SUPPORTING INFORMATION

Air Quality Impacts of Electrifying Vehicles and Equipment Across the US

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43 pages

20 Figures; 13 Tables

SUMMARY

This Supporting Information discusses emissions data (Section 1), and describes model configuration and initialization (Section 2). Section 2 also includes source apportionment analysis of ozone and PM results as discussed in the main paper.

SECTION 1. DESCRIPTIONS OF EMISSIONS

The Electrification scenario results in changes to on-road and off-road mobile source emissions for sources that are electrified. Additionally, the displacement of gasoline and diesel-powered vehicles and equipment in the baseline scenario with electric-powered vehicles and equipment in the Electrification scenario results in reductions in emissions associated with the processing, transport, and storage of crude oil and gasoline. This section provides further information on methodology used to estimate emissions for the Base case and the Electrification Case.

1.1 On-road Sector

On-road Base Case Emissions

The development of the 2030 Base Case on-road inventory (excluding California) began with MOVES2010a emission factors and state-supplied vehicle miles travelled (VMT). California emissions were from the California Air Resources Board (ARB) EMissions FACtor model. Rather than run the model for all US counties, a subset of approximately 200 representative counties was selected based on the underlying county properties within the MOVES database. All gasoline was assumed to be 10 percent ethanol (E10 fuel). The MOVES runs were performed for an average January and July day in 2030. Next, the January and July VMT were projected from 2008[1] to 2030 based on the Energy Information Administration (EIA) 2011 Annual Energy Outlook (AEO) estimates of growth in vehicle activity (Table S1). The 2008 VMT estimates are from the 2008 National Emission Inventory (version 1) for which EPA compiled county-level VMT based on VMT data provided to EPA by state agencies, 2008 Federal Highway Administration VMT estimates, and 2008 Census population estimates.

Table S1. VMT projection factors for 2008 to 2030 from the AEO2011 (ratio of 2030 VMT to 2008 VMT).

SCC Vehicle	SCC Vehicle Type	Fuel Type	Description	Ratio of 2030 VMT to 2008 VMT
2201001	LDGV	Gasoline	Passenger Cars	1.390
2201020	LDGT1	Gasoline	Light-Duty Trucks (0-6,000 lbs. GVWR)	1.017
2201040	LDGT2	Gasoline	Light-Duty Trucks (6,001-8,500 lbs. GVWR)	1.017
2201070	HDGV	Gasoline	Heavy-Duty Gasoline Vehicles (>8500 lbs. GVWR)	1.046
2201080	MC	Gasoline	Motorcycles	1.211
2230001	LDDV	Diesel	Passenger Cars	2.201
2230060	LDDT	Diesel	Light-Duty Trucks	1.054
2230071	HDDV2b	Diesel	Heavy-Duty Diesel Vehicles (8501-10,000 lbs. GVWR)	1.111
2230072	HDDV345	Diesel	Heavy-Duty Diesel Vehicles (10,001-19,500 lbs. GVWR)	1.012
2230073	HDDV67	Diesel	Heavy-Duty Diesel Vehicles (19,501-33,000 lbs. GVWR)	1.495
2230074	HDDV8	Diesel	Heavy-Duty Diesel Vehicles (>33,000 lbs. GVWR)	1.335
2230075	HDDB	Diesel	Heavy-Duty Diesel Buses	1.572

Adjustments to Account for On-road Rulemakings

Three important on-road rulemakings were incorporated into the MOVES-based inventory outside of California and the EMFAC2011 inventory within California. Scaling factors were developed to account for the effects of these rulemakings on 2030 emissions.

1. EPA's proposed Tier 3 emission standards (40 CFR Parts 79, 80, 85, et al.) with lower sulfur content (10 ppm) gasoline, and the LEV-III standards with low sulfur gasoline within California.

The scaling factor development for VOC, CO, and NO_x emissions began with running MOVES to develop emission factors for each vehicle model year in the 2030 fleet (2000 through 2030 models) for two cases: (1) Tier 2 compliant vehicles and (2) vehicles complying with California's LEV-II standards. The latter emission factor set was generated in MOVES using EPA's alternative emission factors for LEV adoption in other states[1]. The by-model-year LEV-II emission factors were then scaled to the LEV-III standard using an ARB tool. The ARB released the Advanced Clean Cars (ACC) program LEV-III Inventory Database Tool[2] that generates California statewide baseline (i.e., LEV-II) and LEV-III inventories by light duty vehicle class and model year. The MOVES LEV-II emission factors were scaled by multiplying by the reduction factors shown in Table S2 produced from runs of the ARB tool, leading to final emissions factors that were significantly lower than the federal Tier 2 base.

The scaling factor development for PM emissions required a different approach because EPA alternative emission factors (LEV-II) did not include PM estimates. Instead, the PM adjustments were developed as a ratio of emissions directly from Tier 2 levels to LEV-III, based primarily on the magnitudes of the two standards. EPA is proposing to reduce the 10 milligrams per mile (mg/mi) standard to 3 mg/mi for exhaust PM over the period 2017-2020. According to MOVES modeling results, the representative Tier 2 standard emission factor for the gasoline light-duty vehicle fleet at the end of useful life is approximately 7.7 mg/mi, which is well below the 10 mg/mi standard. Because vehicles easily meet the 10 mg/mi standard and the margin of compliance with a 3 mg/mi standard may be narrower, the emissions ratio was conservatively estimated as 3 mg/mi divided by 7.7 mg/mi, or approximately 0.389 at full implementation.

Table S2. Emissions ratios of LEV-III to LEV-II by vehicle class.

ARB Tool Ratios	Equivalent Federal Class	THC Exhaust		CO		NO_x	
		Run	Start	Run	Start	Run	Start
LEV III/LEV II PC (LDV)	LDGV	0.373	0.232	0.588	0.489	0.445	0.267
LEV III/LEV II LT1&2	LDGT1	0.375	0.230	0.641	0.552	0.430	0.275
LEV III/LEV II LT3	LDGT2	0.365	0.229	0.624	0.530	0.425	0.281

Also included as part of Tier 3, EPA has proposed to lower gasoline sulfur content to 10 ppm on an annual average basis, down from the current level of 30 ppm. We adopted the approach developed for a study for the American Petroleum Institute[3] in which the California Predictive Model was used to estimate emissions reductions resulting from reducing sulfur content by 2/3. The reductions vary geographically and by SCC, but overall the NO_x from gasoline vehicles operating on lower sulfur fuel was reduced up to 12%, CO up to 2%, and HC exhaust up to 3%.

In California, the scaling factors to incorporate the LEV-III rule into the EMFAC2011 emission inventory were developed using methods similar to those described for the rest of the US in that the ARB tool was used to estimate effects of LEV-III relative to LEV-II.

2. Light-duty greenhouse gas (GHG) rulemaking beginning with 2017 models (49 CFR Parts 523, 531, 533. et al.).

Light-duty vehicles impacted by the GHG rule include five classes tracked in the 2030 base case on-road inventory—gasoline cars (LDGV), diesel cars (LDDV), gasoline truck classes (LDGT1 and LDGT2), and diesel light duty trucks (LDDT). EPA's Regulatory Impact Analysis (RIA) Table 5.4-1 provides estimated gasoline reduction by calendar year resulting from the GHG rule—for year 2030 the gasoline consumption was 18% smaller than the reference case without the GHG rule[4]. Due to an absence of information on diesel consumption, the same 18% reduction was assumed for light-duty diesel fuel to reduce baseline emissions of SO_2, $PM_{10}SO_4$, and $PM_{2.5}SO_4$ in the diesel-fueled light-duty vehicles. The 18% reduction was applied only to affected model years (2017-2030). Aside from the fuel-sulfur effects, this rule only affects upstream emissions.

3. Heavy-duty GHG rulemaking beginning with 2014 models (40 CFR Parts 85, 86, 1036, et al. and 49 CFR Parts 523 and 535).

   Heavy-duty vehicles impacted by the GHG rule include six classes tracked in the on-road inventory: heavy-duty gasoline vehicles (HDGV) and five categories of heavy-duty diesel (HDDV): HDDV2B, HDDV345, HDDV67, HDDV8, and diesel buses (HDDB). EPA's RIA Table 5-13 lists on-road emissions in year 2030 for a reference and control case representing the downstream heavy-duty vehicle sector emissions without and with the GHG rule. Those emissions are transcribed below into Table S3 with an additional column added to show the calculated percent change in emissions by pollutant.

Table S3. Heavy-duty vehicle emissions in year 2030 for reference and control scenarios[5] and percent change in emissions due to the heavy-duty GHG rule.

Pollutant	Reference (tpy)	Control (tpy)	Percent Change
VOC	133,377	108,112	-18.9%
CO	2,646,583	2,594,341	-2.0%
NO_X	1,068,212	832,813	-22.0%
$PM_{2.5}$	20,743	22,503	8.5%
SO_2	4,852	4,424	-8.8%

Adjustments to Account for Cold-temperature PM Exhaust

On-road PM exhaust emission factors were generated in MOVES runs separately from other pollutants, with the ambient temperature set to a flat value of 72°F to prevent the cold-temperature PM adjustments that MOVES applies. The temperature adjustments were instead applied using higher resolution meteorological data in a calculation step after the emissions processing and prior to input to the air quality model. PM emissions increase exponentially with temperature below 72F, and ambient temperatures specific to the modeling episode by grid cell and hour of day were used to determine the appropriate adjustment to PM exhaust from gasoline-fueled vehicles. The net effect of PM adjustments at the nationwide total level was an increase in national total $PM_{2.5}$ from 167 tons/day to 202 tons/day.

2030 Base Case Summary

The final Base Case on-road emission inventory and VMT is summarized in Table S4 by state, showing year 2030 average day emissions and activity.

