural gas	Diesel	CO	0.668	-33.2%	Cooper, Arioli et al. (2012)
			NOx	0.189	-81.1%	Cooper, Arioli et al. (2012)
			SOx	1	0%	Assumed (see text)
			ROG	2.349	134.9%	Cooper, Arioli et al. (2012)
			PM	0.0782	-92.18%	Cooper, Arioli et al. (2012)
Aviation	Biomass-based kerosene jet fuel	Kerosene jet fuel	CO	1	0%	Lobo, Rye et al. (2012)
			NOx	1	0%	Lobo, Rye et al. (2012)
			SOx	0.007	-99.3%	Assumed (see text)
			ROG	0.605	-39.5%	Lobo, Rye et al. (2012)
			PM	0.38	-62%	Lobo, Hagen et al. (2011)

The final emissions for each specific offroad source consuming each specific fuel in 2050 ($em^{2050}_{cell,i,f}$) are then ~~predicted~~ calculated by combining the effects of the VISION and CA-TIMES updates as shown in Eq. (~~6~~7).

$$em^{2050}_{cell,i,f} = SF_{i,f} \cdot em^{2050}_{cell,i,intermediate}$$ (~~6~~7)

Aviation biomass-based kerosene jet fuel (KJF) emissions changes are based on Fischer-Tropsh gas-to-liquid (FT GTL) biofuel aviation emissions tests (Lobo, Hagen et al. 2011, Lobo, Rye et al. 2012). These studies found minor changes to CO and NO_x emissions due to the adoption of biofuels. SO_x reduction was assumed proportional to the fuel sulfur content (Lobo, Rye et al. 2012) leading to reductions of 99% as shown in Table 2.

Off-road equipment (other than trains) operating on biodiesel instead of Ultra low-sulfur diesel (ULSD) was assumed to emit HC and NO_x with scaling factors (relative to conventional diesel emissions) of 0.39 and 1.08, respectively (Durbin, Cocker et al. 2007). No significant changes in CO, SO_x and PM due to the adoption of biodiesel vs. ULSD were identified in the literature and so these emissions were assumed to remain at levels estimated for conventional diesel engines. This approach inherently assumes that the sulfur content of biodiesel will not exceed the current limit of 15 ppm for ULSD. Off-road or agricultural emission changes from switching from diesel to CNG are also found to have large reductions in most pollutants except reactive organic gases (ROGs) (Cooper, Arioli et al. 2012). Military aviation emissions were held constant at 2010 levels in the current study due to an assumption of continued exemptions for military activity.

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2.3.3 Off-Road Mobile PM and Gas Speciation and Size Profile Changes

PM mass size distributions for E85, biodiesel, and CNG are assumed to be similar for off-road and on-road vehicles (Table S15**).** The new PM mass size distribution for biomass-based KJF is shown in Table S18 (Lobo, Hagen et al. 2011). Figure 6 illustrates the size and composition distribution of particulate matter emitted from conventional jet-fuel aircraft and biomass-based kerosene jet fuel aircraft. The conventional profile is based on old source profile measurements that assumed uniform distribution of particles between diameters 0.1-1.0 µm. This conventional profile will be updated with more recent literature values in future work.

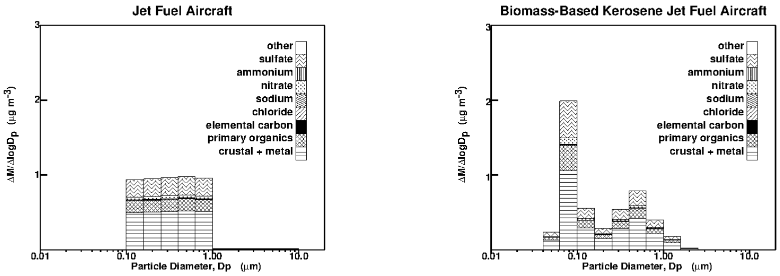


Figure 6: Particle emissions size and composition distribution for jet-fueled aircraft (left panel) and biomass-based kerosene jet-fueled aircraft (right panel).

2.4 CA-REMARQUE Marine Algorithms

The marine emission source category includes all ocean going vessels (OGV), commercial harbor craft (CHC), and recreational boats (see Table S19). An intermediate OGV emissions inventory was predicted for the year 2050 based on the extrapolation of Port of Los Angeles and Port of Long Beach 2020 trends (Starcrest Consulting Group 2009, The Port of Los Angeles and The Port of Long Beach 2010) (see Table S20). All other OGV emissions (not listed in Table S20) in California were held constant at 2010 levels in the intermediate 2050 inventory prior to modifications from CA-TIMES.

2.4.1 CA-TIMES Modification of Intermediate 2050 Marine Emissions

The fuels used to power OGVs were modified based on predictions from the CA-TIMES' scenarios. It should be noted that the CA-TIMES model reports worldwide marine energy consumption. In the current study, it was assumed that marine vessels operating near the California coast would consume the global average mix of biofuels produced by CA-TIMES. For example, if CA-TIMES indicates that a third of the residual fuel oil (RFO) (also call heavy fuel oil) consumed globally by marine vessels would be converted to biomass-based residual fuel oil (BRFO), then a third of the RFO marine vessel emissions near California boundaries were also converted to BRFO. As indicated by Fig. S4, CA-TIMES finds~~ that it is too expensive to~~ other approaches besides biofuel adoption for ships are more cost-effective for meeting the GHG target in 2050~~ adopt biomass-based fuels for ships in the GHG-Step scenario in 2050~~. CA-TIMES ~~predicts~~ determined that it will be more economical to substitute some RFO with a lighter petroleum (diesel) to decrease carbon intensity rather than using biomass-based RFO.

Alternative fuels used in marine sources will modify criteria pollutant emissions. Biomass-based alternatives for marine residual fuel oil (RFO) were estimated to be similar to the average of B100 from palm oil, animal fat, soybean oil, and sunflower oil operating at 75% load (Petzold, Lauer et al. 2011). NO_x was the only regulated pollutant observed to remain constant during emissions testing. Emissions of all other pollutants decreased as summarized in Table 3.

Table 3: Emission rate changes from ships changing from conventional fuels to biofuels.

Alternative Fuel	Reference Conventional Fuel	Pollutant	Alt/ Conv Ratio	Conv % Change	Citations
biomass-based residual fuel oil (RFO)	residual fuel oil (RFO)	CO	0.697	-30.3%	(Petzold, Lauer et al. 2011)
		NOx	1	0%	(Petzold, Lauer et al. 2011)
		SOx	0.012	-98.8%	(Petzold, Lauer et al. 2011)
		ROG	0.413	-58.7%	(Petzold, Lauer et al. 2011)
		PM	0.223	-77.7%	(Petzold, Lauer et al. 2011)
Biodiesel (BDL)	Diesel (DSL)	CO	0.921	-7.9%	(Jayaram, Agrawal et al. 2011)
		NOx	1	0%	(Jayaram, Agrawal et al. 2011)
		SOx	0.0003	-99.97%	Assumed (see text).
		ROG	1	0%	(Jayaram, Agrawal et al. 2011)
		PM	0.684	-31.6%	(Jayaram, Agrawal et al. 2011)

Assuming biodiesel (BDL) and biomass based residual fuel oil (BRFO) has about 1 ppm sulfur content, and that by 2010 the sulfur content regulations ensured that marine diesel oil (MDO) and RFO had 1.5 ppm and 2.5 ppm S, respectively, then the switch to biofuels would reduce SO_x emissions by 33.3% (relative to conventional MDO) and 60% (relative to conventional RFO). Additional reductions in CO, TOG, and PM were also projected based on (Jayaram, Agrawal et al. 2011, Petzold, Lauer et al. 2011) as summarized in Table 3.

Several international and California shoreline regulations were applied to marine emissions in the year 2050 as summarized in Table S21 and Table S22. At-berth or hotelling container, passenger (cruise), and refrigeration OGVs will use shoreline power instead of auxiliary engines for 80% of their berthing hours by 2020, (California Air Resources Board 2007). It was also assumed that MDO or marine gasoline oil (MGO) used within 24 nautical miles of the California shore will have sulfur content of <0.1% by 2050 (California Air Resources Board 2011). Further offshore, all marine fuels used within 100 nautical miles of North America were assumed to have sulfur content < 1% after the year 2012 (leading to reductions shown in Table 3).

