

Projected Air Quality Impacts of Plug-in Electric Vehicles

Marcus Alexander¹, Luke Tonachel², Eladio Knipping³

¹*Marcus Alexander (corresponding author) Electric Power Research Institute, 3420 Hillview Ave., Palo Alto, CA 94304, USA, malexander@epri.com*

²*Natural Resources Defense Council, 40 West 20th Street, New York, NY 10011, USA*

³*Electric Power Research Institute, 1325 G St NW Suite 1080, Washington, DC 20005, USA*

Summary

Plug-in electric vehicles propelled by stored electrical energy do not directly emit tailpipe emissions during operation, but indirect emissions can occur when electricity is generated to recharge the vehicle batteries. This paper presents a comprehensive analysis of the net effects of transportation electrification, which are complicated by the differing nature of emissions in these two sectors. The analysis indicates that in 2030 transportation electrification will lead to modest, but widespread, improvements in air quality in the United States. Electrification of non-road transportation equipment leads to important air quality improvements in several urban areas where air quality is historically poorer and challenging to improve.

Keywords: electricity, emissions, environment, pollution, United States of America

1 Introduction

Plug-in electric vehicles (PEVs), including battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), have the potential to significantly reduce transportation emissions. BEVs are propelled exclusively by energy from the electricity grid and stored in batteries, and PHEVs are propelled by a combination of grid-derived energy and power produced on-board by an internal combustion engine or fuel cell. Both types of vehicles have greatly reduced direct emissions while operating on electricity, and qualify to varying levels as ‘zero emissions vehicles’ in different regulatory contexts.¹ However, recharging the batteries from the grid requires increased generation from power plants, and can result in indirect emissions if electricity is sourced from generation sources that have emissions. Due to the nature of electricity grids, it is difficult or impossible to determine the precise source of electricity for a given load, so it is necessary to use complex analysis to attribute emissions to this electricity. Further, forecasting future generation is even more difficult since sophisticated tools are required to model the grid, and there are different approaches to estimating the effects of future load, which can lead to significantly different results. This report describes an analysis of the effects of widespread transportation electrification on United States air quality in 2030.

This paper summarizes the discussion and air quality results in a joint study of the Electric Power Research Institute and Natural Resources Defense Council, *Environmental Assessment of a Full Electric Transportation Portfolio* (see [1] and [2]). The full reports describe an extensive literature review, discuss methodological development in detail, provide additional information on data sources and model configuration, and document the full results.

¹ BEVs have small amounts of direct emissions, such as brake dust and plastics off-gassing, and PHEVs have direct emissions from the auxiliary power source which depend in complex ways on the design of the powertrain, and may occur during ‘all-electric’ operation.

2 Emissions Projection Best Practices

Projecting grid emissions is difficult due to the highly technical nature of grid analysis and due to different approaches for estimating the effects of incremental load. For the analysis described in this report, best practices were developed for modeling the effects on the grid due to the additional charging load due to the introduction of large numbers of PEVs.

One important best practice that distinguishes this work from previous work is the use of a ‘large-scale’ marginal grid modeling methodology. In this methodology, incremental load is added to a full grid model over time, as the load will occur in reality (this model should at a minimum include capacity expansion and retirement and a full suite of emissions policies). Using a realistic load change and a comprehensive grid model ensures that the grid is able to respond with a combination of redispatch of existing resources and introduction of new resources. Alternately, adding load at an unrealistic rate or using an incomplete grid model will result in grid behavior that exceeds regulated limits and provides a distorted view of the potential benefits of PEVs.

3 Transportation Submodel

The analysis considered the electrification of a large amount of light-duty and heavy-duty vehicles and non-road equipment. This large-scale shift towards electricity necessarily occurs over a long time period, so it was necessary to create long-term projections of the changes in the transportation sector. This section describes the development of models for each segment of the sector.

3.1 Electrification of On-road Vehicles

The electrification of on-road vehicles was modeled by dividing on-road vehicles into categories that could be electrified with near-term technology and those that could not, then assuming that electrifiable categories were electrified based on an aggressive, but plausible, introduction trajectory described by the U.S. National Research Council [3]. Table 1 shows which on-road vehicle categories were electrified. Most vehicle classes that did not require long distance travel with heavy loads were considered to be electrifiable.

Table 1: Electrification of vehicle categories

	Vehicle Class	PEVs Allowed	Conventional Vehicles Only	Vehicle Class Description
Personal	Motorcycle	X		Motorcycle
	Passenger Car	X		Passenger Car
	Passenger Truck	X		Minivans, pickups, SUVs, and other 2-axle / 4-tire trucks used primarily for personal transportation This category is approximately 93% light-duty and 7% heavy-duty (on a VMT basis).
Commercial	Light Commercial Truck	X		Minivans, pickups, SUVs, and other 2-axle / 4-tire trucks used primarily for commercial applications This category is approximately 83% light-duty and 17% heavy-duty (on a VMT basis).
	Intercity Bus		X	Buses that are not transit buses or school buses (e.g., those used primarily for city-to-city transport)
	Transit Bus	X		Buses used for public transit
	School Bus	X		School and church buses
	Refuse Truck	X		Garbage and recycling trucks
	Single-unit Short-haul Truck	X		Single-unit trucks with majority of operation within 200 miles of home base
	Single-unit Long-haul Truck		X	Single-unit trucks with majority of operation outside of 200 miles of home base
	Motor Home		X	Motor Home
Comm.	Combination Short-haul Truck		X	Combination trucks with majority of operation within 200 miles of home base
	Combination Long-haul Truck		X	Combination trucks with majority of operation outside of 200 miles of home base

For the electrified vehicle categories, it was assumed that vehicles would be replaced by a mix of plug-in hybrid electric vehicle (PHEV) and battery electric vehicles (BEV) types, which would change over time as battery technology progressed. Figure 1 shows the combined effects of the introduction trajectory referenced above and the mix of PEVs on new vehicle sales.