Table S4. Annual average 2030 Base Case on-road criteria pollutant emissions and VMT by state, units of tons or miles per average day

State	VOC	CO	NO_X	PM_{10}	$PM_{2.5}$	SO_2	NH_3	VMT
AL	35.7	851.1	70.4	8.4	3.1	0.5	4.6	194,758,938
AR	24.0	538.7	51.2	4.6	1.8	0.3	2.5	102,342,770
AZ	42.4	714.2	82.0	10.5	4.0	0.6	5.0	203,644,015
CA	174.0	1,461.0	290.7	78.5	35.8	5.0	29.7	1,200,801,308
CO	32.3	793.7	48.8	8.2	3.1	0.4	3.8	159,331,703
CT	19.2	421.7	33.8	5.8	2.2	0.2	2.5	103,542,099
DC	2.3	56.7	3.1	0.7	0.2	0.0	0.3	11,608,727
DE	5.3	136.8	10.1	1.6	0.6	0.1	0.7	28,726,781
FL	131.8	2,438.3	183.0	31.0	10.9	1.7	15.5	645,921,819
GA	60.8	1,489.3	121.1	15.8	5.9	0.8	7.8	318,028,423
IA	19.6	613.9	38.1	5.2	2.1	0.3	2.4	101,544,084
ID	11.2	334.3	23.3	2.6	1.0	0.1	1.2	47,196,890
IL	72.5	1,940.5	145.7	21.1	8.1	0.9	8.4	334,590,513
IN	47.9	1,347.8	113.4	12.4	4.8	0.6	5.7	235,450,017
KS	18.1	504.6	33.4	4.5	1.7	0.2	2.3	96,052,580
KY	30.0	690.7	68.6	7.2	2.8	0.4	3.7	154,574,737
LA	29.9	617.6	61.8	6.3	2.4	0.4	3.6	148,988,434
MA	27.9	835.8	52.9	9.9	3.8	0.4	4.3	179,746,303
MD	33.3	856.2	54.6	9.0	3.4	0.4	4.4	181,446,613
ME	9.8	306.3	17.5	2.6	1.1	0.1	1.1	45,128,647
MI	72.3	2,173.6	118.5	19.9	7.7	0.8	7.9	321,177,548
MN	40.7	1,389.8	68.3	12.0	4.8	0.5	4.5	185,817,963
MO	49.4	1,209.3	97.8	11.4	4.4	0.6	5.4	220,166,675
MS	23.5	583.0	52.1	5.5	2.1	0.4	3.4	148,778,468
MT	6.9	209.1	16.6	1.8	0.7	0.1	0.9	35,754,966
NC	66.6	1,735.0	117.2	16.2	6.1	0.8	8.0	325,590,191
ND	5.1	166.1	10.1	1.4	0.5	0.1	0.6	25,849,667
NE	12.0	377.6	23.9	3.4	1.4	0.2	1.5	62,808,726
NH	7.2	229.2	12.4	2.3	0.9	0.1	1.0	42,546,300
NJ	39.8	1,103.2	58.3	12.2	4.5	0.5	5.7	238,846,469
NM	19.1	378.2	39.8	4.1	1.6	0.2	2.1	86,460,162
NV	18.6	238.7	22.0	3.0	1.1	0.2	1.7	69,995,542
NY	72.2	2,287.1	120.6	22.4	8.4	0.9	10.3	430,429,180
OH	65.7	2,110.6	133.0	18.5	7.2	0.9	8.7	361,612,276
OK	32.1	734.9	58.2	7.4	2.8	0.4	3.8	159,463,696
OR	21.7	630.3	43.4	5.5	2.1	0.3	2.6	108,612,332
PA	108.1	1,991.6	119.1	18.5	7.2	0.9	8.8	358,636,848
RI	7.0	128.8	6.9	1.4	0.5	0.1	0.7	27,334,030
SC	33.0	774.9	62.0	7.3	2.7	0.4	3.8	156,373,234
SD	5.7	182.0	11.5	1.5	0.6	0.1	0.7	29,724,827
TN	45.4	1,075.9	87.9	10.9	4.2	0.6	5.4	218,137,867
TX	125.2	2,780.1	321.8	38.6	14.8	2.2	20.2	851,113,808
UT	19.2	476.9	31.8	4.7	1.8	0.2	2.0	83,117,777
VA	53.7	1,338.2	92.3	12.6	4.7	0.6	6.3	257,693,753
VT	4.5	147.3	6.3	1.1	0.4	0.1	0.6	25,129,191
WA	34.0	998.2	65.8	9.9	3.8	0.5	4.4	181,683,524
WI	39.7	1,181.9	58.9	10.3	4.1	0.4	4.4	182,342,205
WV	13.8	424.4	25.4	2.9	1.2	0.2	1.6	66,175,767
WY	6.5	193.3	15.2	1.6	0.7	0.1	0.8	31,260,223
Total	**1,876.7**	**44,198.4**	**3,400.6**	**514.0**	**202.0**	**26.8**	**237.3**	**9,786,058,616**

On-road Electrification Case Emissions

Electric Vehicle Market Penetration

For each electrified vehicle type, the analysis included several different vehicle powertrain types including conventional vehicle (CV), HEV, PHEV, and BEV. The PEVs were further classified into sub-types according to all-electric range (AER), the distance an individual vehicle can travel on electricity after a full recharge. For 'blended' PHEVs this is the equivalent distance that a non-blended PHEV could drive on electric power. This report identifies the AER of PHEVs and BEVs by appending the AER in miles to the 'PHEV' or 'BEV' descriptor. For example, a PHEV 20 is a plug-in hybrid with 20 miles of electric range. The study team chose to consider PHEV 20, PHEV 40, and PHEV 60 configurations, and a single BEV type with a 100 mile range.

Figure S1 shows how the new PEV sales are distributed across the various PEV types over the study period. Through the middle of 2013 the ratios are based on actual data, then the allocation over time shifts towards longer AERs based on the assumption that as battery costs decrease the PEV market will shift toward vehicles with greater electric utility. By 2030, the allocation of new PEV sales is 25% PHEV 40, 25% PHEV 60, and 50% BEV 100.

This study assumes that the vehicle types with internal combustion engines (all types except BEV) are fueled by either gasoline or diesel, so this analysis does not explicitly consider alternative fuels such as biofuels, natural gas or hydrogen.

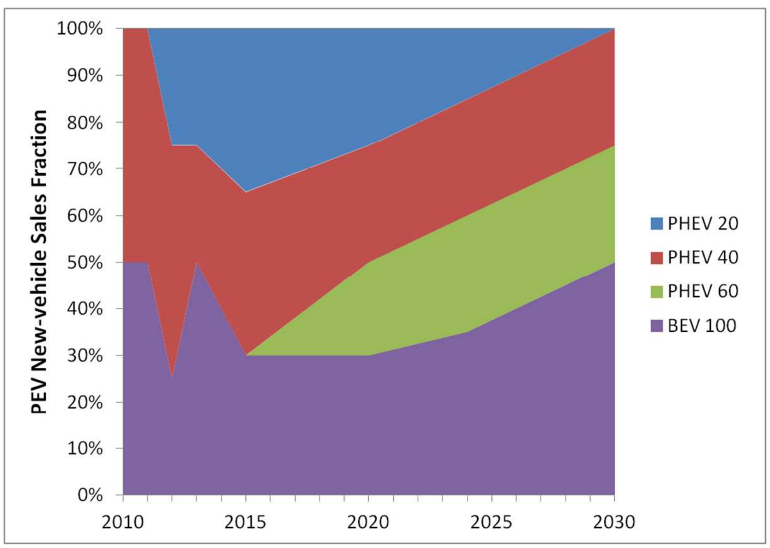

Figure S1. Distribution of new PEV sales among various PEV types.

A high-electrification scenario from the National Academy of Sciences Transitions to Alternative Fuels report[6] was selected to represent PEV adoption. The PEV type split from Figure S1 was applied to the PEV market share to create the new vehicle market share projection, shown in Figure S2.

The market share projection illustrated in Figure S2 was applied to the vehicle categories that were considered for PEV adoption. The other vehicle categories have zero PEV sales; therefore, the PEV market share for the entire on-road vehicle fleet is less than the levels indicated in Figure S2.

Although the National Academy of Sciences study was focused on light-duty vehicles, the same market share was applied to all electrifiable vehicle categories.

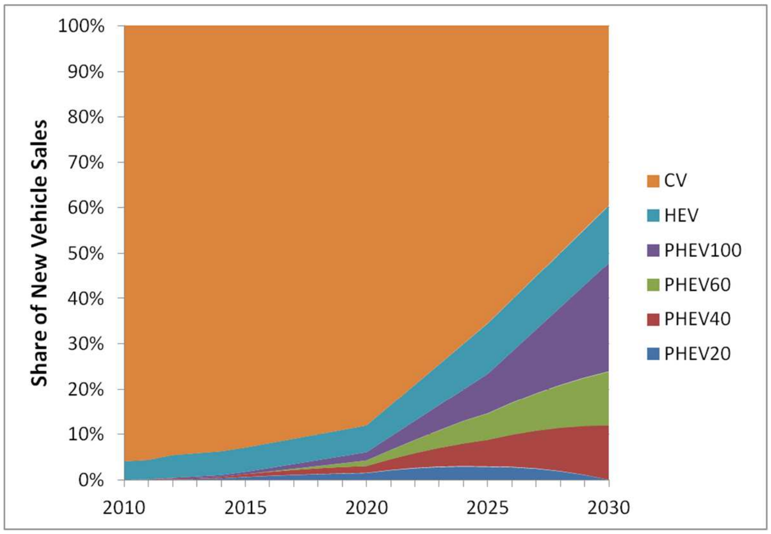

Figure S2. Distribution of new vehicle sales among various types, for vehicle categories that include PEV sales.

Vehicle Energy Economy in Electric Mode

PEV energy economy assumptions are based upon projections in AEO2013 for various light-duty vehicle types through 2025, with continued improvement at 0.5% per year beyond 2025. For simplicity, this study assumes that various PEV types (BEVs and PHEVs of different electric ranges) have the same electricity consumption per mile. However, this analysis assumes that diesel-fueled PHEVs have slightly higher electricity consumption than gasoline PHEVs when operating as electric vehicles, based on the fact that a diesel hybrid powertrain would typically weigh more than a gasoline powertrain.

There is very limited data available on the electricity consumption of heavy-duty PEVs. The study team developed a projection methodology based on the HEV fuel economy (mpg) for the corresponding vehicle category multiplied by an appropriate energy efficiency ratio.

PEV Utility Factor

The utility factors are based on EPRI estimates assuming that charging is available at the driver's home and work locations at a charge rate of 6.6 kW. While the evaluation of BEV utility factors is more complex than for PHEVs, this study makes a simplifying assumption that the BEV utility factor is equal to that of a PHEV100. This simple but conservative estimate assumes that long trips that cannot be completed with the BEV are instead driven using a substitute conventional vehicle. Utility factors for PHEV20, PHEV40, PHEV60, and BEV100 are 56%, 73%, 80%, and 87%, respectively.

PEV Petroleum and Electricity Consumption

The EPRI PEV market analysis tool uses a cohort model that tracks vehicles as they age over time, which accounts for changes in vehicle performance as the market evolves. The VMT and energy consumption assumptions, which vary by vehicle type, category, model year, and age, are based on data equivalent to that used in MOVES for the air quality modeling.

Figure S3 presents the PEV electricity consumption over the study period. The "Other Bus and Truck" group includes three vehicle categories: Transit Bus, School Bus, and Refuse Truck. These categories, along with Motorcycles, comprise a very small portion of the overall electricity consumption. Since the Passenger Car and Passenger Truck categories account for a majority of the total VMT within the categories considered for electrification, those two categories dominate the PEV electricity use. In 2030, the total PEV electricity use is 176 TWh.