2.4.2 Marine PM and Gas Speciation and Size Profile Changes

PM size distribution changes caused by the switch to alternative marine fuels were based on (Jayaram, Agrawal et al. 2011) (see Table S23). The size and composition distribution profiles used to represent marine emission associated with different fuels are displayed in Fig. 7.

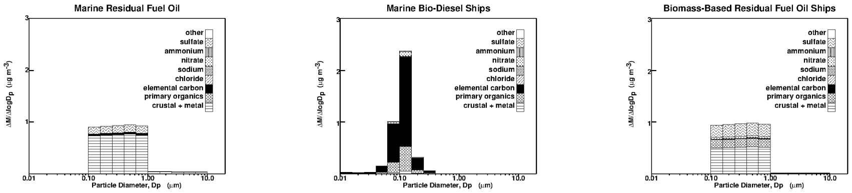
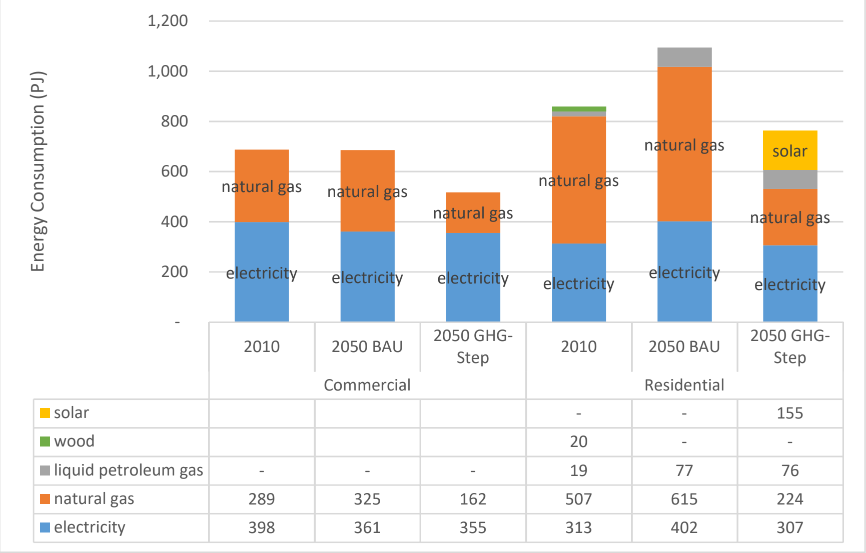


Figure 7: Particle emissions size and composition distribution for ships powered by marine residual oil (left panel), marine bio-diesel (center panel), and biomass-based residual fuel oil (right panel).

2.5 CA-REMARQUE Residential and Commercial Algorithms

Major emissions sources within the residential and commercial sectors include natural gas combustion (space heating and water heating)~~appliancesappliances used for space and water heating~~, biomass combustion (~~wood burning~~ fireplaces and stoves), and ~~as well as~~ food cooking (especially charbroiling and frying). The residential and commercial emissions associated with natural gas and food cooking were assumed to scale according to population growth projected for each county (Table S24) (State of California 2013) to produce an intermediate emissions inventory. These intermediate residential and commercial gridded emissions were then scaled to reflect 2010 versus 2050 results from CA-TIMES (Fig. 8).

Natural gas consumption in the commercial sector reduced by half (325 PJ to 162 PJ) in the GHG-Step scenario relative to the BAU scenario in 2050. Most of commercial energy reduction is due to efficiency gains and switch from natural gas to electrification of end uses. Natural gas consumption in the residential sector also decreases (615 PJ to 507 PJ) under the GHG-Step scenario relative to the BAU scenario. Much of the energy that would have been supplied by natural gas is replaced by renewable sources such as solar (155 PJ) which was assumed to have no criteria pollutant emissions in California. Improved energy efficiency and conservation also plays a role, with residential electricity consumption decreasing (402 PJ to 313 PJ) in the GHG-Step scenario. ~~It was assumed that o~~Other combustion sources, including wood burning and distillate oil fuel consumption, were allowed to compete in CA-TIMES subject to the constraint that they could not increase above the 2010 levels in order to maintain compliance with ~~but would not increase due to inconsistency with~~ current air quality regulations.



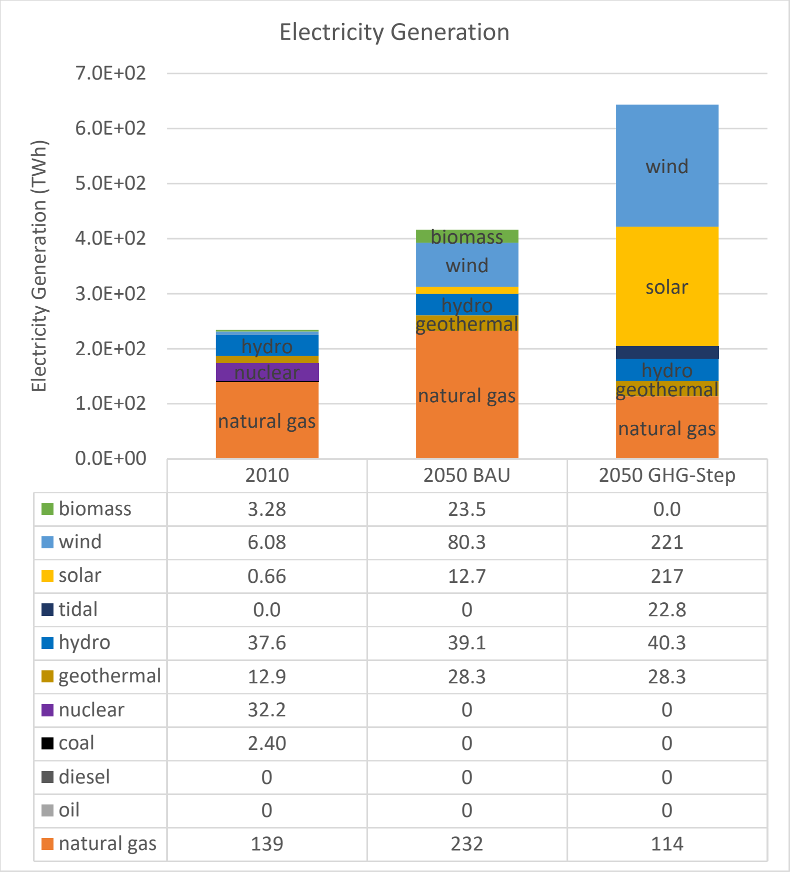
	Commercial 2010	Commercial 2050 BAU	Commercial 2050 GHG-Step	Residential 2010	Residential 2050 BAU	Residential 2050 GHG-Step
🟨 solar				-	-	155
🟩 wood				20	-	-
■ liquid petroleum gas	-	-	-	19	77	76
🟧 natural gas	289	325	162	507	615	224
🟦 electricity	398	361	355	313	402	307

Figure 8: CA-TIMES' energy consumption by energy resource and scenario for commercial and residential.

2.6 CA-REMARQUE Electricity Generation Algorithms

The electricity generation emissions category includes all fuel-burning and renewable power plants for industrial, residential, or commercial use. Annual generation totals for different types of California power plants were extracted from national power plant data (US Energy Information Administration Independent Statistics and Analysis 2012, US Environmental Protection Agency 2014). Emissions rates per unit of fuel burned were estimated for each power plant described in the basecase 2010 emissions inventory.

CA-TIMES finds that non-hydro renewable (geothermal, tidal, solar, wind, and biomass) increases from 10% (22,938 GWh) of the electricity generation mix in 2010 (144,825 GWh) to 35% and 76% (489,493GWh) in the 2050 BAU and 2050 GHG-Step scenario, respectively (see Fig. 9). However, total in-state and out-of-state electricity generation in the GHG-Step scenario is 1/3rd larger than the BAU scenario (416,219 GWh versus 643,373 GWh) to meet the increased demand from sectors such as the on-road vehicles with growing hybridization and electrification needed to meet the 2050 carbon constraint. Statewide scaling factors for electricity generation in the 2050 BAU scenario vs. 2010 and the 2050 GHG-Step scenario vs. 2010 are listed in Table S25.