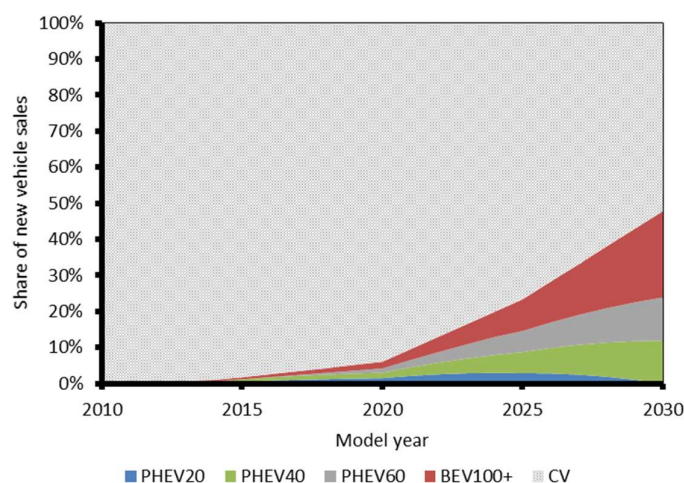


Figure 1: Distribution of new-vehicle sales among various types, for vehicle categories that include PEV sales

In the transportation model, the new PEVs sold are assumed to replace conventional vehicles which are improving over time in response to current and anticipated emissions regulations. The starting points for developing on-road emissions for these two scenarios were 2030 emission factors from the U.S. EPA's Motor Vehicle Emissions Simulator (MOVES) model [4] and state-supplied VMT specific to 2008. The VMT were projected to 2030 using the data on vehicle sales and activity projections from the 2011 Annual Energy Outlook (AEO). At the time when on-road vehicle emissions were prepared for this study, several rulemakings with significant emissions impacts in year 2030 were not yet included in MOVES (2010a version). To account for these rulemakings, the emissions effects were incorporated into the Base Case by applying scaling factors to the MOVES-based inventory. The rulemakings accounted for externally to MOVES include:

- EPA's Tier 3 emission standards with lower sulfur content (10 ppm) gasoline
- Light-duty greenhouse gas (GHG) rulemaking, beginning with 2017 models
- Heavy-duty GHG rulemaking, beginning with 2014 models

In order to account for these rulemakings, scaling factors were developed and applied to the MOVES inventory to generate the 2030 Base Case. In the Electrification Case, the Base Case results were modified to account for the effects of increasing transportation electrification. These modifications varied depending on the types of emissions, but generally electric vehicles had no direct running or starting emissions, and reduced brake particulate emissions, while plug-in hybrid electric vehicles had reduced direct running and startup emissions, and reduced brake particulate emissions. PEVs also had reduced liquid fuel usage, resulting in reductions in petroleum upstream emissions. As shown in Figure 2, 17% of miles traveled by passenger vehicles were electrified in 2030. Commercial vehicles followed a similar trajectory, but with lower shares due to the lower fraction of electrifiable vehicles.

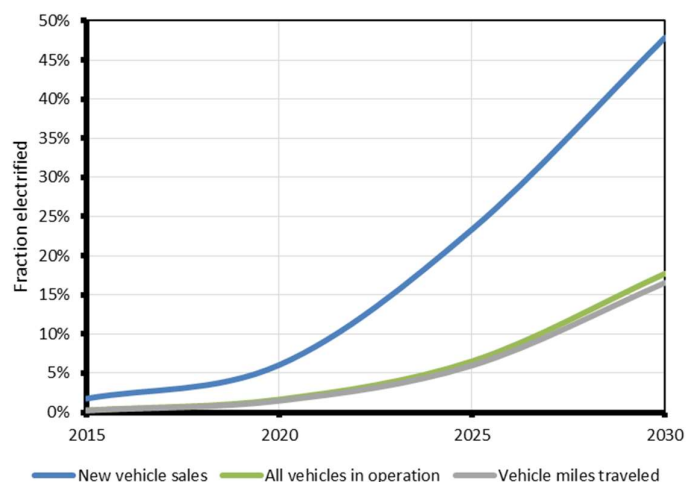


Figure 2: Effects of electrification on new vehicle sales, vehicles in the fleet, and vehicle miles travelled for passenger vehicles

The electrification of on-road vehicles resulted in reductions in direct emissions. Figure 3 shows the effects of these changes on on-road vehicle emissions. California emissions are calculated using the more detailed EMFAC model [5], so results are presented for California (right) and for the rest of the United States without California (left).