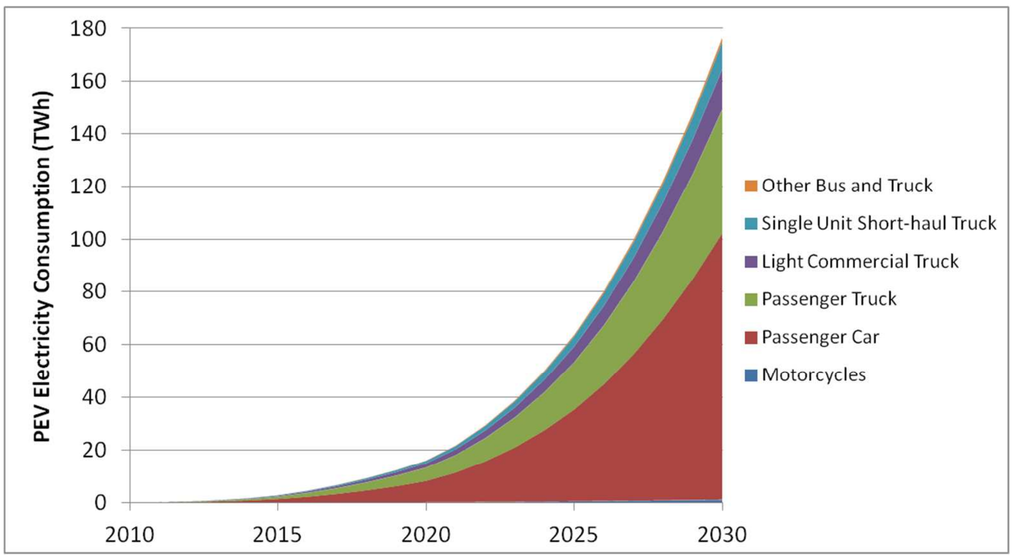

Figure S3. PEV electricity consumption

2030 Electrification Case Emissions Development

Electric vehicles in this scenario include a mix of plug-in hybrids (PHEV) and battery electric vehicles (BEV). Estimates of electric vehicle penetration of the vehicle fleet for each model year (2010 to 2030) as described above affect the electrified vehicle classes according to the phase-in schedule shown in Figure S4. The affected vehicle classes, categorized by MOVES source types, include *passenger car*, *passenger truck*, *light commercial truck*, *motorcycle*, *refuse truck*, *single unit short-haul truck*, *school bus*, and *transit bus*. Single unit long-haul trucks, motor homes, intercity buses, and combination unit trucks (short- and long-haul) are assumed to operate entirely on conventional fuel in 2030 (no electrification). The vehicle classes that are impacted by electrification have increasing amounts of activity share (VMT and population) in the on-road fleet each year beginning with 2010. Table S5 summarizes the emissions reduction assumptions. The resulting state level emissions from the 2030 Electrification Case are reported in Table S6.

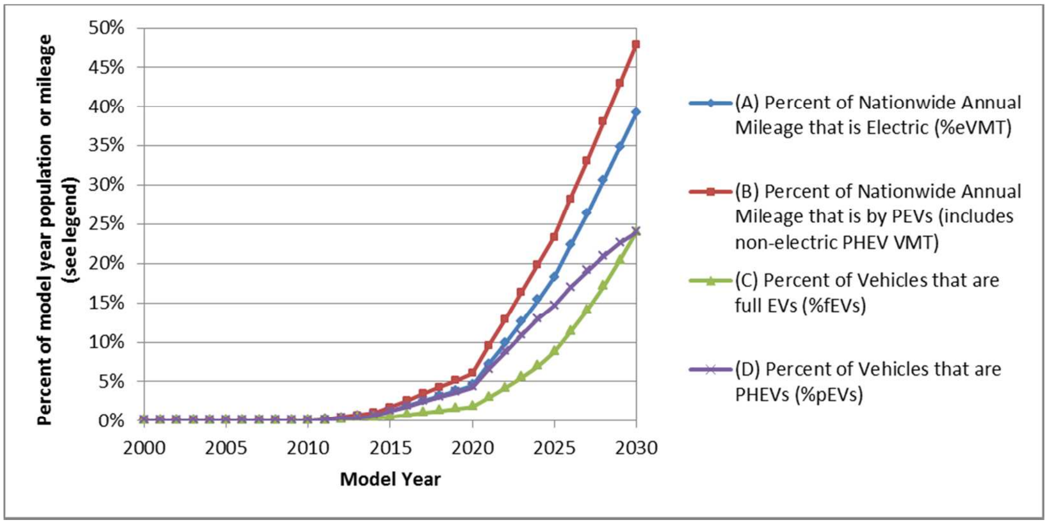

Figure S4. Electric vehicle activity phase-in by model year from 2000 to 2030

Table S5. Emissions reduction assumptions for electric vehicles.

Emissions Process	Activity Source Used for Emissions Reductions	Emissions Reduction Assumptions
Running Exhaust	(A) Percent of nationwide annual mileage that is electric (%eVMT)	Running exhaust emission reductions equivalent to electric vehicle mileage fraction
Start Exhaust	(C) Percent of vehicles that are full EVs (%fEVs)	No start emissions for full EVs
	(D) Percent of vehicles that are PHEVs (%PHEVs)	PHEV start emissions are reduced by 80% compared to conventional vehicle start emissions
Evaporative	(C) Percent of vehicles that are full EVs (%fEVs)	No evaporative emissions from full EVs. PHEV evaporative emissions are similar to conventional vehicle evaporative emissions
Brake Wear	(B) Mileage that is by plug-in electric vehicles ('plug-in electric vehicles' includes fully electric vehicles and PHEVs). This activity includes non-electric PHEV VMT.	Full EV and PHEV emissions reduced by 25%.
Tire Wear	Assume no change	

Table S6. Annual average 2030 Electrification Case on-road criteria pollutant emissions and VMT by state, units of tons or miles per average day.

State	VOC	CO	NO_X	PM_{10}	$PM_{2.5}$	SO_2	NH_3	VMT
AL	33.7	771.8	65.4	7.9	2.9	0.4	4.0	194,758,938
AR	22.6	489.9	47.6	4.3	1.6	0.2	2.2	102,342,770
AZ	40.2	649.8	76.4	9.9	3.7	0.5	4.3	203,644,015
CA	164.2	1,309.5	272.7	75.3	34.1	4.3	25.4	1,200,801,308
CO	30.5	718.5	45.2	7.6	2.9	0.3	3.2	159,331,703
CT	18.2	382.2	31.4	5.4	2.1	0.2	2.1	103,542,099
DC	2.1	51.6	2.9	0.6	0.2	0.0	0.2	11,608,727

State	VOC	CO	NO_X	PM_{10}	$PM_{2.5}$	SO_2	NH_3	VMT
DE	5.0	124.2	9.4	1.5	0.6	0.1	0.6	28,726,781
FL	124.4	2,213.0	169.9	29.4	10.3	1.4	13.2	645,921,819
GA	57.9	1,357.9	112.8	14.9	5.5	0.7	6.7	318,028,423
IA	18.5	556.3	35.5	4.8	1.9	0.2	2.1	101,544,084
ID	10.6	303.5	21.3	2.4	0.9	0.1	1.0	47,196,890
IL	68.8	1,765.3	135.4	19.6	7.5	0.8	7.2	334,590,513
IN	45.2	1,221.9	105.7	11.6	4.5	0.5	4.9	235,450,017
KS	17.1	457.6	31.0	4.2	1.6	0.2	1.9	96,052,580
KY	28.3	626.5	63.9	6.7	2.6	0.3	3.2	154,574,737
LA	28.2	560.7	57.6	6.0	2.2	0.3	3.1	148,988,434
MA	26.5	757.0	49.1	9.2	3.5	0.4	3.7	179,746,303
MD	31.5	776.7	50.6	8.4	3.2	0.4	3.7	181,446,613
ME	9.3	278.5	16.2	2.4	1.0	0.1	0.9	45,128,647
MI	68.1	1,969.7	109.8	18.6	7.2	0.7	6.7	321,177,548
MN	38.5	1,260.6	63.3	11.0	4.4	0.4	3.9	185,817,963
MO	46.6	1,098.3	90.8	10.7	4.1	0.5	4.7	220,166,675
MS	22.1	526.9	48.4	5.2	2.0	0.3	2.9	148,778,468
MT	6.5	189.6	15.5	1.6	0.7	0.1	0.7	35,754,966
NC	63.0	1,578.3	108.7	15.2	5.7	0.7	6.9	325,590,191
ND	4.8	150.5	9.4	1.3	0.5	0.1	0.5	25,849,667
NE	11.3	342.0	22.2	3.2	1.3	0.1	1.3	62,808,726
NH	6.8	207.6	11.5	2.1	0.8	0.1	0.9	42,546,300
NJ	37.7	1,000.9	53.9	11.4	4.2	0.4	4.8	238,846,469
NM	18.0	343.1	37.2	3.8	1.5	0.2	1.8	86,460,162
NV	17.4	216.0	20.3	2.8	1.0	0.1	1.4	69,995,542
NY	68.5	2,074.9	111.0	20.8	7.8	0.7	8.8	430,429,180
OH	62.2	1,912.3	123.6	17.3	6.6	0.7	7.4	361,612,276
OK	30.3	666.8	54.1	6.9	2.6	0.3	3.3	159,463,696
OR	20.5	572.0	40.3	5.1	2.0	0.2	2.3	108,612,332
PA	99.6	1,776.0	109.3	17.1	6.6	0.7	7.5	358,636,848
RI	6.5	115.4	6.3	1.3	0.5	0.0	0.6	27,334,030
SC	31.2	703.6	57.5	6.9	2.6	0.4	3.3	156,373,234
SD	5.4	164.9	10.7	1.4	0.6	0.1	0.6	29,724,827
TN	42.9	977.9	81.8	10.3	3.9	0.5	4.6	218,137,867
TX	119.2	2,529.5	301.3	36.6	13.9	1.9	17.4	851,113,808
UT	18.2	433.6	29.4	4.4	1.7	0.2	1.8	83,117,777
VA	50.9	1,217.7	85.7	11.8	4.4	0.5	5.4	257,693,753
VT	4.2	131.8	5.7	1.0	0.4	0.0	0.5	25,129,191
WA	32.1	903.6	60.9	9.2	3.5	0.4	3.8	181,683,524
WI	37.5	1,072.4	54.6	9.5	3.7	0.4	3.8	182,342,205
WV	13.1	384.8	23.5	2.7	1.1	0.1	1.4	66,175,767
WY	6.1	175.2	14.2	1.5	0.6	0.1	0.7	31,260,223
Total	**1,772.3**	**40,067.9**	**3,160.8**	**482.7**	**188.2**	**22.6**	**202.9**	**9,786,058,616**

1.2 Off-road Sector

Off-road Base Case Emissions

NONROAD Equipment

EPA's National Mobile Inventory 2008 Model (NMIM)[7] runs the EPA NONROAD2008a model using area-specific inputs for all US counties. The NMIM-NONROAD platform was used to generate the 2030 national off-road equipment inventory. NMIM was run for each county in the US for 2030 for both a winter (January) and a summer (July) month. We utilized the Western Regional Air Partnership (WRAP) 2018 PRP18b emission inventory as the basis for the California criteria air pollutant emissions and forecasted these emissions to 2030 based on ARB OFFROAD2007 model runs for 2018 and 2030.

Cargo Handling Equipment

The approach taken to estimate cargo handling equipment emissions was to develop average emission estimates on a unit of activity basis, twenty foot equivalent unit (TEUs) in the case of ports and lifts in the case of rail yards. The average emissions per unit of activity were extrapolated to the regional and national level based on publicly available datasets.

Ports

Calendar year 2005 cargo handling equipment emission inventories by equipment type available for the Port of Los Angeles[8] and the Port of Long Beach[9] were used to estimate per TEU emissions by equipment type for all ports. Port cargo handling equipment emissions by equipment type were allocated to the county level in the US based on the fraction of container traffic TEUs by port[10].

Rail

Cargo handling equipment emissions per lift by equipment type for all US rail yards were estimated using data from various sources[10-15]. Total lift counts were obtained from the Association of American Railroads US rail intermodal traffic statistics. Rail yard cargo handling equipment emissions by equipment type were allocated to the county level based on facility count[16].