	2010	2050 BAU	2050 GHG-Step
🟩 biomass	3.28	23.5	0.0
🟦 wind	6.08	80.3	221
🟨 solar	0.66	12.7	217
■ tidal	0.0	0	22.8
🟦 hydro	37.6	39.1	40.3
🟫 geothermal	12.9	28.3	28.3
🟪 nuclear	32.2	0	0
⬛ coal	2.40	0	0
■ diesel	0	0	0
■ oil	0	0	0
🟧 natural gas	139	232	114

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Figure 9: CA-TIMES' electricity generation resource mix by scenario.

CA-TIMES calculates aggregated state-wide energy totals but energy resources (especially for renewables) are not uniformly distributed across the state. In the current study, renewable electricity production in 2050 was spatially allocated in a manner that was consistent with the energy resource potential in 12 regions (Fig. S5) as projected in 15 scenarios by the grid load distribution model SWITCH (Fripp 2012, Johnston, Mileva et al. 2013, Nelson, Mileva et al. 2013). Table S26 lists the electrical generation by energy source for each SWITCH region averaged across these 15 scenarios. This profile of resource potential was then applied to the CA-TIMES predictions summarized in Table S25 yielding the 2050/2010 scaling factors for the BAU scenario (Table S27) and the GHG-Step scenario (Table S28).

The scaling factors summarized in Tables S27 and S28 assume that the out-of-state portion of electricity generation for a given fuel or energy resource in the year 2050 remained constant at 2010 levels. CA-TIMES does not provide additional information describing out-of-state generation except for a few renewables. This out-of-state portion of the electricity generation was subtracted from the CA-TIMES totals prior to scaling emissions from each power plant in California. Table S29 summarizes the out-of-state portion of electricity generation for each fuel in 2010 and assumed portions in each of the 2050 scenarios.

Additional emissions adjustments were made for new renewable fuels such as those produced by the Biomass Integrated Gasification Combined Cycle (IGCC), a process that gasifies biomass for electricity production. Much of the biomass electricity generation projected by CA-TIMES for 2050 in the BAU scenario uses biomass IGCC (see Tables S30 through S32). There are currently several coal IGCC plants in the US (U. S. Department of Energy National Energy Technology Laboratory 2010, U. S. Department of Energy National Energy Technology Laboratory 2015) but no biomass IGCC plants (Lundqvist 1993, Ståhl and Neergaard 1998, U. S. Department of Energy National Energy Technology Laboratory 2010). Future biomass IGCC emissions in California were estimated using several models that incorporate biomass IGCC, such as GREET, CA-GREET (California Air Resources Board 2009, Argonne National Laboratory Transportation Technology R&D Center 2014, California Air Resources Board 2015), and an NREL analysis (Mann and Spath 1997). Ultimately, biomass IGCC power plant emissions were estimated from conversion of conventional steam turbines in the 2010 ARB inventory based on emissions rates inferred from CA-GREET1.8 for 2050 (Table S33). An inter-comparison study between GREET1.8, GREET 2014, and CA-GREET2.0 showed that theCA-GREET1.8b model had the best agreement with emissions rates from approximately 30 biomass plants operating on wood residue in California.~~The CA-GREET1.8b model was used because it was found to had have the highest accuracy among all the tested models in emission rates relative to average emission rates from existing biomass plants in California based from eGRID 2010 data (US Environmental Protection Agency 2014) among all the tested models when projecting emissions from biomass power plants~~ (California Air Resources Board 2011, US Environmental Protection Agency 2014).

2.7 CA-REMARQUE Industrial and Agricultural Algorithms

The industrial and agricultural emissions category covers many manufacturing industries such as metal, wood, glass, textile, mining, and chemical. Food and agricultural sectors include farming livestock, crops, food production, bakeries, and breweries. Most of these industries were unchanged in the CA-TIMES energy scenarios, with the notable exception that biofuel and hydrogen fuel production replaced some traditional petroleum production, causing changes in refinery and storage emissions (shown in Figs. S6 to S8).

2.7.1 Fossil and Renewable Fuel Production

All fossil petroleum refining and storage emissions in the 2010 ARB emissions inventory were scaled according to the amount of oil production and refining that was required in California for each 2050 CA-TIMES scenario (see Fig. S6). Scaling factors were applied uniformly to all emission processes including seepage, evaporative~~ /~~ or fugitive, and other processes. Fossil petroleum consumption generally decreased in future scenarios, but was not eliminated. As discussed in previous sections, transportation modes (e.g. marine, heavy duty trucks) still consume fossil fuel such as diesel, and the stationary sources (electricity generation, residential, and commercial) still consume natural gas. CA-TIMES ~~predicted~~ determined that much of the extracted petroleum used by refineries would be imported to the state rather than extracted locally. This can be seen by the reduction of crude oil supply in California from 1510 PJ in 2010, to 426.5 PJ in the 2050 BAU scenario and 0.0PJ in the GHG-Step scenario (see Fig S6). Refining is also are projected to decline slightly between 2010 and the 2050 scenarios, with reductions of 25% in the BAU scenario and 44% in the GHG-Step scenario. This suggests that it is more cost effective ~~and/~~or less carbon intensive to import fuel than to extract oil and gas in~~/~~ or around California. The total (imported and in-state) oil supply also decreases in 2050, by -26% ~~from~~ in the BAU (3200PJ) and -44% in the GHG-Step (2400PJ) relative to 2010 (4300PJ). This reflects the adoption of ~~is indicative that~~ electrification and alternative fuels to ~~are~~ replacing petroleum consumption in the presence of ~~and thus supply despite~~ growing energy demand in 2050.

Hydrogen (H_2) production ~~was assumed to i~~increased in both 2050 CA-TIMES scenario results~~s~~, but the increases in the GHG-Step scenario are much larger (Fig. S7). It was assumed that new hydrogen production facilities would be located at current H_2 production facilities ~~and/~~or existing refineries. Overall 32 new natural gas steam methane reforming (SMR) H_2 facilities and 15 new biomass gasification facilities were projected to meet the demand summarized in Fig. S7. In the current study, criteria pollutant emission rates from SMR H_2 production (summarized in Table 4) were calculated from the top 3 SMR H_2 production facilities (California Air Resources Board 2010, California Air Resources Board 2014). Few studies have been published describing criteria pollutant emissions from biomass gasification H_2 production and so emissions rates for this production pathway were obtained from the CA-GREET model (California Air Resources Board 2015). Direct criteria pollutant emissions from hydrogen production using electrolysis were zero since this process uses electricity to split water molecules into H_2 and oxygen (emissions from these facilities appear under electricity generation).

Table 4: Pollutant emission rate associated with hydrogen production. Unis are grams of pollutant per mmBtu of hydrogen produced.

	SMR - average of top CA H2 SMR facilities	Gasification - CA-GREET2015 Gasification vs. SMR Scaling	Electrolysis
CO	4.303	0.997	0
NOx	1.701	0.34	0
SOx	0.092	0.406	0
VOC	2.33	1.118	0
PM10	0.433	0.048	0

The CA-TIMES model ~~predicts~~ determined that ~~high~~ biofuel consumption and~~/~~ production will be high in California in the year 2050 (Fig. S8). Biofuel refineries for different feedstock classes (wood, municipal solid waste (MSW), herbaceous, yellow grease~~/~~ or tallow, or corn ethanol) (see Tables S34 and S35) ~~and~~ were located using a spatial biomass optimization model which seeks to minimize cost within resource and regulatory constraints (Tittmann, Parker et al. 2010). Biofuel refineries were prohibited in NAAQS non-attainment areas, an added constraint based on the high feedstock case described by (Parker 2012). Production rates at in-state biorefineries were scaled to match the in-state volumes produced in CA-TIMES for each type of biofuel. Out-of-state imports and refining were assumed for crops that could not be grown at a large enough scale to meet the demand in California, such as herbaceous crops and the bulk of corn-ethanol (see Tables S34 and S35). Emissions for each biofuel refinery were estimated using CA-GREET1.8b emission rates per unit of fuel produced.

2.7.2 Biogas Capture and Use

CA-TIMES assumes that landfill gas reduces over time due to better management of organic matter in landfills, and the consumption of existing landfill stock material over many decades. All biogas in CA-TIMES is converted to biomethane through removal of CO_2 and impurities, and further blended with natural gas so that it is undistinguishable from extracted fossil natural gas.