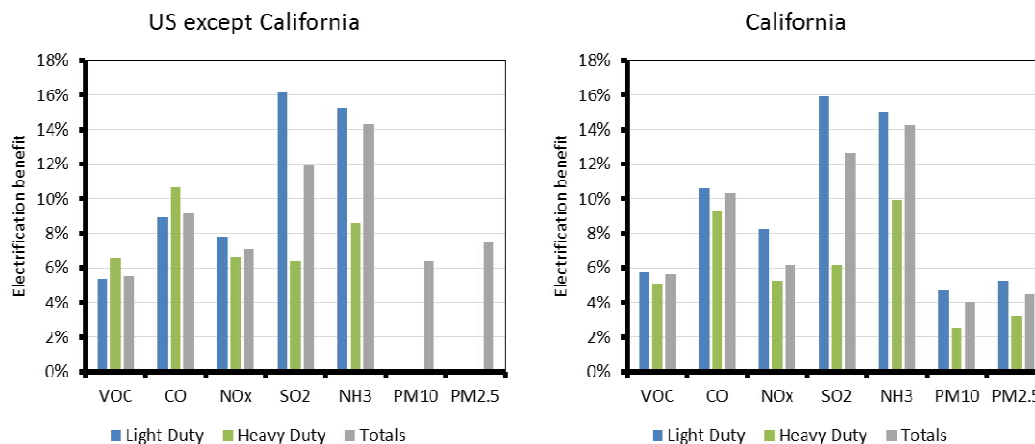


Figure 3: Comparison of electrification benefit on light-duty, heavy-duty, and all on-road vehicle emissions

3.2 Electrification of Non-road Equipment

Non-road equipment is responsible for a significant fraction of the criteria emissions in the United States, and many non-road categories have significant electrification potential. This analysis considered the potential effects of non-road electrification on air quality, since current trends indicate that the electrification of the on-road fleet will be accompanied by non-road electrification due to reductions in costs of components like batteries, high-quality motors, and charging equipment.

The non-road emissions inventory was primarily derived from the Environmental Protection Agency's NONROAD model [6], with adjustments to emissions for cargo-handling equipment, ports, and rail equipment. In the Electrification Case, it was assumed that non-road equipment would be electrified by changes in new-unit sales, which varied by equipment type. Figure 4 shows sample electrification trajectories for lawn and garden and recreational equipment, which are generally highly electrifiable. Other categories, such as construction equipment, were not electrified at all in this analysis.

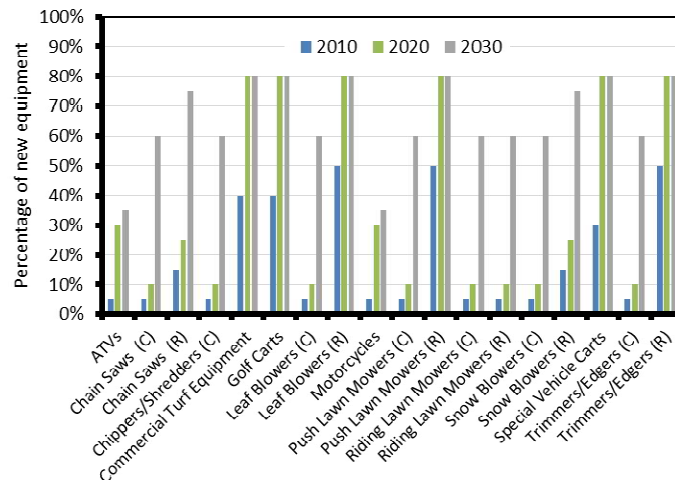


Figure 4: Lawn and garden and recreational equipment new-unit electrical sales fractions for 2010, 2020, and 2030. (C) denotes commercial-use equipment and (R) denotes residential- use equipment

The varying new-unit market shares resulted in varying levels of total fleet adoption and resulting emissions reductions. Figure 5 shows the effects of electrification on modelled non-road categories, by emissions species. The effects on overall non-road emissions vary from 3% (for SO₂, sulfur dioxide) to 22% (for CO, carbon monoxide).

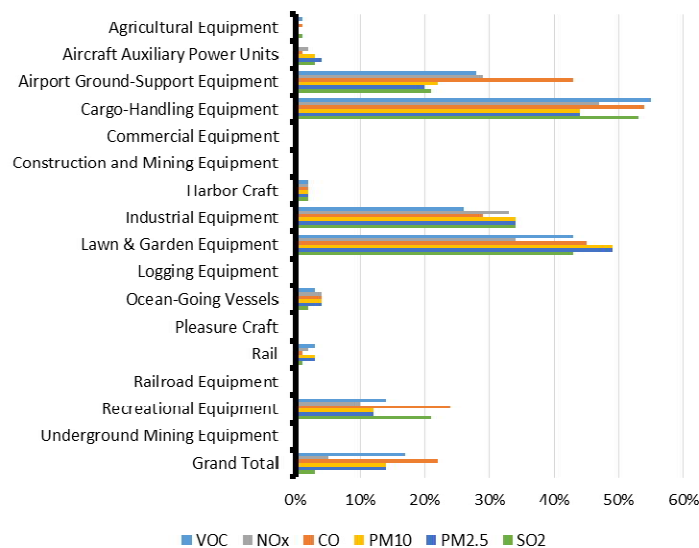


Figure 5: Year 2030 U.S. lower-48 state Electrification Case emissions reductions by non-road category