Growth and Control

The TEUs for ports and lifts for rail yards were grown at the rate of 4.9% per year following EPA's assumption of a long term container traffic growth[17]. Nationwide average fuel properties[18] were used to conduct EPA NONROAD model runs for the calendar year 2005 and 2030. The percentage changes in emissions from calendar year 2005 to 2030 were estimated by equipment type and pollutant.

Aircraft

Aircraft emissions were forecasted to 2030 from 2008 aircraft emissions developed by the EPA for the 2008 National Emissions Inventory (NEI). Activity data for aircraft emissions are landing-takeoff cycles (LTOs); emission factors are primarily from the Federal Aviation Administration (FAA) Emissions and Dispersion Modeling System (EDMS).

The International Civil Aviation Organization (ICAO) has promulgated NO_x and CO emission standards for commercial aircraft (exempting general aviation and military engines from the rule)[19]. EPA officially promulgated the ICAO standards for air carriers in a final rule in November 2005 (40 CFR Part 87). NO_x may be reduced by introducing engines fitted with double annular combustion chambers, resulting in reduction of NO_x, HC, and CO emissions[20]. Changes to VOC emissions are assumed to equal the changes in HC emissions on a percent reduction basis. Mean 2030 control factors relative to the 2008 NEI were assumed to be equal to those projected by the European *Monitoring and Evaluation Programme* (EMEP) in 2020.

Locomotive

2030 locomotive emissions were available on a nationwide basis in the EPA 2008 Regulatory Impact Analysis (RIA). The RIA forecasted national emissions were allocated to counties using the 2005 NEI emission as surrogates.

Commercial Marine

EPA datasets were relied upon to generate 2030 harbor craft emission estimates. The 2008 NEI provides emissions for harbor craft on a by county basis and the RIA estimated nationwide future harbor craft emissions for calendar years 2006 to 2040. The RIA forecasted national emissions for 2030 were allocated to counties using the 2008 NEI emissions as surrogates.

Ocean going vessel emission estimates were taken from the EPA PM National Ambient Air Quality Standard (NAAQS) modeling platform. Modeling platform 2020 emissions were used to represent 2030 emissions.

Crude oil transport was assumed to be reduced due to the EPA light duty and heavy duty greenhouse gas rulemakings and due to electrification. It was assumed that reductions in petroleum transport of 12.5% would result in reductions in OGV emissions of 2.5% for the Base Case relative to PM NAAQS modeling platform estimates.

2030 Base Case Emission Summary

Emissions by major source category are presented in Table S7.

Table S7. 2030 lower-48 state off-road emissions by major source category (tons per year).

Category	VOC	CO	NO_x	PM_{10}	$PM_{2.5}$	SO_2
Agricultural Equipment	20,714	187,113	113,962	5,354	5,175	274
Airport Ground Support Equipment	746	15,649	2,620	66	59	9
Commercial Equipment	106,075	3,021,781	71,636	5,857	5,399	283
Construction and Mining Equipment	52,047	431,460	173,091	8,605	8,173	503
Industrial Equipment	14,420	373,817	104,402	3,259	3,203	469
Lawn and Garden Equipment	446,690	6,522,730	71,606	27,551	25,304	406
Logging Equipment	9,843	81,916	1,627	1,215	1,113	11
Pleasure Craft	245,528	2,020,082	159,889	13,807	10,924	466
Railroad Equipment	247	3,838	955	90	88	2
Recreational Equipment	544,854	2,233,635	52,320	14,757	13,507	686
Underground Mining Equipment	506	2,238	3,016	257	249	3
Aircraft	65,151	705,898	117,353	15,145	11,294	14,866
Cargo Handling Equipment	516	1,485	4,073	65	63	1

Harbor Craft	6,696	139,314	299,005	10,006	9,705	3,471
Ocean-Going Vessels[a]	44,095	116,988	923,175	18,044	16,553	59,421
Rail	17,658	195,388	436,939	8,834	8,583	463
Totals	**1,575,786**	**16,053,332**	**2,535,669**	**132,912**	**119,392**	**81,334**

[a] modeling domain-wide totals

Electrification Case

Electrification Potential

It was assumed that the highest electric market share for new equipment sales in 2030 would be 80% and that this would only be achieved by equipment that was already subject to widespread electrification or for which there are very few impediments to electrification. For equipment with few impediments to electrification, but with lesser current electrification, it was generally assumed that 60% of equipment sales would be electric by 2030. For equipment with significant impediments to electrification, electric sales less than 60% in 2030 were assumed. ATVs, off-road motorcycles, and switching locomotives were all assumed to have electrical sales fractions less than 60%. For ATVs and off-road motorcycles, it was assumed that lack of charging during remote use would slow adoption of electric units. Figure S5 shows electric sales fractions for lawn and garden (L&G) and recreational equipment and Figure S6 shows electric sales fractions for industrial equipment.

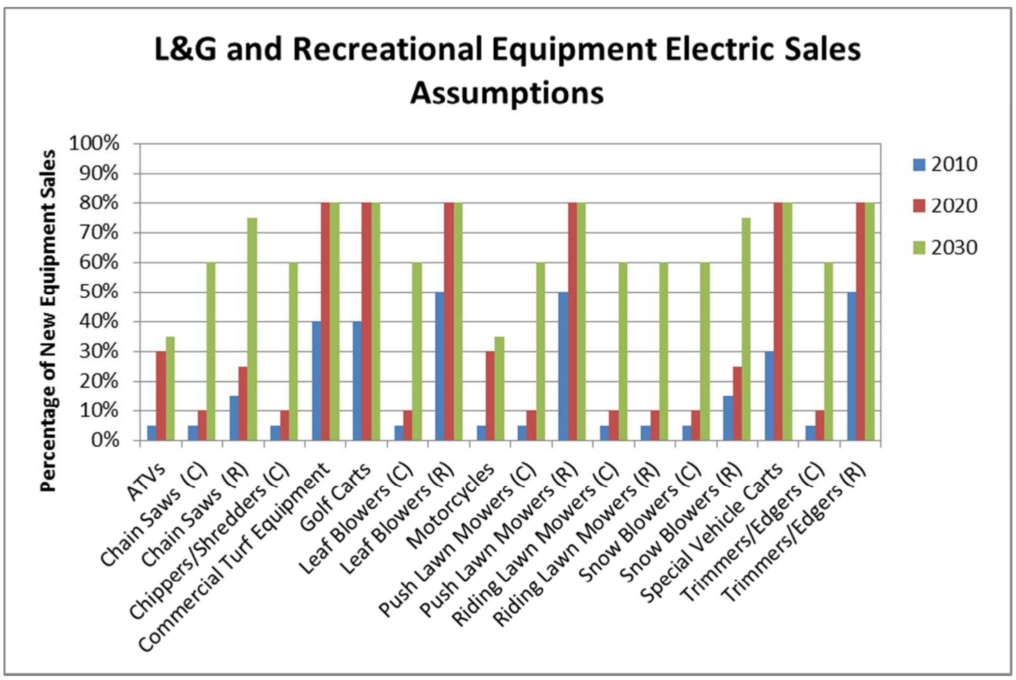

Figure S5. Lawn and garden (L&G) and recreational equipment new unit electrical sales fractions for 2010, 2020, and 2030. (C) denotes commercial use equipment and (R) denotes residential use equipment.

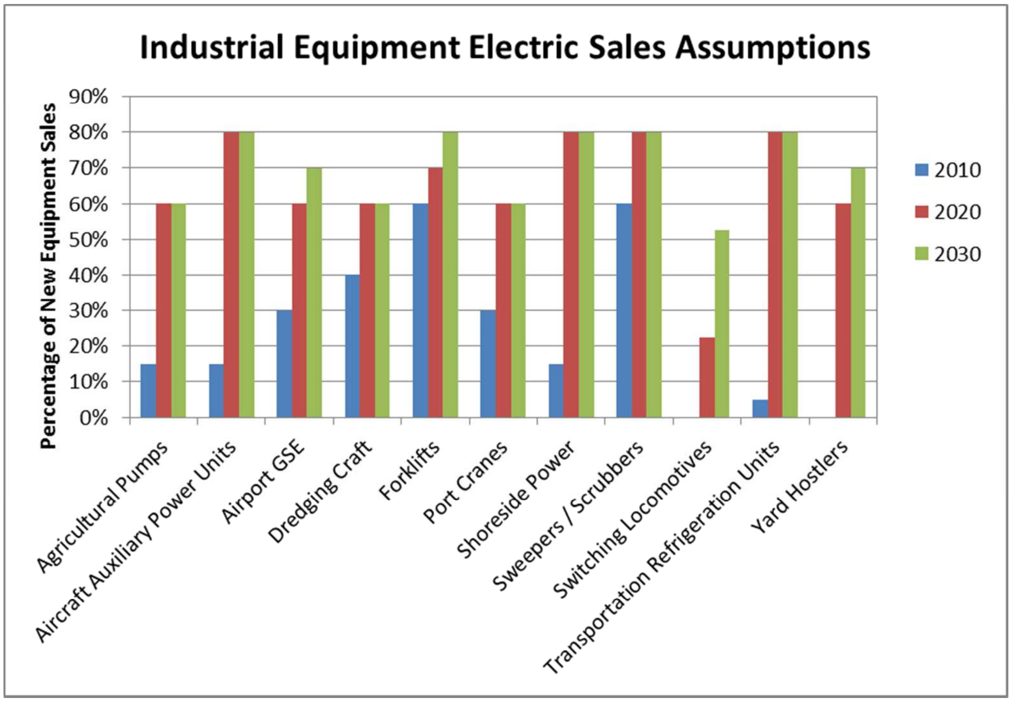

Figure S6. Industrial equipment new unit electrical sales fractions for 2010, 2020, and 2030.

Off-road Equipment Electricity Consumption

The same models and calculation methods that were used to calculate Base Case emissions were used to calculate electrified off-road equipment electricity consumption. The power usage of a piece of off-road equipment can be estimated by combining its rated horsepower, load factor, and average annual hours of use. It was assumed that electrified off-road equipment would have the same output power as the fossil-fueled equipment being replaced. Table S8 presents the electricity consumption for each equipment category. In 2030, the total additional off-road equipment electricity consumption is 35.2 TWh.

Table S8. US 2030 off-road equipment electricity consumption by equipment type.

Equipment Type	2030 Annual Electricity Consumption (GWh)
Commercial Lawn and Garden Equipment	
Chain Saws	333
Chippers/Shredders	<1
Commercial Turf Equipment	2,662
Riding Mowers	954
Push Lawn mowers	488
Leaf Blowers	732
Snow Blowers	17
Trimmers/Edgers	202
Subtotal	***5,386***
Residential Lawn and Garden Equipment	
Chain Saws	73
Riding Mowers	1,587
Push Lawn mowers	783
Leaf Blowers	68

Equipment Type	2030 Annual Electricity Consumption (GWh)
Snow Blowers	11
Trimmers/Edgers	114
Subtotal	***2,636***
Recreational Equipment	
All Terrain Vehicles	732
Golf Carts	460
Motorcycles: Off-Road	337
Specialty Vehicle Carts	133
Subtotal	***1,662***
Industrial Equipment	
Agricultural Pumps	522
Aircraft Auxiliary Power Units	104
Airport Ground Support Equipment	547
Forklifts	11,234
Harbor Craft (Dredging)	1,350
Intermodal Cranes and Side/Top Picks	282
Intermodal Yard Trucks	1,198
Ocean Going Vessel (Shoreside Power)	5,719
Sweepers / Scrubbers	15
Switching Locomotives	612
Transportation Refrigeration Units	3,977
Subtotal	***25,559***
Grand Total	**35,243**

Off-road Electrification Case Emissions

The emissions reduction estimates by equipment type shown in Table S9. Table S10 shows emission reductions for the Electrification Case.