Dairy biogas is a significant renewable energy source in CA-TIMES. California produced a fifth of the milk in the US in 2010 (California Department of Food and Agriculture 2011) and an exponential regression using 2001–2013 CFDA data estimates the number of dairy cows in California may increase by a factor of 1.5 by the year 2050. Methane emission rates were estimated from GHG inventory Documentation (California Air Resouces Board 2014) for each manure management practice: liquid/slurry, anaerobic lagoon, anaerobic digester, daily spread, deep pit, pasture, and solid storage. The increase in the cow population was assumed to occur uniformly across all management practices except for the systems used in biogas capture. These systems, including anaerobic digester, anaerobic lagoon, and liquid/slurry management practices, were adjusted to meet the quantities of biogas specified by each CA-TIMES scenario. The amount of waste produced by each dairy cow each year was used to estimate the annual biomethane production and energy potential of each animal. The electricity potential from biomethane is then calculated using AgSTAR conversion rates (Environmental Protection Agency 2010, U.S. Environmental Protection Agency AgSTAR Program 2011). The overall fugitive VOC emissions from animal waste declines in the biogas production scenarios since a large fraction of the waste is treated. Overall, fugitive dairy manure VOC emissions increased by 50% due to cow population growth in the BAU scenario, and decreased by a factor of a 33% for the GHG-Step scenario relative to 2010.

Future biomethane production sites were selected based on recommendations from the USDA's Cooperative Approaches for Implementation of Dairy Manure Digesters (U.S. Department of Agriculture Rural Development Agency 2009). Mainly, locations were selected with nearby pipeline networks (Gilbreath, Rose et al. 2014) to transport raw biogas to a centralized clean-up facility, where it can then be compressed and sold for use by electric generation power plants or transportation fuels. This was considered a more viable option as natural gas pipeline infrastructure is easy to access, demand from electric utilities for biomethane is high to meet the renewable portfolio standard (RPS), and a centralized clean-up facility is more economical than distributed facilities.

3 Results and Discussion

3.1 On-Road Mobile Emissions

Figure 10 illustrates particulate matter emissions of tire and brake wear from on-road vehicles under the BAU and GHG-Step scenarios. The fine spatial distribution of the emissions reflects the spatial distribution of tire and brake wear emissions in the base 2010 inventory that is updated using EMFAC predictions to produce the intermediate

2050 emissions inventory. The technology changes inherent in the CA-TIMES BAU and GHG-Step scenarios are then applied uniformly across the state yielding virtually identical spatial distributions for the final 2050 BAU and GHG-Step scenario emissions. Tire and brake wear emissions patterns illustrated in Figure 10 essentially follow predicted vehicle activity patterns in the state. Predicted emissions are highest in major urban centers and along major transportation corridors. Although increase in vehicular activity was part of this study, expansion of roadways between 2010 and 2050 were not considered in this study and may be updated in newer versions of the model.

California's environmental regulations apply uniformly across the state, which supports the assumption of uniform GHG emissions reductions for on-road vehicles. Despite the uniform regulatory landscape, some of the measures described in the CA-TIMES GHG-Step scenario rely on modified behavioral patterns and willingness ~~and/~~or ability to adopt new technologies, which may change by region. Education levels, personal wealth, and environmental attitudes vary sharply across California. Capturing these trends in sub-regions of the state will require surveys of consumer choice and predictions of future behavior that are beyond the scope of the current manuscript.

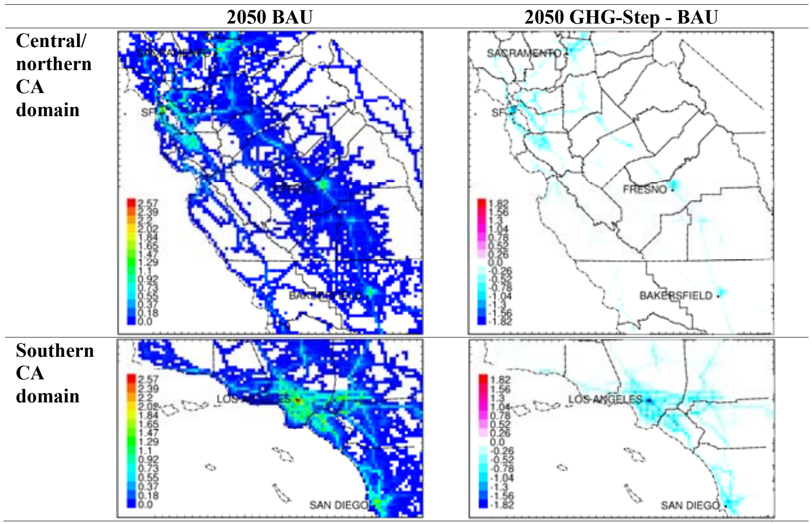

Figure 10: Particulate matter emissions from vehicle tire and break wear in the BAU scenario ~~µg m^{-2} min^{-1}~~(left panels) and emissions change in the GHG-Step scenario (right panels). Units are µg m^{-2} min^{-1}.

Figure 11 illustrates the particulate matter emissions from tailpipe exhaust under the 2050 BAU scenario and the 2050 GHG-Step scenario. Similar to the tire and brake wear emissions, the spatial pattern for mobile sources is identical under both scenarios because the technology changes specified by the CA-TIMES model are applied uniformly over the entire state. Tailpipe particulate matter emissions once again follow patterns of vehicle activity as predicted by EMFAC. Of greater interest is the prediction that tire and brake wear emissions (Fig. 10) will exceed tailpipe emissions (Fig. 11) in both the 2050 BAU and GHG-Step scenarios due to the adoption of increasingly clean vehicle technology. Tailpipe emissions in the GHG-Step scenario are a factor of ~1.8 lower than tailpipe emissions in the BAU scenario. In contrast, tire and brake wear emissions are predicted to decrease by a factor of +3 under the GHG-Step scenario.   This reflects the fact that BAU gasoline and diesel tailpipe emissions already incorporate significant emissions control technology yielding fewer opportunities for further improvement. Tire and brake wear emissions have almost no control technology in the BAU scenario, which makes the widespread adoption of electric or~~/~~ hybrid drivetrains using regenerative braking particularly effective at reducing emissions.

The current analysis assumes that no new major highways will be built in California and population growth is accommodated partially through increased urban density such that traffic volumes increase uniformly across the transportation network. These assumptions are simplistic but a previous study of smartgrowth in the San Joaquin Valley indicated that more detailed accounting of population growth had minimal impact on air quality (Hixson, Mahmud et al. 2010).

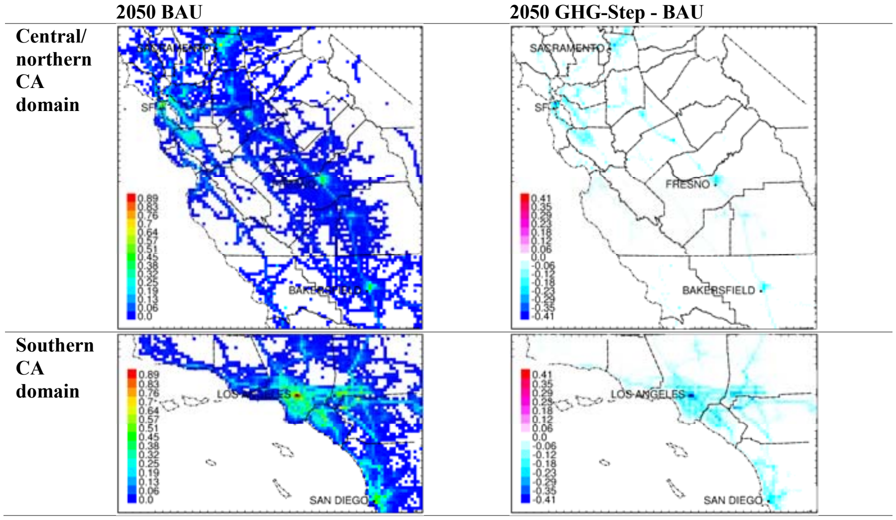

Figure 11: Particulate matter emissions of vehicle tailpipe exhaust in the BAU scenario (left panels) and emissions change in the GHG-Step scenario (right panels). Units are µg m^{-2} min^{-1}.