4 Electricity Grid Modeling

The load required to charge the PEVs and non-road devices described in Section 3 was applied to a detailed grid model to project incremental generation. The analysis used EPRI's U.S. Regional Economy, Greenhouse Gas, and Energy (US-REGEN) model to determine the generation emissions which would result from this incremental load. As discussed in Section 2, the grid modeling used a large-scale marginal approach with least-cost dispatch, a full suite of modeled criteria emissions policies, endogenous capacity expansion and retirement, and realistic rates and magnitudes of load increase. Notably, the Clean Power Plan was not modeled since it was finalized after modeling was completed, but the Environmental Protection Agency's modeled total grid greenhouse gas emissions are between the two modeled scenarios in 2030, the beginning of the full compliance period for the Plan.

In considering the effects of generation on air quality, it is important to calculate when emissions occur and where they occur. Emissions were allocated to each hour of the year and were calculated for all 15 US-REGEN modeling regions and spatially allocated to individual generation sites, but are summarized for the regions shown in Figure 6 in the following discussion.



Figure 6: Divisions for presentation of generation results

4.1 Generation without Transportation Electrification

Figure 7 and Figure 8 show the forecast for generation without electrification. For the set of assumptions used, coal generation remained relatively constant to 2030, while new load was met through a combination of renewable and nuclear generation (as discussed in an appendix in [2], the scenario used in this analysis allowed a higher amount of new nuclear generation than in other related analyses in this study). Incremental renewable generation was supplied by a combination of wind and solar in the West and East regions; primarily from wind in the Midwest; and primarily from nuclear in the South. These trends reflect the resource endowments in each region.

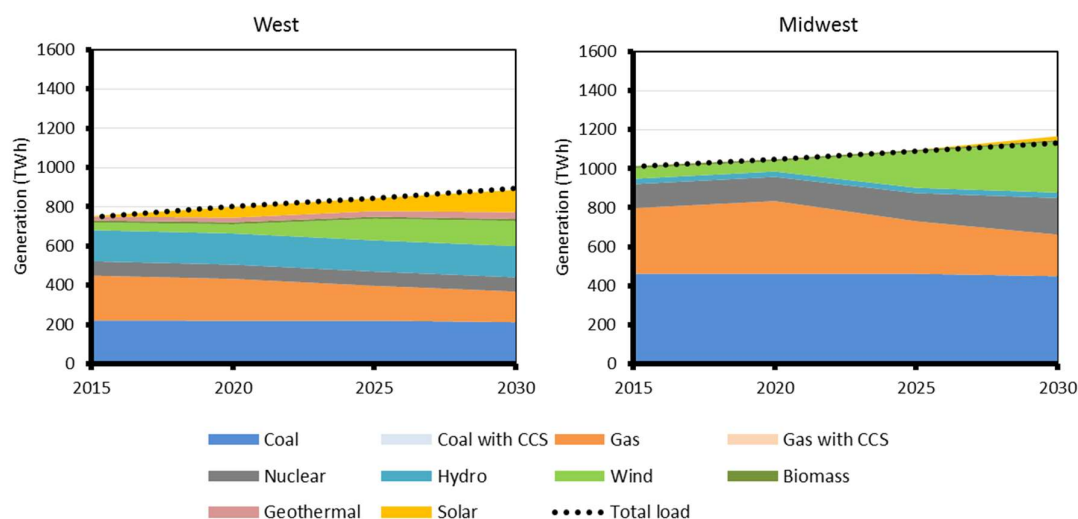


Figure 7: Generation without transportation electrification (West and Midwest)

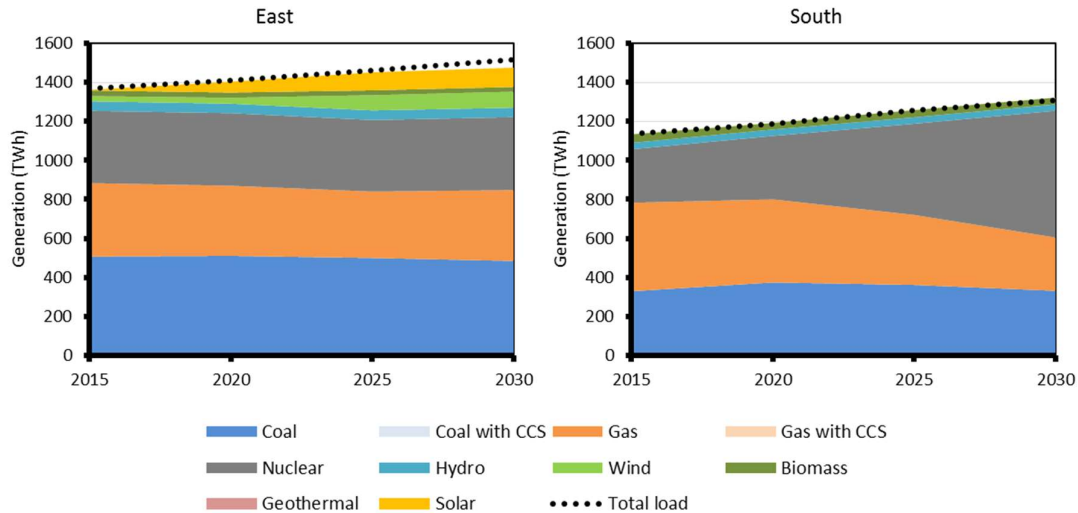


Figure 8: Generation without transportation electrification (East and South)