Table S9. Percent reduction in 2030 emissions due to electrification.

Airport, Aircraft, Agricultural, Industrial. Marine, Rail		Recreational and Lawn and Garden (continued)	
Agricultural Pumps	48%	Chippers/Shredders (C)	26%
Aircraft Auxiliary Power Units	65%	Commercial Turf Equipment	67%
Airport GSE	48%	Golf Carts	67%
Dredging Craft	33%	Leaf Blowers (C)	52%
Forklifts	40%	Leaf Blowers (R)	60%
Port Cranes	40%	Motorcycles	27%
Shoreside Power	65%	Push Lawn Mowers (C)	53%
Sweepers / Scrubbers	49%	Push Lawn Mowers (R)	60%
Switching Locomotives	17%	Riding Lawn Mowers (C)	47%
Transportation Refrigeration Units	39%	Riding Lawn Mowers (R)	42%
Yard Hostlers	67%	Snow Blowers (C)	46%
Recreational and Lawn and Garden		Snow Blowers (R)	58%
ATVs	26%	Special Vehicle Carts	64%
Chain Saws (C)	57%	Trimmers/Edgers (C)	52%
Chain Saws (R)	58%	Trimmers/Edgers (R)	60%

Table S10. 2030 US lower-48 State Electrification Case emissions by source category.

	VOC		CO		NO_x		PM_{10}		$PM_{2.5}$		SO_2	
Major Subcategory	**tpy**	**(%)**	**tpy**	**(%)**	**tpy**	**(%)**	**tpy**	**(%)**	**tpy**	**(%)**	**tpy**	**(%)**
Agricultural Equipment	-136	(-1%)	-1,195	(-1%)	-466	(0%)	-19	(0%)	-18	(0%)	-2	(-1%)
Airport Ground Support Equipment	-210	(-28%)	-6,664	(-43%)	-757	(-29%)	-14	(-22%)	-12	(-20%)	-2	(-21%)
Commercial Equipment	0	(0%)	0	(0%)	0	(0%)	0	(0%)	0	(0%)	0	(0%)
Construction and Mining Equipment	0	(0%)	0	(0%)	0	(0%)	0	(0%)	0	(0%)	0	(0%)
Industrial Equipment	-3,749	(-26%)	-109,779	(-29%)	-34,861	(-33%)	-1,094	(-34%)	-1,079	(-34%)	-161	(-34%)
Lawn and Garden Equipment	-190,011	(-43%)	-2,926,110	(-45%)	-24,591	(-34%)	-13,588	(-49%)	-12,466	(-49%)	-174	(-43%)
Logging Equipment	0	(0%)	0	(0%)	0	(0%)	0	(0%)	0	(0%)	0	(0%)
Pleasure Craft	0	(0%)	0	(0%)	0	(0%)	0	(0%)	0	(0%)	0	(0%)
Railroad Equipment	0	(0%)	0	(0%)	0	(0%)	0	(0%)	0	(0%)	0	(0%)
Recreational Equipment	-74,577	(-14%)	-547,155	(-24%)	-5,307	(-10%)	-1,774	(-12%)	-1,618	(-12%)	-141	(-21%)
Underground Mining Equipment	0	(0%)	0	(0%)	0	(0%)	0	(0%)	0	(0%)	0	(0%)
Aircraft Auxiliary Power Units	-283	(0%)	-3,664	(-1%)	-2,587	(-2%)	-412	(-3%)	-412	(-4%)	-401	(-3%)
Cargo Handling Equipment	-283	(-55%)	-807	(-54%)	-1,919	(-47%)	-29	(-44%)	-28	(-44%)	-1	(-53%)
Harbor Craft	-112	(-2%)	-2,322	(-2%)	-4,983	(-2%)	-167	(-2%)	-162	(-2%)	-58	(-2%)
Ocean-Going Vessels[a,b]	-1,497	-3%	-4,652	-4%	-32,760	-4%	-655	-4%	-609	-4%	-1,310	-2%
Rail	-571	(-3%)	-2,429	(-1%)	-10,412	(-2%)	-221	(-3%)	-215	(-3%)	-6	(-1%)
Grand Total	-271,429	(-17%)	-3,604,776	(-22%)	-118,645	(-5%)	-17,974	(-14%)	-16,619	(-14%)	-2,255	(-3%)

[a] modeling domain-wide totals
[b] Electrification Case OGV emissions incorporate reductions due to shoreside power and emission reductions based on reduced crude oil shipments

1.3 Electric Sector

U.S. Regional Economy, Greenhouse Gas, and Energy Model (US-REGEN)

US-REGEN combines a detailed dispatch and capacity expansion model of the United States electric sector with a high-level dynamic computable general equilibrium (CGE) model of the United States economy. It considers 15 sub-regions of the continental U.S. to account for differences in resource endowments, energy demand, costs, policies, and policy impacts. Figure S7 shows a map of the regions in the model. US-REGEN is an inter-temporal optimization model which solves in five-year time steps through 2050.

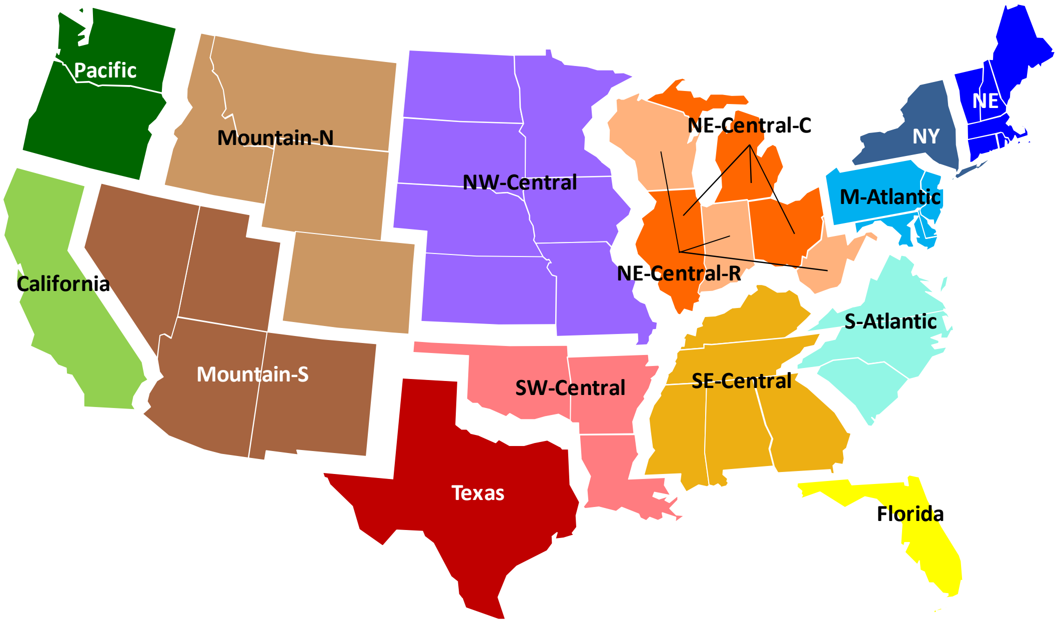

Figure S7. Regional structure of US-REGEN model Reprinted from US-REGEN Model Documentation: PRISM 2.0: Regional Energy and Economic Model Development and Initial Application. Electric Power Research Institute: Palo Alto, CA, September, 2013.[21] Copyright 2013 Electric Power Research Institute.

US-REGEN is built on economic data sourced from the IMPLAN database, energy data from the Energy Information Administration (EIA) of the U.S. Department of Energy, U.S. generation fleet data from Ventyx (now ABB Velocity Suite), and a variety of other sources providing economic growth, wind, solar, and biomass data. For this analysis, a Base Case was constructed using the REGEN baseline electricity assumptions and exogenously-supplied transportation assumptions, and an Electrification Case was constructed with increased on-road and non-road transportation electrification, which modified the transportation assumptions and added electrical load.

<u>Assumptions Used</u>

The model was calibrated to the AEO 2011 reference case for key variables – including gross domestic product (GDP), electricity demand, industrial growth, and most fuel prices. Gas price trends were taken from the AEO 2013 reference case. However, US-REGEN uses an independent set of assumptions on electric sector technologies which may differ significantly from the AEO.

In designing the scenarios for this analysis, assumptions on the technology options in the future were set as follows.

- All existing nuclear units received a license extension to 60 years, and 80% of those received a further license extension to 80 years.
- New nuclear units permitted with limited new build restrictions (7GW) before 2025.
- Carbon capture and storage technology available after 2020.

- Declining cost pathways for renewable capital costs, per the EPRI Generation Options Report and the judgment of EPRI's renewables staff.
- Biomass supply curves were generated from the FASOM model by US-REGEN region, as described in Appendix D of the US-REGEN Documentation.
- New biofueled units possible and existing coal units have the option of converting to biomass, or co-firing up to 10% biomass.
- Existing coal units can also convert to gas, retrofit with CCS technology, and retrofit with non-CO_2 pollutant controls as described below.
- New inter-regional transmission permitted at a cost of $3.84 million per mile constructed for a high-voltage line capable of carrying 7.2GW.
- Existing coal units retire at 70 years of age.

US-REGEN explicitly models four types of passenger transport vehicles – internal combustion, plug-in hybrid, all electric, and compressed natural gas vehicles. This requires an exogenously supplied trajectory for the evolution of the vehicle fleet, which for this analysis was supplied to the US-REGEN model for both the Base Case and Electrification Case by the on-road sector analysis described above.

Environmental Regulations

The scenarios were constructed to incorporate pending EPA regulations and other restrictions on pollutants. This included:

- Existing State Renewable Portfolio Standards as of 2012, including separate mandates for solar where applicable
- A full suite of non- CO_2 environmental control regulations, pending or expected by to be implemented by model year 2015. These cover the following five environmental pathways:

    1. New requirements and emissions limits for sulfur oxide pollutants (SO_x), under the Hazardous Air Pollutants Maximum Achievable Control Technology (HAPs MACT) regulations
    2. New requirements and emissions limits for nitrogen oxide pollutants (NO_x), again under HAPs MACT
    3. New requirements for the control of mercury and related heavy metal pollutants in stack emissions, also under HAPs MACT
    4. New protections for aquatic species impacted by cooling water intake structures, leading potentially to far more closed-loop cooling systems, as a part of Section 316 (b) of the Clean Water Act
    5. New, more restrictive classification of coal ash solid waste (coal combustion residuals, or CCRs) under relatively more elaborate and expensive disposal requirements across the fleet, through Subtitle D of the Resource Conservation and Recovery Act.

- An implementation of the Cross-State Air Pollution Rule, which was vacated at the time the model was run, but was expected to be reinstated (the Supreme Court has subsequently upheld the Rule, but additional decisions and rule promulgations will have to occur before the details of the Rule will be final).