3.2 Rail, and Off-Road Emissions

Particulate matter emissions from off-road and rail sources are plotted in Fig. 12 for the BAU and GHG-Step scenarios examined in the current study. Maximum statewide particulate matter emissions for this source category are centered at the location of major construction projects with lower emissions rates for "routine" off-road emissions distributed more broadly according to typical activity patterns for smaller construction projects, rail, etc. The 2010 emissions inventory that acts as the basis for the 2050 projections in the current project correctly identified replacement of the east span of the Bay Bridge in the San Francisco Bay Area as the leading construction project with the highest overall emissions in the state. This ~$6.5B project spanned more than 10 years with the new bridge completed in 2013 and final decommissioning and demolition of the old eastern span scheduled for 2018.

It is difficult to predict the location of major construction projects in 2050 but it is reasonable to expect that several large projects will be active in that timeframe. Candidate projects currently under discussion include additional replacement of California's numerous highways and bridges, upgrading California's water conveyance systems to better withstand earthquakes, development of high speed rail lines, reinforcement~~/~~ or expansion of seawalls to protect property, etc. Each of these projects will potentially emit criteria pollutants that would affect air quality over major urban centers. In the present study, the peak emissions associated with the major construction project around the Bay Bridge were retained in the future scenario as an example of a major construction project near an urban area. Future model analysis that uses these emissions should conduct sensitivity tests to ensure that the assumed placement of this example major construction project does not influence the overall conclusions of the study.

Maximum particulate matter emissions shown in Fig. 12 decrease by a factor of approximately 1.6 4in the GHG-Step scenario relative to the BAU scenario. Adoption of biomass based fuels was also found to reduce emissions of SO_x, HC, PM, and occasionally CO from off-road and rail sources, but NO_x emissions increased for some fuel choices.

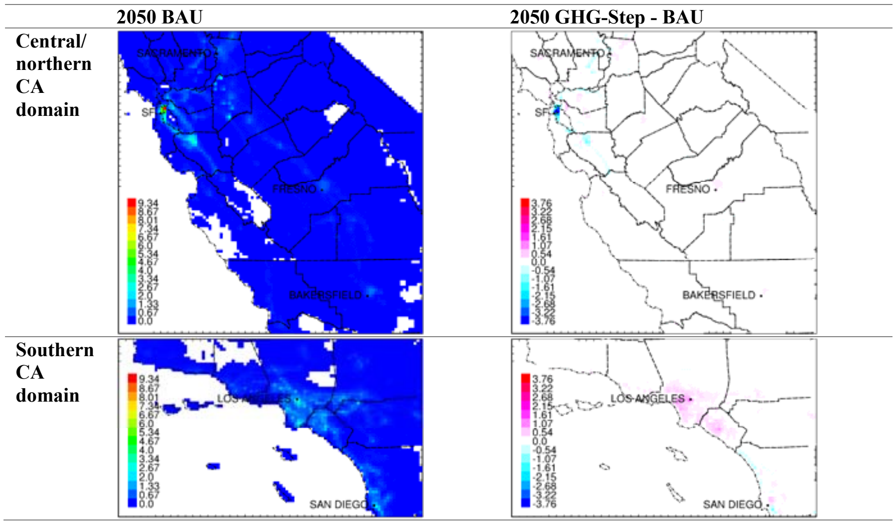

Figure 12: Particulate matter emissions from rail and other off-road sources in the BAU scenario (left panels) and emissions change in the GHG-Step scenario (right panels). Units are μg m^{-2} min^{-1}.

3.3 Marine and Aviation Emissions

Particulate matter emissions from marine and aviation sources are shown in Fig. 13 for the BAU and GHG-Step scenarios considered in the present study. The highest particulate matter emissions rates occur in off-shore shipping lanes that converge on the Port of Los Angeles, the Port of Long Beach, and the Port of Oakland. Emissions rates change with proximity to California shores due to regulations governing sulfur content of marine fuel ~~and/~~or ship speed. Emissions patterns at inland locations reflect shipping activity on inland waterways ~~and/~~or activity surrounding small regional airports.

Maximum particulate matter emissions rates from marine sources increase under the GHG-Step scenario as illustrated most clearly in the ~~lower~~ right panels of Fig 13. CA-TIMES ~~predicts~~ determined that the available biofuel capacity could be more efficiently used to offset traditional fossil fuels for on-road transportation sources and so the GHG-Step scenario is predicted to incorporate additional fossil fuels for marine sources under the GHG-Step scenario vs. the

BAU scenario. The net result of the disbenefits associated with increased marine emissions vs. the benefits of the decreased on-road emissions will be considered in future studies that include analysis with regional air quality models.

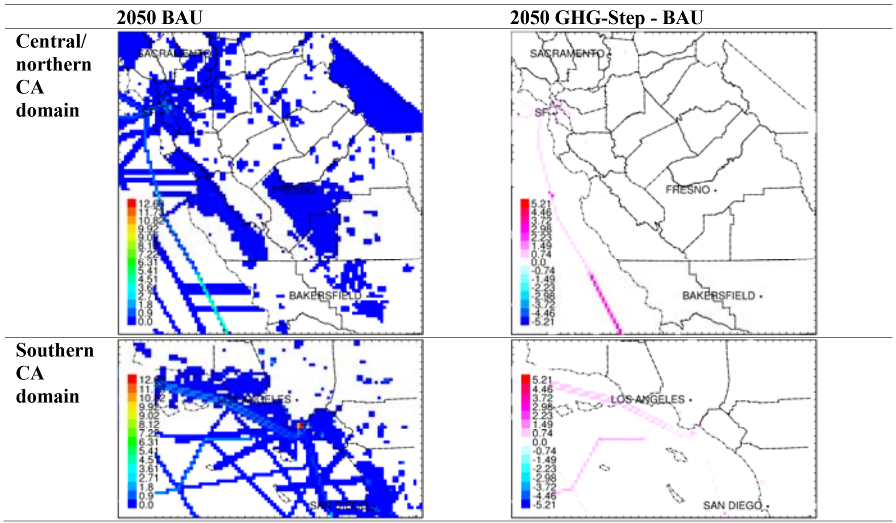

Figure 13: Particulate matter emissions from marine and aviation sources in the BAU scenario (left panels) and emissions change in the GHG-Step scenario (right panels). Units are μg m^{-2} min^{-1}.

3.3 Residential and Commercial Emissions

Fig. 14 illustrates particulate matter emissions from residential and commercial sources under the 2050 BAU and GHG-Step scenarios. The spatial patterns of emissions largely follow the estimated population projections in California in the year 2050 as summarized in Table S24. Population growth was assumed to be identical under the BAU and GHG-Step scenarios yielding virtually identical spatial distributions for both scenarios. The adoption of new technologies and altered behavioral patterns predicted by the CA-TIMES model under the GHG-Step scenario were applied uniformly over the state without modification by income, education level, or regional differences in environmental attitudes. Predicted changes to particulate matter emissions from residential and commercial sources are modest with slight reductions of ~10% mostly attributed to energy efficiency measures. Widespread adoption of biomethane to replace natural gas is predicted in the GHG-Step scenario but this fuel change has little impact on criteria pollutant emissions.

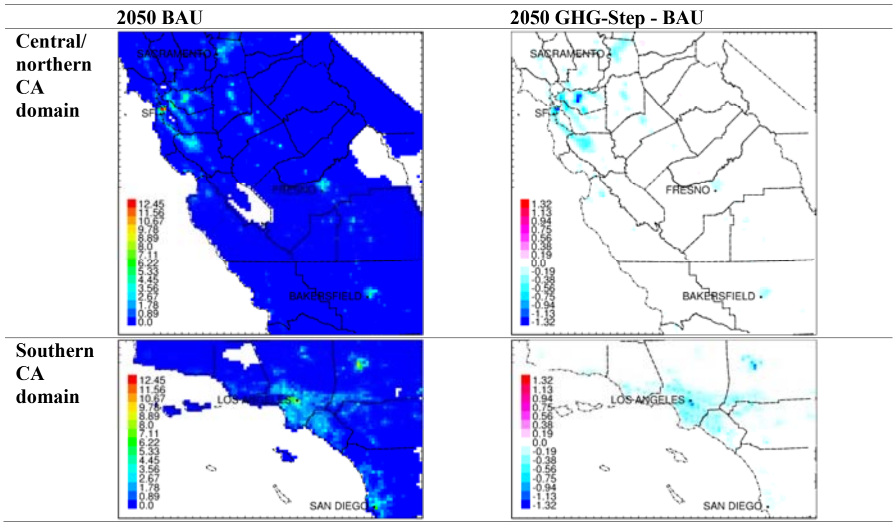

Figure 14: Particulate matter emissions from residential and commercial sources in the BAU scenario (left panels) and emissions change in the GHG-Step scenario (right panels). Units are µg m^{-2} min^{-1}.