4.2 Incremental Generation Due to Transportation Electrification

Figure 10 and Figure 10 show the incremental generation required to meet the additional load from transportation electrification. Incremental generation comes from a combination of combined cycle natural gas and renewables, with some shifting of nuclear generation from the Midwest to the South (the total quantity of nuclear generation capacity is fixed, but in this scenario new plant builds occur in the South instead of the Midwest due to shifts in the economics of generation due to the new load). Many generation types, including coal, hydroelectric, biomass, and geothermal, are fully utilized in the Base Case and do not provide incremental generation as load increases.

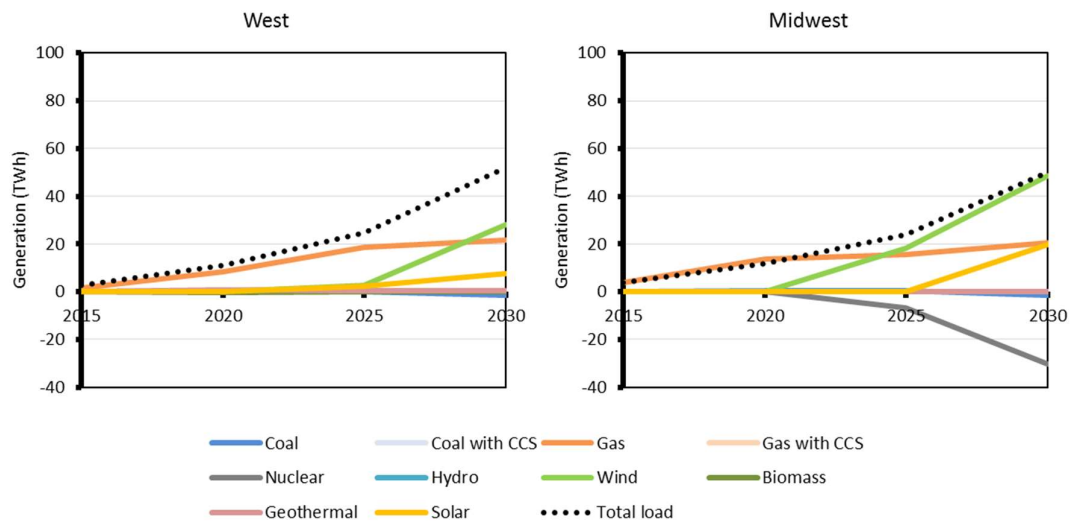


Figure 9: Incremental generation due to transportation electrification load (West and Midwest)

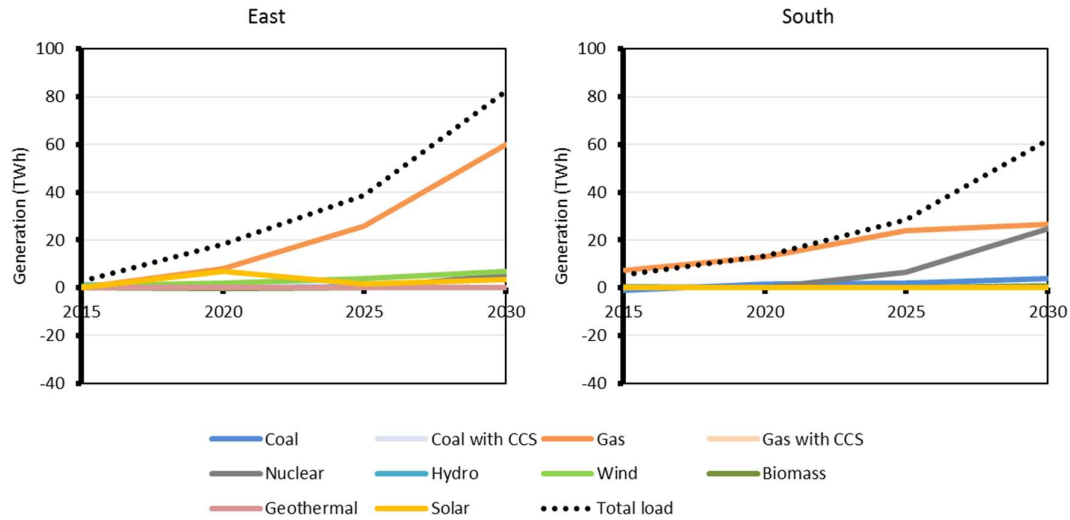


Figure 10: Incremental generation due to transportation electrification load (East and South)

5 Overall Changes in Emissions

The changes in the transportation sector, fuel supply sector, and electricity sector due to transportation electrification result in changes to emissions. Figure 11 shows the net changes in emissions due to transportation electrification, separated by source and emissions species. Generation emissions (EGU) do increase slightly, but are more than compensated for by changes to emissions in other sources. The largest emissions reductions come from the non-road, heavy-duty, and area sources (area emissions are mainly due to refuelling and evaporative emissions). Light-duty transportation is relatively highly regulated, so even though the highest level of transition happened in these vehicles the effects on emissions was relatively low. The overall effect of transportation electrification is a reduction in each species.