- The EPA proposed New Source Performance Standards for new Fossil Fueled Generation. Specifically, this is assumed to prohibit the construction of new coal units without carbon capture and storage technology.

Note that the version of the model used in this analysis did not have an implementation of the California cap and trade scheme authorized under AB32, the New England 'RGGI' cap and trade market, or the EPA's Clean Power Plan.

Electrification Case Generation Scenario

Demand: Electricity demand forecasts in the Base Case were taken from the AEO 2011 reference case, and extended to 2050 based on the 2030-2035 demand growth rates. These forecasts include a modest penetration of electric vehicles in the AEO, however for this analysis, fuel use by vehicles and equipment in the Base Case and Electrification Case were supplied by the results of the modeling described above. The Electrification Case resulted in higher demand than the Base Case, 5.0% higher in 2030 due to the increased use of plug-in hybrid and all electric vehicles.

Load shape: There is a significant amount of uncertainty about when load from electrified vehicles will occur. Although there are grid-connected non-road vehicles in the total electrification demand, most of the load comes from battery charging, which has a high degree of time-flexibility relative to most loads due to the low average daily utilization of batteries and extended charging periods available. We reviewed a variety of potential load shapes, but finds that the variation in criteria emissions between different load shape scenarios is low. For this analysis, the 'Scaled' load shape was selected, which scales the default REGEN load shape and therefore proportionally distributes electrification load onto existing load. This load varies between regions and throughout the year, but has the average hourly load shape shown in Figure S8. This load shape contains a balance of on-peak and off-peak load, and is less likely to cause instability in the timing of emissions, which could cause the air quality results to change due to numerical characteristics of the model rather than due to characteristics of the changing load.

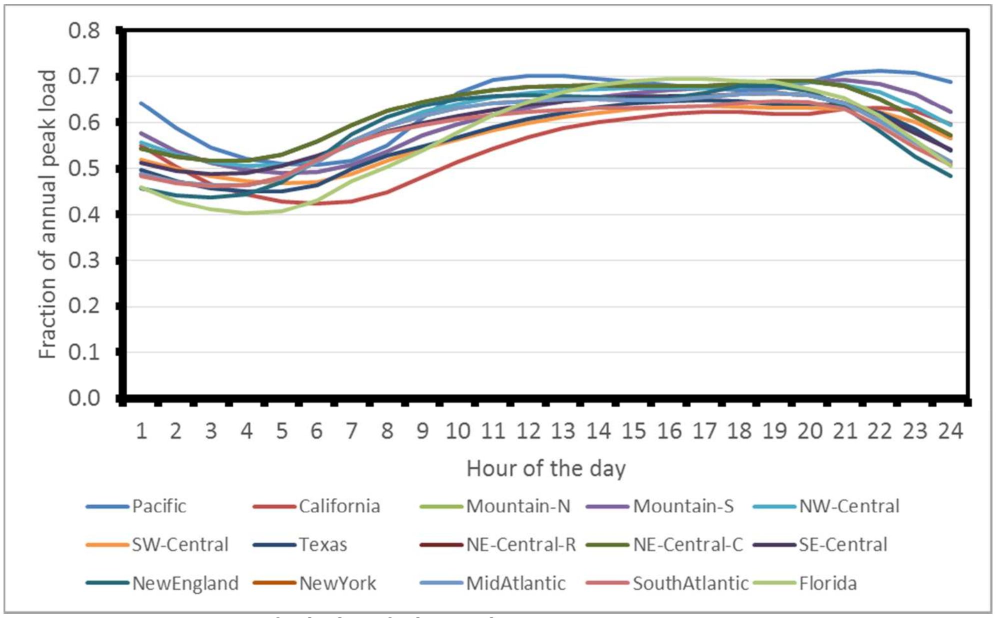

Figure S8. Average daily load shape by region.

<u>Generation and Capacity Mix</u>

Generation Mix: Figure S9 depicts the generation mix in the Base Case, and Figure S10 shows the generation mix for the Electrification Case. The Base Case assumes the AEO 2013 reference case gas price path, which reaches $5.4/MMBtu by 2030. The resulting economics favor new nuclear and renewables, to the detriment of the gas fleet. New solar is mostly rooftop PV, which is assumed to take the retail price. The additional Electrification Case envisages considerable load growth. New load is met through additional nuclear, renewables, and gas generation. The mix of new generation varies significantly across regions compared to the Base Case generation. The additional load in the Electrification Case is primarily met with new gas generation, but significant amounts of wind and solar generation occur in the West and Midwest. Since nuclear is constrained nationally, additional new nuclear in the South reduces new nuclear in the Midwest.

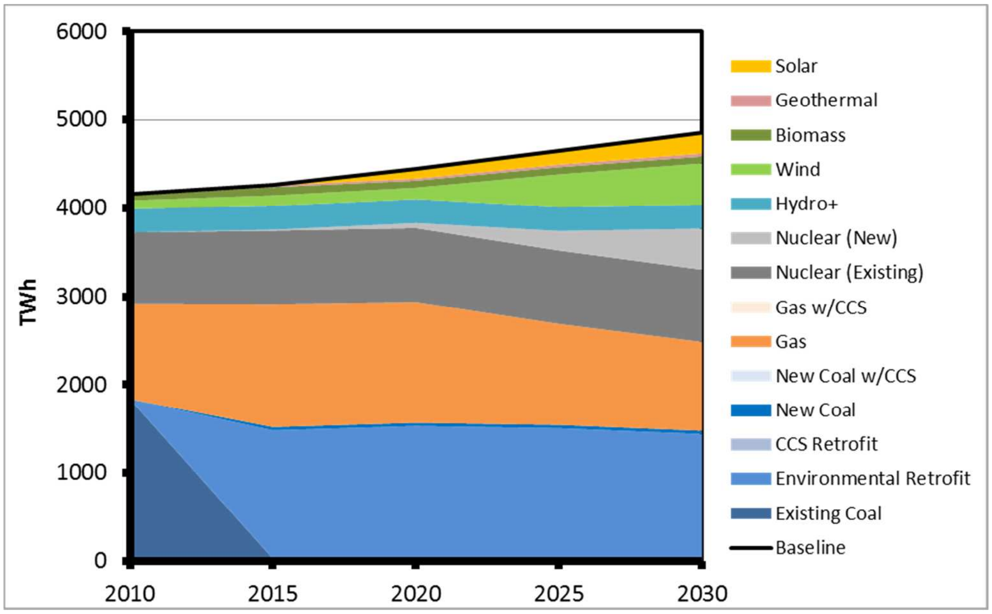

Figure S9. Generation mix in the Base Case.

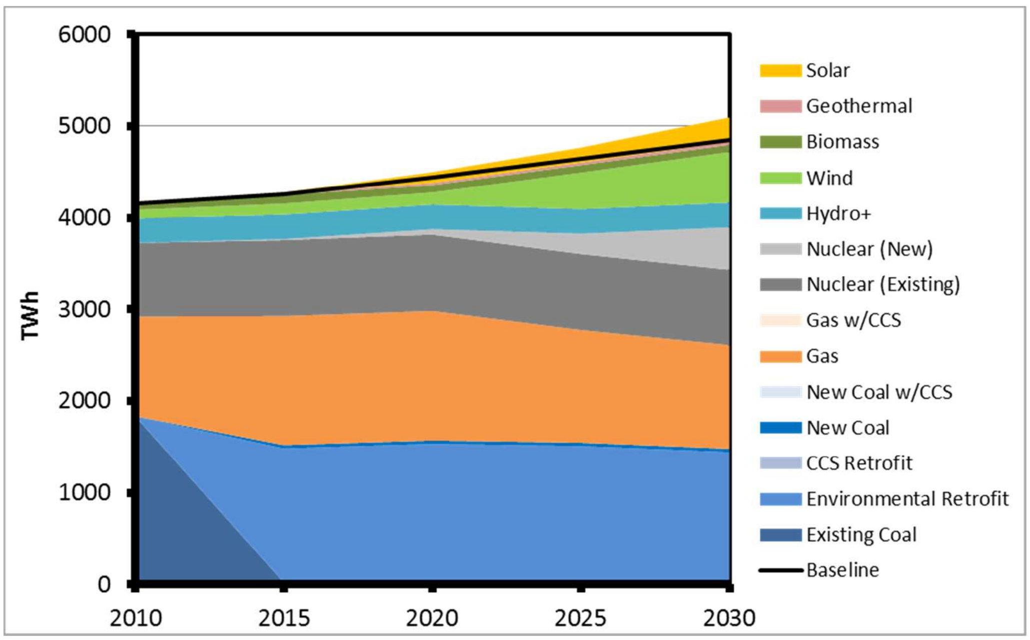

Figure S10. Generation in the Electrification Case.

Capacity Mix: Figure S11 and Figure S12 show the total national capacity for the Base Case and Electrification Case, respectively. Total rated capacity edges upwards in the Electrification Case. Wind and solar each gain 20GW of capacity, accompanied by 30GW of natural gas generation. Again this mix varies by region; the Wind and Solar are concentrated in the West and Midwest, New nuclear occurs in the South instead of the Midwest, and combined cycle natural gas generation increases in all regions.

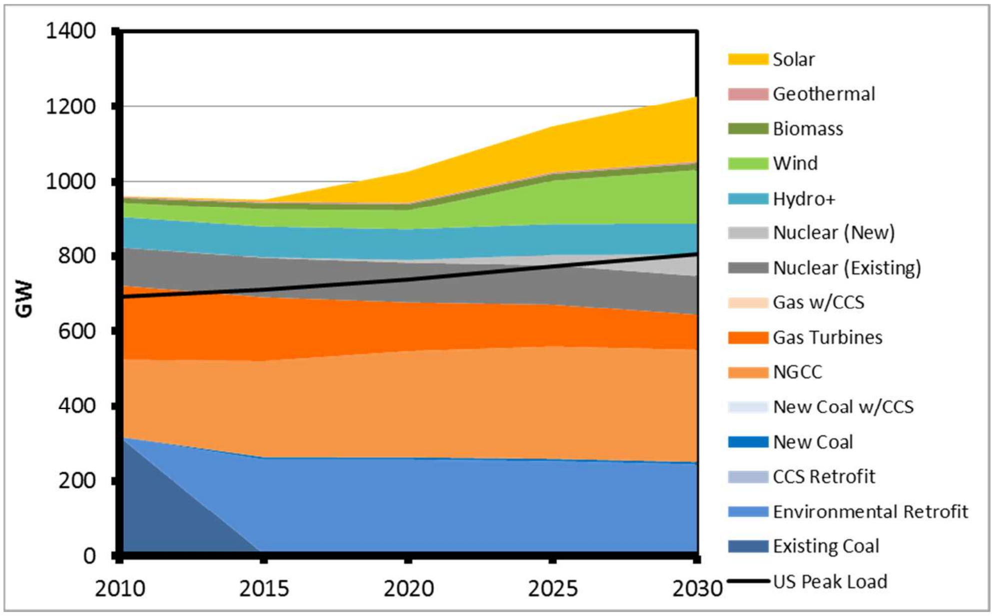

Figure S11. Capacity mix in the Base Case.