3.4 Electricity Generation Emissions

Fig. 15 illustrates predicted emissions of particulate matter from combustion processes used to generate electricity. These emissions are represented as point sources and so only the grid cell containing an electrical generation unit are colored. The highest emissions rates for individual grid cells are associated with a small number major electrical generation stations typically powered by natural gas in the BAU scenario. The majority of the colored grid cells in Fig. 15 are associated with smaller backup generators that operate intermittently and therefore have very low emissions. These backup units are typically powered by a fossil fuel such as diesel fuel in the BAU scenario, with a shift to biofuels in the GHG-Step scenario. This fuel switch has modest impact on total emissions given the low utilization of these units.

Peak emissions rates of particulate matter in the GHG scenario decrease by a factor of ~1.7 in the GHG-Step scenario primarily due to a reduction in fossil fuel electricity generation in favor of a shift to solar and wind sources (see Fig. 9). All generating stations are assumed to continue operation at a reduced rate in the GHG-Step scenario rather than selectively decommissioning some stations. The age and efficiency of existing natural gas generating stations will likely be key factors determining how they are operated in the future scenarios. Solar and wind electricity generation does not emit criteria pollutants and so the location of these facilities is not shown in Fig 15.

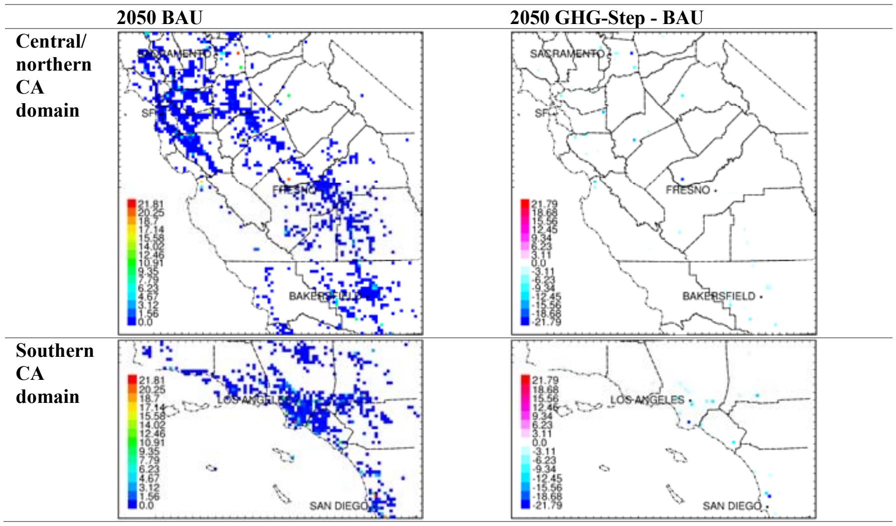

Figure 15: Particulate matter emissions from electricity generation (emission source category type 6) in the BAU scenario (left panels) and emissions change in the GHG-Step scenario (right panels). Units are μg m^{-2} min^{-1}.

3.5 Biorefinery Emissions

Figure 16 shows the locations of refineries producing biofuels (bio-refineries) in California under the BAU and GHJG-Step scenarios considered in the present study. The location of future bio-refineries was chosen to minimize transportation costs for the raw materials feeding into the refinery and the delivery of fuel to the final point of end-use. Additional zoning constraints were considered to prevent the placement of bio-refineries near schools, hospitals or other locations with sensitivity populations. More generally, a constraint was considered to restrict the placement of new bio-refineries in regions that currently violate the NAAQS. The top panels of Fig. 10 therefore do not allow the placement of bio-refineries in either the SJV or the SoCAB, while the less constrained scenarios illustrated in the lower panels of Fig. 16 do not impose this restriction. In practice, bio-refineries were generally sited near landfills, industrial, or agricultural areas within each city selected as economically optimal within the specified constraints. The enforcement of NAAQS constrains on bio-refineries lead to a smaller number of larger refineries under both the BAU and GHG-Step scenarios. Note that overall bio-refining output is higher in the BAU scenario than in the GHG-Step scenario. Bio-fuels have lower associated GHG emissions than traditional fossil fuels but their carbon intensity is still too high to meet the GHG emissions target represented in the GHG-Step scenario. The CA-TIMES model therefore predicts that a portion of the energy supplied by biofuels in the BAU scenario will be supplied instead by wind and solar in the GHG-Step scenario.

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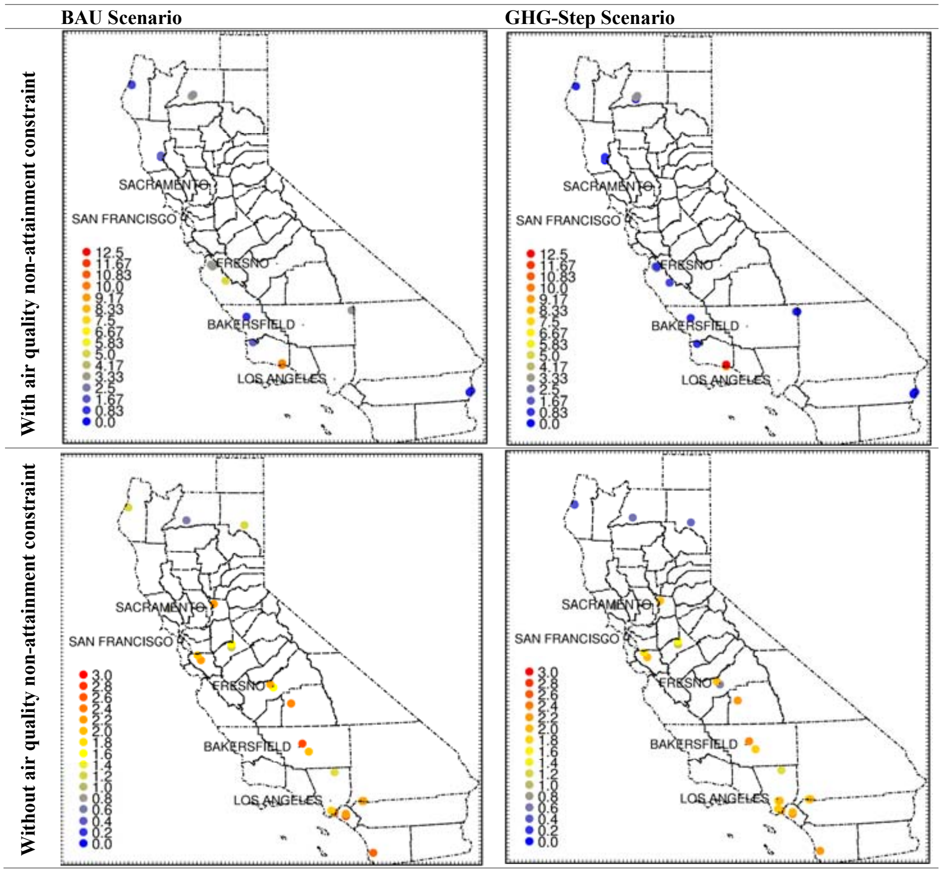

Figure 16: Biorefinery locations under the BAU scenario (left column) and the GHG-Step scenario (right column). Legend shows PM2.5 mass emission rates per facility in μg m^{-2} min^{-1}. Top panels represent the constrained case where biorefineries cannot be located in air basins out of compliance with National Ambient Air Quality Standards (NAAQS). Bottom panels are not constrained by NAAQS status.