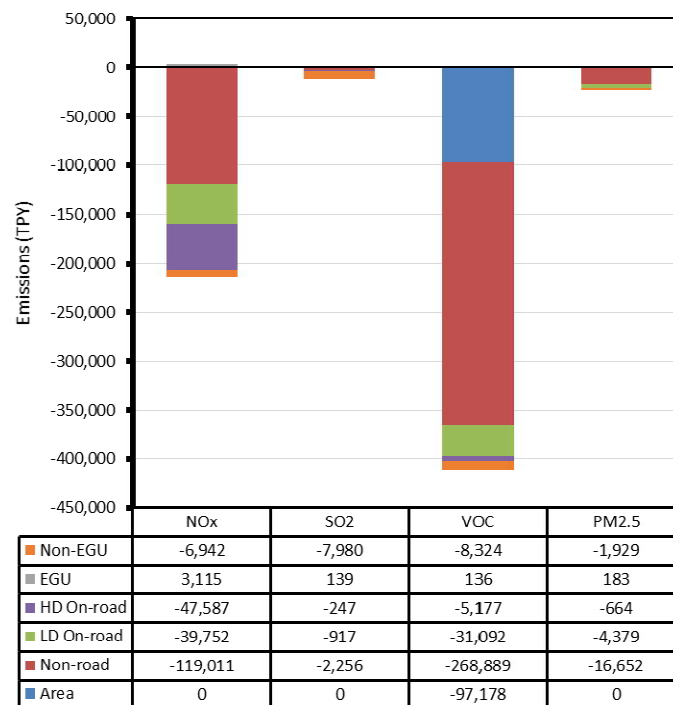


Figure 11: Overall changes in 2030 emissions between the Base Case and Electrification Case

6 Effects of Transportation Electrification on Air Quality

Reductions in emissions are generally beneficial, but emissions reductions are primarily desired because of the effects that these emissions have on air quality, which is a result of both these direct emissions and secondary reactions that occur in the atmosphere. For example most $\text{PM}_{2.5}$ ² and ozone, the two principle components of smog, are generated by secondary reactions. These reactions are also very sensitive to the specific spatial and temporal distribution of the emissions described above, so reductions alone may not be adequate to ensure improvements in air quality. A national-scale air quality modeling analysis was performed with the CAMx air quality model to estimate ozone and $\text{PM}_{2.5}$ concentrations. CAMx is a 3-D photochemical transport and dispersion model that calculates emissions allocation, advection and dispersion, photochemical transformation, aerosol thermodynamics and phase transfer, aqueous chemistry, and wet and dry deposition of trace species.

6.1 Changes in Ozone Air Quality Indicators

Air quality modeling results indicate that the air quality benefits associated with electrification, although modest, are widespread across the Continental United States. Figure 6 shows widespread ozone benefits related to electrification.³ For reference, the National Ambient Air Quality Standard (NAAQS) for ozone is 70 ppb for the 4th highest 8-hour ozone concentration, measured as the average over three years. Most ozone reductions are modest—generally less than 1 ppb. Many urban areas, including cities that exceed the current level of the ozone standard, see larger ozone reductions (many up to 3 ppb). The largest reduction (of 4 ppb) is estimated to occur in Los Angeles. These ozone reductions result mostly from decreases in non-road sector emissions, as a result of the electrification of non-road vehicles and equipment. Ozone benefits from non-road sector electrification are widespread. In the Electrification Case, areas near the Gulf Coast and Los Angeles also receive benefits from commercial marine emissions reductions associated with reduced crude-oil imports. Ozone increases (less than 1.5 ppb) are restricted to a few grid cells in rural areas.

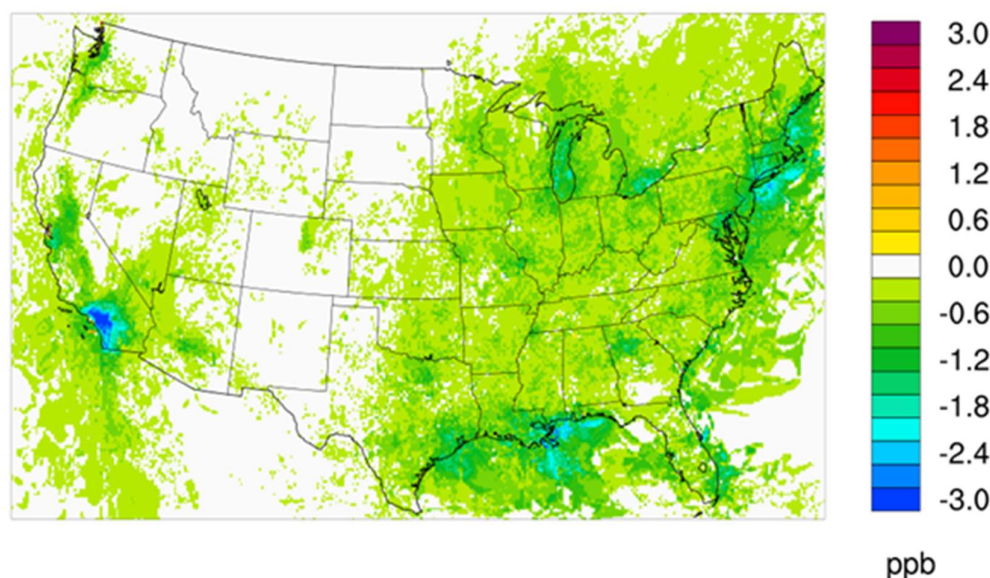


Figure 12: Changes in maximum ozone concentration between the Base Case and Electrification Case (measured as the 4th highest 8-hour concentration for the year, calculated separately for each cell)