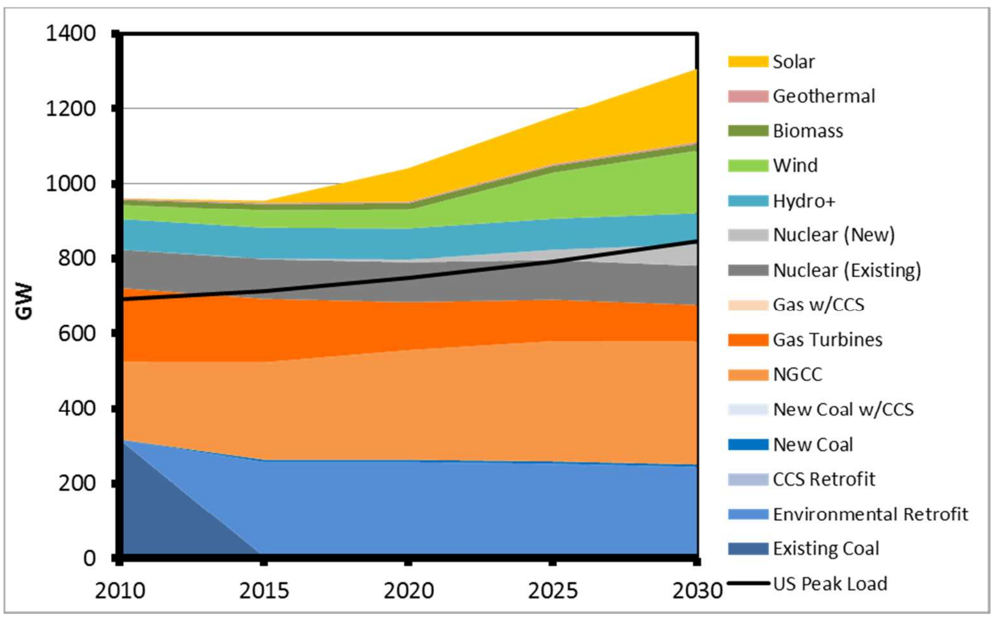

Figure S12. Capacity mix in the Electrification Case.

1.4 Hydrocarbon Fuel Sector: Crude-Oil Shipping, Refining and Gasoline Distribution Emissions

Emissions in the PM NAAQS air quality modeling platform do not incorporate the effects of the light duty 2017+ or heavy duty 2014+ greenhouse gas emission standards. Per the light duty 2017+ greenhouse gas RIA, 23.0 billion gallons of gasoline is estimated to be saved in 2030 which yields a 10% reduction in refinery crude supply.[4] Per the heavy duty greenhouse gas rulemaking RIA, 5.8 billion gallons of diesel and gasoline is estimated to be saved in 2030 which yields a 2.5% reduction in refinery crude supply[5]. Combining the crude throughput reductions resulting from the light duty and heavy duty greenhouse gas rulemakings, refinery crude throughput is reduced by 12.5% in 2030. Crude shipment and refinery emissions were assumed to be reduced by the same amount. Combining the gasoline consumption reductions resulting from the light duty and heavy duty greenhouse gas rulemakings, a total gasoline shipment reduction of 18% is estimated. Reductions were assumed to be uniform across the US.

Base case emission reductions were made to account for reductions in fuel consumption as a result of the EPA's light duty and heavy duty vehicle greenhouse gas rulemakings. Estimates of hydrocarbon fuel sector emission reductions for the base case are shown by source type in Table S11. The majority of VOC emission reductions are from the downstream sector which is made up primarily of evaporative losses.

Table S11. 2030 Lower-48 state upstream emissions and base case adjustments.

Category	VOC	CO	NO_x	PM_{10}	$PM_{2.5}$	SO_2
Emissions Change from PM NAAQS to Base Case (tons per year)						
Marine[1]	-966	-2,563	-20,224	-395	-363	-1,302
Refinery	-5,235	-5,361	-8,804	-2,775	-2,453	-10,147
Downstream	-108,664	-304	-109	-17	-16	-10
Refueling	-11,655	0	0	0	0	0
Percent Change from PM NAAQS to Base Case						
Marine[a]	-2%	-2%	-2%	-2%	-2%	-2%
Refinery	-13%	-13%	-13%	-13%	-13%	-13%
Downstream	-18%	-18%	-18%	-18%	-18%	-18%
Refueling	-18%	0%	0%	0%	0%	0%

[a] domain-wide emissions

Electrification case upstream emissions were further reduced to account for substitution of fossil fuel consumption associated with on-road vehicles and off-road equipment with electricity consumption.

Crude oil shipment reductions were estimated as follows for the electrification case:

1. **On-road vehicles:** Fuel savings for the electrification case over the base case for the lower-48 states in 2030 of 17% (light duty gasoline vehicles and trucks), 16% (light duty diesel vehicles and trucks), 18% (medium and heavy duty gasoline vehicles and trucks), and 3% (medium and heavy duty diesel vehicles and trucks) were estimated based on

the modeling described in Section 1.1. The total reduction in fuel consumption across all vehicle types was estimated to be 13% and was assumed to be uniform across all states.

2. **Off-road equipment:** Fuel savings for the electrification case over the base case for the lower-48 states in 2030 of 8% were estimated across all liquid fuels (gasoline, diesel, liquefied petroleum gas or LPG, and jet fuel) based on the modeling described in Section 1.2. The percent reduction across all states varied from 2% to 15% as the suite of off-road equipment and usage patterns in each state determine the magnitude of reductions.
3. **Volumetric reductions** in fossil fuel consumption in 2030 were estimated to be 18.8 billion gallons from on-road vehicles and 4 billion gallons from off-road equipment for a total of 22.8 billion gallons. The resulting reduction in crude oil shipments is 11% from the base case scenario (or a 23% reduction from the 2030 scenario when accounting for both the reduction in fuel use due to EPA's on-road vehicle greenhouse gas rulemakings and additional electrification of on-road vehicles and off-road equipment).

Gasoline shipment reductions were estimated as follows for the electrification case:

1. **On-road vehicles:** Lower-48 state, 2030 fuel savings for the electrification case over the base case of 17% (light duty gasoline vehicles and trucks) and 18% (medium and heavy duty gasoline vehicles and trucks) were estimated based on the modeling described in Section 1.1. The total reduction across all gasoline-fueled vehicle types was estimated to be 17% and was assumed to be uniform across all states.
2. **Off-road equipment:** Lower-48 state, 2030 fuel savings for the electrification case over the base case of 15% were estimated for gasoline fuels for the lower-48 states based on the modeling in Section 1.2. The percent reduction across all states varied from 5% to 31% as the suite of gasoline-fueled off-road equipment and usage patterns in each state determine the magnitude of reductions.
3. **Volumetric reductions** in gasoline consumption for the lower-48 states in 2030 were estimated to be 17.5 billion gallons from on-road vehicles and 1.6 billion gallons from off-road equipment or a total of 19.2 billion gallons. The resulting reduction in gasoline shipments is 17% from the base case scenario (or a 32% reduction from the 2030 scenario when accounting for both the reduction in fuel use due to EPA's on-road vehicle greenhouse gas rulemakings and additional electrification of on-road vehicles and off-road equipment).

Estimates of upstream emissions reductions for the electrification case are shown in by source in Table S12.

Table S12. 2030 lower-48 state upstream emissions and electrification case adjustments.

Category	VOC	CO	NO_x	PM_{10}	$PM_{2.5}$	SO_2
Emissions Change from Base Case to Electrification Case (tons per year)						
Marine[1,2]	-1,497	-4,652	-32,760	-655	-609	-1,310
Refinery	-4,110	-4,163	-6,859	-2,169	-1,917	-7,973
Downstream	-86,715	-221	-83	-13	-13	-8
Refueling	-8,875	0	0	0	0	0
Percent Change from Base Case to Electrification Case						
Marine[a]	-3%	-4%	-4%	-4%	-4%	-2%
Refinery	-11%	-11%	-11%	-11%	-11%	-11%
Downstream	-17%	-16%	-17%	-17%	-17%	-17%
Refueling	-17%	0%	0%	0%	0%	0%

[a] domain-wide emissions; includes emission reductions due to both upstream adjustments and shoreside power electrification

SECTION 2. AIR QUALITY MODELING DESCRIPTIONS

2.1 Modeling Configuration and Initialization

<u>CAMx Model Configuration</u>

CAMx version 6.0 is a 3-D photochemical transport and dispersion model that has an Eulerian (grid-based) formulation. The key processes treated by CAMx are emission, transport and dispersion, atmospheric chemical transformation, and deposition to the earth's surface of trace gases and aerosols. CAMx was set up to use Carbon Bond 05 (CB05) gas phase chemistry[22] and other common configurations listed in Table S13. The CAMx modeling grid was the 12-km CONUS grid as used in the EPA's PM NAAQS modeling. The grid is defined using a Lambert-Conformal map projection (Alpha = 33º, Beta = 45º and Gamma = -97º, with a center of X = -97º and Y = 40º) with the southwest corner at (-2412 km, -1620 km). The domain covers the 48 contiguous states along with southern portions of Canada and northern portions of Mexico (Figure S13) with 12-km grid resolution, and has 396 by 246 grid cells and 14 vertical layers.

The CAMx model has mass-tracking algorithms to explicitly simulate the fate of emissions from specific sources accounting for chemical transformations, transport and pollutant removal. This study utilizes the CAMx Anthropogenic Precursor Culpability Assessment (APCA) version of the Ozone Source Apportionment Technology (OSAT) and the Particulate Source Apportionment Technology (PSAT). Both source apportionment techniques use reactive tracers (also called tagged species) that run in parallel to the host model to determine the contributions to ozone and PM from individual user selected Source Groups.

Table S13. Model configurations options for CAMx model.