3.6 Summary of Statewide Emissions

Fig. 17a illustrates the net change in emissions related to criteria pollutants in California in the GHG-Step scenario vs. the BAU scenario analyzed in the current study. Emissions of each pollutant are broken down by the major emissions categories analyzed in Section 2. The miscellaneous category is equivalent in the BAU and GHG-Step scenarios and hence is not plotted. Contributions below 0% indicate emissions reductions, while contributions above 0% indicate emissions increases. Each of these changes represents the statewide average for the sources within the indicated sector. Note that the changes within each sector may not be uniform across the entire state. The net change in total emissions is indicated by the black horizontal line for each species. It is immediately apparent that the emissions reductions illustrated in Fig. 17a are not uniform for all pollutants. Maximum reductions of ~60% are observed for CO_2 and particulate copper (Cu) emissions. In contrast, emissions of particulate SO_4^{2-}, gaseous CO and gaseous SOx actually increase under the GHG-Step scenario due to tradeoffs in the technologies adopted in the off-road mobile categories (rail, marine, aviation, etc) needed to optimize the overall GHG emissions across the state. Emissions of pollutants that experience increasing trends in Fig. 17a are minor in the present-day inventory and so that they do not currently trigger NAAQS violations. Changes in ~~major~~ key, highly emitted pollutants ~~emissions~~ ~~including particulate EC, particulate OC, and gaseous NOx~~ fall in between the extreme cases described above (see results for particulate EC, particulate OC, and gaseous NOx). Each of these ~~major~~ pollutants ~~experiences~~experience a net decrease in total emissions averaged across California, but emissions changes are not uniform across all categories. Some technology and fuel changes cause higher emissions which are offset by savings in other categories. This complex mixture of tradeoffs reflects the optimal economic approach to GHG reductions ~~predicted~~ determined by the CA-TIMES model.

The changing activity patterns, fuels, and technologies included in the GHG-Step scenario lead to changes in the emitted particle size and composition distribution. This leads to differences in the response of primary particulate matter with aerodynamic diameter less than 2.5 µm (PM2.5) and less than 0.1 µm (PM0.1; ultrafine particles). Ultrafine particles are an emerging pollutant of concern expected to influence public health (Delfino, Sioutas et al. 2005, Knol, de Hartog et al. 2009, Hoek, Boogaard et al. 2010). The results shown in Fig. 17a illustrate that the GHG-Step scenario leads to only a 4% decrease in primary PM2.5 emissions but a much larger 36% reduction in PM0.1 emissions. Recent epidemiology results indicate that PM0.1 is associated with mortality in the California Teachers Study (Ostro, Hu et al. 2015). Enhanced PM0.1 emissions reductions ~~This enhanced reduction~~ could amplify the potential health benefits of the future GHG-Step scenario beyond the level expected from PM2.5 emissions reductions.

Fig 17b. shows the net change in criteria pollutant emissions predicted using the expert analysis approach described by Shindell et al. (2012). These results are presented as a comparison point to the results illustrated in Fig. 17a and listed in SI Table S36 through Table S38. The expert analysis scenario focused on a small number of measures targeted for countries which are in the early stages of adopting policies to reduce GHG emissions ~~and/~~or mitigate regional air quality problems. As a result, the measures described by Shindell et al. have a large impact on global

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Comparison of Fig. 17a and Fig. 17b illustrates that only reductions in particulate EC are comparable in the Shindell et al. and CA-TIMES scenarios due to the mitigation of emissions from off-road diesel engines. CA-TIMES accomplishes this reduction through a combined switch in fuels and adoption of diesel particle filters on remaining diesel and bio-diesel sources to achieve a combined reduction in GHG emissions and criteria pollutant emissions. Shindell et al. assume uniform adoption of diesel particle filters on all off-road diesel engines with no fuel switching. Shindell et al. also specify the adoption of digesters for dairy waste and increased use of landfill gas as renewable methane sources. CA-TIMES predicts similar adoption resulting in a ~35-40% reduction in ammonia (NH_3) emissions from these sources. The CA-TIMES approach considered in the present study additionally considers how the emissions of bio-methane differ from the emissions of traditional natural gas. The only other significant measure specified by Shindell et al. that could reduce criteria pollutant emissions in California is a complete ban on burning of agricultural waste. California already limits agriculture burns to avoid stagnation periods. Thus, even the apparent savings associated with reduced agricultural burns apparent in Fig. 17b are likely to have limited practical impact on air quality in the state. Shindell et al. do not consider the adoption of low carbon fuels or electrification of on-road vehicles which are necessary to achieve deep GHG reductions in CA.

Overall, the analysis presented by Shindell et al. (2012) is appropriately targeted at global health but the measures considered in this analysis do not achieve California’s GHG objectives and the criteria pollutant emissions changes associated with them will not support calculations for future air quality in California. Energy economic models such as CA-TIMES represent a more realistic tool for development of scenarios in regions like California that have already considered all simple measures. Careful analysis is required to understand the resulting complex pattern of tradeoffs between emissions in different categories that results from these scenarios.

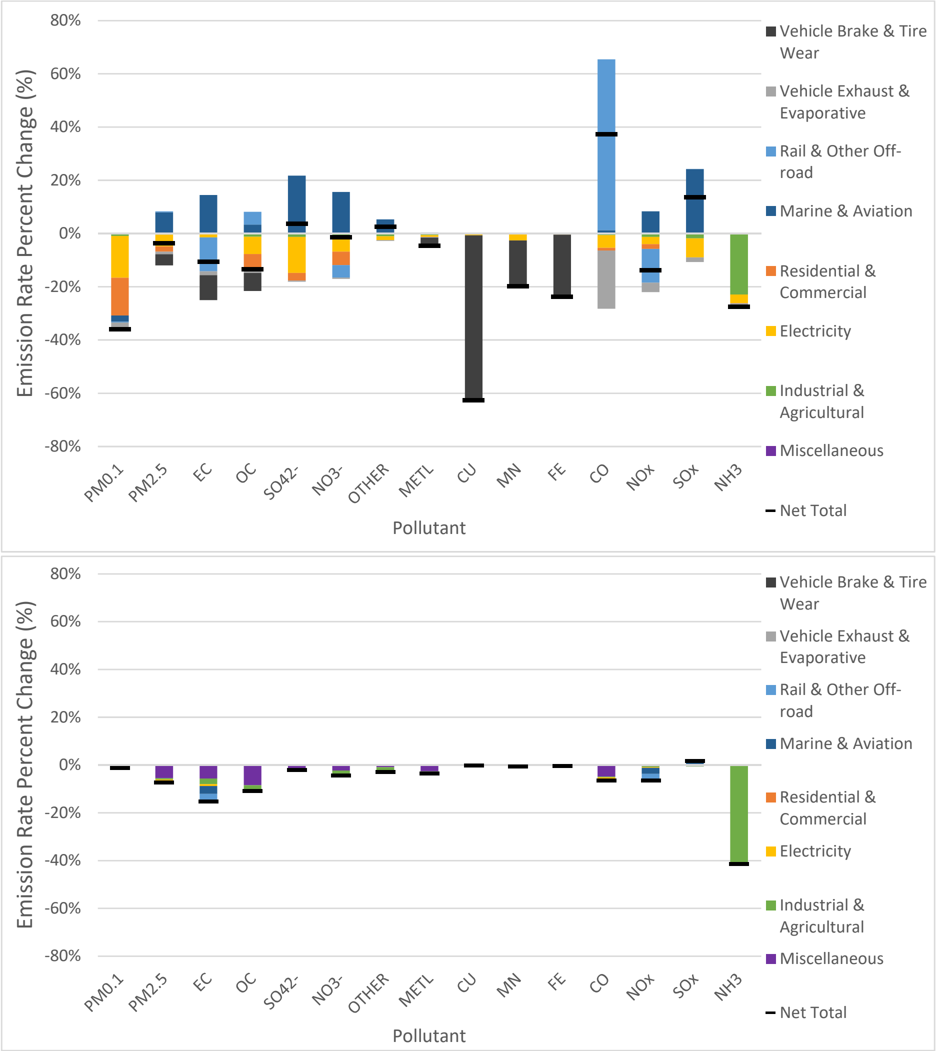

Figure 17: Change in pollutant emission rate relative to BAU scenario. Panel (a) represents GHG-Step analyzed in the current study using the CA-TIMES model. Panel (b) represents expert analysis presented by Shindell et al. (2012).