6.2 Changes in $\text{PM}_{2.5}$ Air Quality Indicators

Electrification of mobile sources reduces the 8th highest 24-hour average $\text{PM}_{2.5}$ concentrations in many areas of the Eastern United States, in California, and in the Pacific Northwest, as shown in Figure 13. These

² Particulate matter with a diameter of less than 2.5 micrometers.

³ The 4th highest 8-hour ozone concentration is calculated separately for each cell; therefore, the same color represents the same concentration level, but adjacent cells may experience this maximum concentration during different days.

reductions are modest (generally less than $0.5 \mu\text{g m}^{-3}$), but they are consistent. PM benefits are mostly from electrification of non-road sources, with close to $2 \mu\text{g m}^{-3}$ reductions in Los Angeles. Annual average concentrations of $\text{PM}_{2.5}$ (Figure 14) show a similar pattern of modest reductions—mostly in urban areas because of electrification of mobile sources.

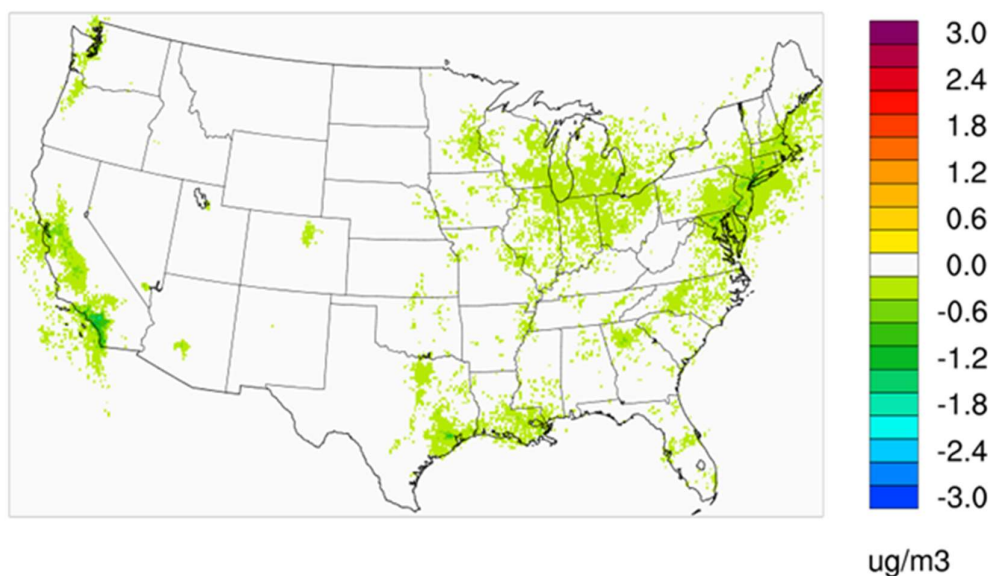


Figure 13: Changes in maximum $\text{PM}_{2.5}$ concentrations between the Base Case and Electrification Case (measured as the 8th highest 24-hour average concentration ($\mu\text{g m}^{-3}$) of $\text{PM}_{2.5}$ for the year, calculated separately for each cell)

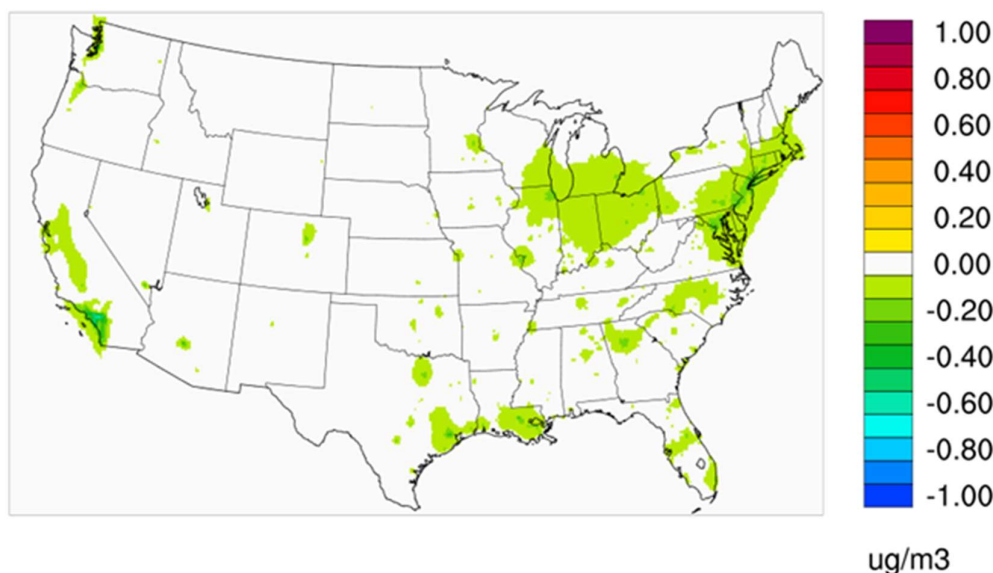


Figure 14: Changes in average $\text{PM}_{2.5}$ concentrations between the Base Case and Electrification Case (measured as the annual average concentrations ($\mu\text{g m}^{-3}$) of $\text{PM}_{2.5}$, averaged separately for each cell)