Fig. 18 illustrates examples of spatial patterns of emissions changes under the GHG-Step scenario predicted by CA-TIMES in the current study. The offsetting increasing and decreasing emissions changes illustrated in Fig. 17 do not occur uniformly over the state but instead appear as regions of localized increasing and decreasing emissions. As an even greater complication, the spatial pattern of increasing and decreasing emissions changes for each pollutant. The top panels of Fig. 18 illustrate changes in the commercial and residential sector for NOx emissions (Fig 18a) and OC emissions (Fig 18b) in central California. Patterns of emissions increases~~/~~ or decreases are similar in major urban centers (San Francisco and Sacramento) but different patterns are predicted for emissions of NOx and OC in the heavily polluted San Joaquin Valley (Fresno and Bakersfield). The lower panels of Fig. 18 illustrate even stronger variation in the spatial pattern of emissions changes in the off-road and rail categories in southern California. The spatial pattern of the change in particulate EC emissions (Fig. 18c) differs strongly from the spatial pattern of the change in particulate OC emissions (Fig. 18d).

All of the emissions illustrated in Fig. 18 will produce regions of increased or~~/~~ decreased pollutant concentrations. Given that each region is highly populated, these emissions patterns will have ~~an immediate~~ a direct effect on population exposure. Detailed analysis with regional air quality models at a resolution of 4km or finer will be required to understand the health implications of these changing emissions. California requires this level of fine-scale emissions analysis to accurately predict the air quality impacts of future GHG mitigation strategies in the state. Similar efforts will be required to analyze the effects of GHG mitigation strategies on criteria pollutants in other highly-populated regions that have already moved beyond simple emissions regulations banning obvious sources of air pollution. ~~are seeking to apply second and higher rounds of~~additional or more stringent ~~emissions controls~~ and ~~regulations.~~

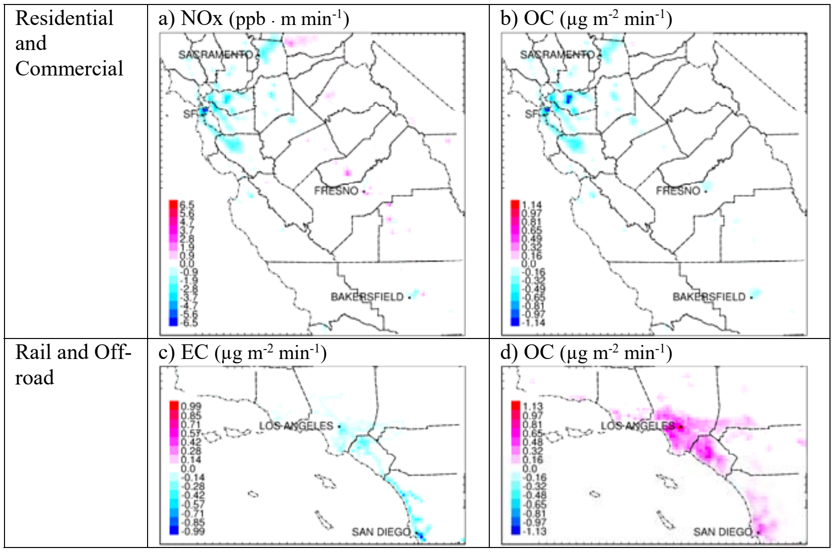

Figure 18: Change in emissions in the GHG-Step scenario relative to the BAU scenario ~~analyzed in the current study~~. (a) NOx from residential and commercial sources (ppb · m min^{-1}), (b) particulate OC from residential and commercial sources (μg m^{-2} min^{-1}), (c) particulate EC from off road and rail sources (μg m^{-2} min^{-1}), and (d) particulate OC from off road and rail sources (μg m^{-2} min^{-1}).

~~The application of~~ The CA-REMARQUE projections for criteria pollutant emissions~~ projection changes~~ associated with optimal climate policies in California should not be directly extrapolated to other regions or countries ~~emission~~

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~~inventories should be done cautiously~~. Instead, the methods used by CA-REMARQUE should be applied to each new region to fully consider the appropriate ~~Many localities, regions, and nations have very unique and different~~ energy resources available, consumption patterns, equipment vintages, ~~population and economic growth rates, and~~ aftertreatment regulations and population and economic growth rates.~~,~~ Each region may have a different optimal set of ~~These~~ GHG mitigation technologies and policies ~~found in the CA-TIMES GHG-Step scenario may be less essential to meet GHG goals elsewhere and likely cause~~that will lead to different rates and spatial patterns of emission compared to the changes predicted in California. Many developing regions will be able to select less expensive ~~rate spatial patterns depending on the energy mix and emission contribution. For these reasons, other regions may find different~~ GHG mitigation strategies that also reduce GHG and ~~more inexpensive and/or beneficial for~~ criteria pollutant emission relative to their BAU scenario. Within developed regions such as other U.S. states, the elements of the mobile emissions inventory maintained by the U.S. EPA (MOVES and mobile portion of the National Emissions Inventory) can be adapted to replace the corresponding California information (EMFAC, mobile portion of the CARB inventory). Changes to off-road emissions would need to be estimated following procedures similar to those employed in the CARB ~~reduction.~~off-road VISION model. Effort would be needed to estimate how changes to marine fuel sources would influence emissions at major ports. Studies would need to be conducted describing potential locations for new facilities producing low-carbon fuels and the resulting emissions from those facilities. This information would support a fully resolved analysis of the criteria pollutant emissions associated with climate policies outside of California.

4 Conclusions

The California ~~Regional~~ REgional Multisector AiR ~~Quality~~ QUality Emissions (CA-REMARQUE) model has been developed to translate optimized GHG mitigation policies to criteria pollutant emissions in California. Minimum-cost GHG policies are first selected with the energy economic model CA-TIMES. Tailored methods are then used to predict corresponding changes in criteria-pollutant emissions for individual categories including on-road vehicles, off-road vehicles, marine, aviation, rail, residential, commercial, electricity generation, industrial, and agricultural emissions. Translation methods account for efficiency improvements, changing technology, and changing fuels with corresponding changes to criteria pollutant emissions. Modifications to the composition of reactive organic gases and the size and composition of airborne particulate matter are considered. Translation methods also account for increased emissions associated with some measures, such as the need to produce new bio-fuels including bio-diesel, ethanol, and hydrogen.

The CA-REMARQUE model is demonstrated by predicting emissions in 2050 under a Business as Usual scenario (BAU) and an optimized GHG mitigation scenario (GHG-Step) in California. The results show that the optimal scenario for GHG mitigation produces increasing criteria pollutant emissions in some categories that are offset by decreases in other categories. These tradeoffs yield a complex pattern of emissions trends with sub-regions of increasing emissions and sub-regions of decreasing criteria pollutant emissions across California when viewed at 4km spatial resolution. In contrast, a simplified expert analysis scenario designed to address global GHG emissions

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may~~does~~ not necessarily ~~have significant~~ ~~impact~~ reduce ~~on~~ criteria pollutant emissions in California because many emission sources ~~of the targeted emissions sources~~ have already been controlled by the state's air pollution regulations. The expert analysis method does not consider complex fuel switching scenarios beyond the replacement of natural gas with biomethane. Choosing an economically optimal scenario of additional measures needed to achieve GHG mitigation goals in California requires tools beyond expert analysis opinions. Likewise, fully accounting for the corresponding changes to criteria pollutant emissions requires sophisticated analysis in fully developed countries and states with strict existing environmental regulations.

The California sub-regions of increasing and decreasing criteria pollutant emissions predicted in the current project occur in close proximity to major population centers and so they will almost certainly influence population exposure and public health. The emissions inventories created in the current study will be analyzed using regional air quality models in a future study to fully calculate impacts on public health.

4 Code and~~/or~~ Data Availability:

All of the data necessary to calculate changes to emissions inventories are published in full in the main text and supporting information section of the manuscript. Collaborators may request the CA-REMARQUE model code ~~and/~~or final criteria pollutant emissions inventories by contacting the corresponding author. Note that t~~T~~he CA-REMARQUE v1.0 model is separate from ~~and thus does not include~~ the CA-TIMES energy-economic model.

5 Acknowledgments:

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