7 Key Findings

The key results of the analysis of the effects of electrification on emissions of criteria pollutants and ambient air quality can be summarized as follows:

- Considering the electric and mobile sectors together, total emissions of VOC, NO_x , SO_2 , and PM decrease in the Electrification Case.
- Ozone benefits related to electrification of on-road and non-road mobile sources occur across the United States. Many urban areas—including cities with ambient air quality exceeding the current

ozone standard—see reductions in the 4th highest 8-hour average ozone concentration of up to 4 ppb. The ozone decreases are mostly a result of decreases in non-road sector emissions resulting from electrification of non-road equipment.

- Electrification of mobile sources reduces the 8th highest 24-hour average PM concentrations in many areas of the Eastern United States, in California, and in the Pacific Northwest. These reductions are modest (generally less than 0.5 $\mu\text{g m}^{-3}$), but they are widespread. PM benefits derive mostly from electrification of non-road sources.
- Electrification of mobile sources reduces nitrate and total nitrogen deposition across the United States.

These findings demonstrate that even with the recently promulgated Tier 3 vehicle-emission standards, the electrification of on-road vehicles has a small but significant and widespread benefit to air quality. In addition, electrifying non-road equipment provides significant benefits that are in some cases larger than the benefits of on-road electrification—particularly in urban areas where air quality exceeds national ambient air quality standards. Few adverse effects of electrification were found, and air quality impacts related to increased power plant emissions are confined in extent and small in magnitude.

8 References

- [1] EPRI-NRDC. *Environmental Assessment of a Full Electric Transportation Portfolio: Volume 1: Background, Methodology, and Best Practices*. Palo Alto, CA: 2015. 3002006875.
- [2] EPRI-NRDC. *Environmental Assessment of On-road Vehicle and Off-road Equipment Electrification: Volume 3: Air Quality Impacts*. EPRI, Palo Alto, CA: 2015. 3002006880.
- [3] National Research Council (U.S.). Committee on Transitions to Alternative Vehicles and Fuels. *Transitions to Alternative Vehicles and Fuels*. Washington, D.C.: National Academies Press. 2013.
- [4] Environmental Protection Agency. Motor Vehicle Emission Simulator Model, Version 2010a. Available online: <http://www.epa.gov/otaq/models/moves/moves-docum.htm#moves2010a>. 2010.
- [5] California Air Resources Board. *EMFAC2011 Model*, Updated January 2013. Available online: http://www.arb.ca.gov/msei/modeling.htm#emfac2011_web_based_data. 2013.
- [6] Environmental Protection Agency. *NONROAD2008a Model*. United States Environmental Protection Agency, Assessment and Standards Division, Office of Transportation and Air Quality. Available Online: <http://www.epa.gov/otaq/nonrdmdl.htm>. 2009.

9 Authors



Marcus Alexander: Mr. Alexander has a B.S. in Mechanical Engineering and a M.S. in Electrical Engineering, both from the University of California, Davis, is currently Manager, Vehicle Systems Analysis at the Electric Power Research Institute. He has worked the PEV industry for almost 20 years in a variety of roles, from helping design and build them, to modeling them, to modeling their effects on the utility grid.



Luke Tonachel: Mr. Tonachel holds a B.S. in Mechanical Engineering from the University of Rochester and Masters in Public Policy from University of California, Berkeley. He is the Director of the Clean Vehicles and Fuels team and a senior analyst for the Natural Resources Defense Council (NRDC), an international nonprofit environmental advocacy organization. Since joining NRDC in 2004, his focus has been on reducing the environmental impacts of the world's transportation demands by advocating for policies that develop and commercialize cleaner, more efficient vehicles and non-petroleum fuels. Mr. Tonachel has authored and contributed to numerous nationally-recognized reports and analyses covering vehicle electrification, improved vehicle efficiency and other oil and emissions reduction opportunities.



Eladio Knipping: Dr. Knipping received his BS degree in civil engineering from the Instituto Tecnológico de Santo Domingo (Dominican Republic). He received both his MS degree in environmental engineering and his PhD degree in mechanical and aerospace engineering from the University of California, Irvine. He is currently Manager of Air Quality Modeling and Analysis in the Environment Sector of the Electric Power Research Institute. His principal research activities focus on evaluating the origin and fate of environmental pollutants, with emphasis on gases, particulate matter and the atmospheric deposition of acids and nutrients. Dr. Knipping is also involved in several cross-discipline initiatives evaluating the environmental impacts of emerging technologies, such as plug-in electric vehicles and distributed energy resources.