Science Options	2007 Baseline
Version	Version 6.0
Vertical Grid Mesh	14 Layers
Horizontal Grids	12 km
Initial Conditions	10 days full spin-up
Boundary Conditions	2007 GEOS-CHEM day specific 3-hour average data
Sub-grid-scale Plumes	No PiG treatment
Probing Tool	APCA/PSAT
Chemistry	
Gas Phase Chemistry	CB05
Aerosol Chemistry	ISORROPIA equilibrium
Secondary Organic Aerosols	SOAP
Cloud Chemistry	RADM-type aqueous chemistry
Meteorological Processor	WRFCAMx v3.4
Horizontal Transport	
Eddy Diffusivity Scheme	K-theory with Kh grid size dependence
Source Apportionment	None
Vertical Transport	
Eddy Diffusivity Scheme	K-Theory
Vertical Diffusivity Corrections	Kv-patch depending on landuse category up to 100 m and to cloud tops
Planetary Boundary Layer	From MM5 with PBL below convective clouds raised to cloud top
Deposition Scheme	Zhang
Numerics	
Gas Phase Chemistry Solver	Euler Backward Iterative (EBI) solver
Horizontal Advection Scheme	Piecewise Parabolic Method (PPM scheme)
Parallelization	OMP-MPI

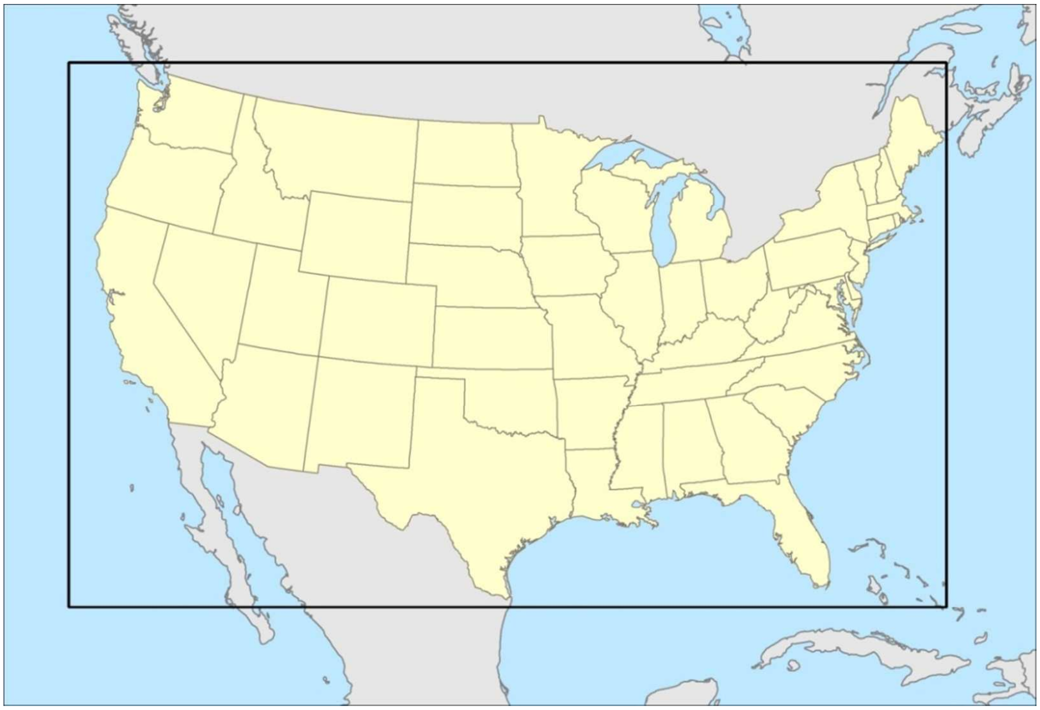

Figure S13. The CAMx 12-km modeling domain covering the 48 contiguous states along with southern portions of Canada and northern portions of Mexico.

<u>CAMx Initialization</u>

Initial and boundary conditions define the air quality at the start of the CAMx simulation and the chemical composition of air transported into the model domain during the simulation via lateral boundaries. The boundary and initial conditions were obtained from a GEOS-Chem global model simulation performed for 2007, as in the EPA's PM NAAQS modeling. The BCs for 2030 were assumed to be unchanged from the 2007 base year BCs. The CAMx model was run separately for each of two-month periods of 2030 with a 10 day spin-up period added to limit the influence of the initial concentrations. The CAMx model requires inputs for three-dimensional gridded wind, temperature, humidity, cloud/precipitation, and vertical mixing. EPA applied the WRF meteorological model on 36-km and 12-km continental US grids for the year 2007 and reported reasonably good performance.[23] This WRF dataset was used in the PM NAAQS modeling and is used in this study. WRFCAMx version 3.4 was used to format WRF data for CAMx and provide the complete set of meteorological data required by CAMx.

2.2 Additional Analysis of Ozone/PM Source Contribution Results

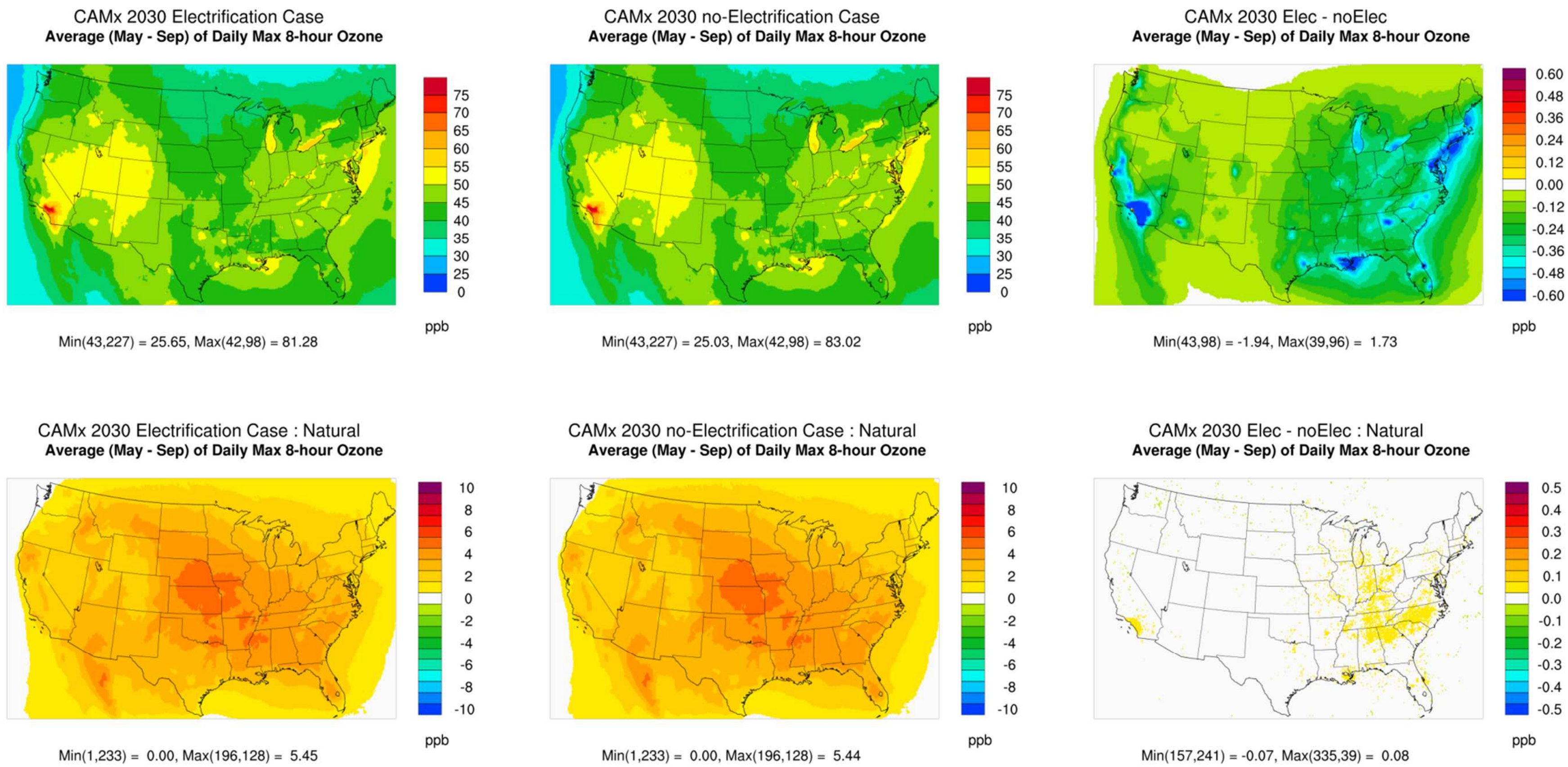

Figure S14. Source contributions to summer average daily maximum 8-hour ozone concentrations for the electrification scenario (left), the base case (middle), and difference between electrification scenario and base case (right).

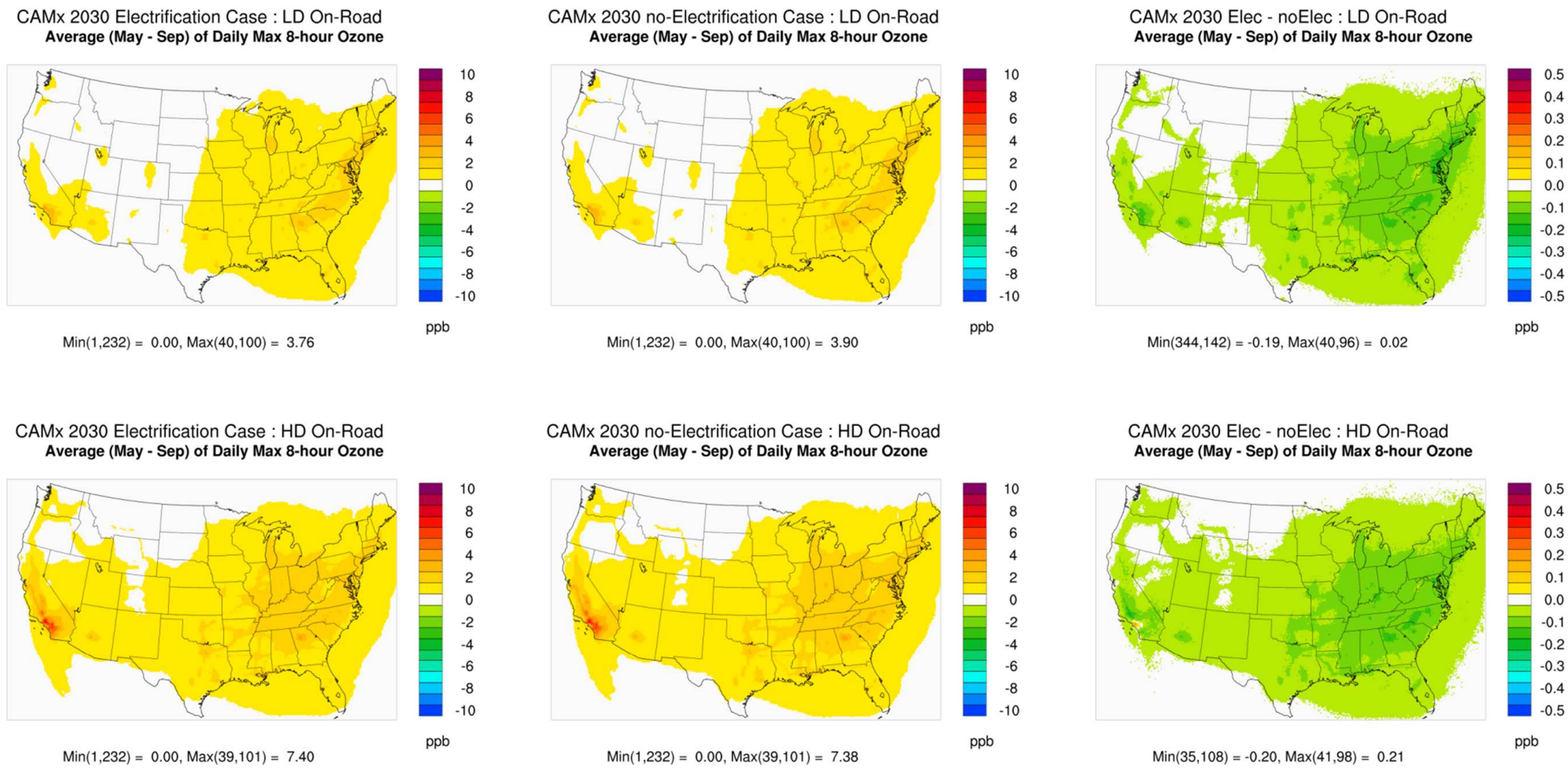

Figure S14. Source contributions to summer average daily maximum 8-hour ozone concentrations for the electrification scenario (left), the base case (middle), and difference between electrification scenario and base case (right) (Continued from previous page).

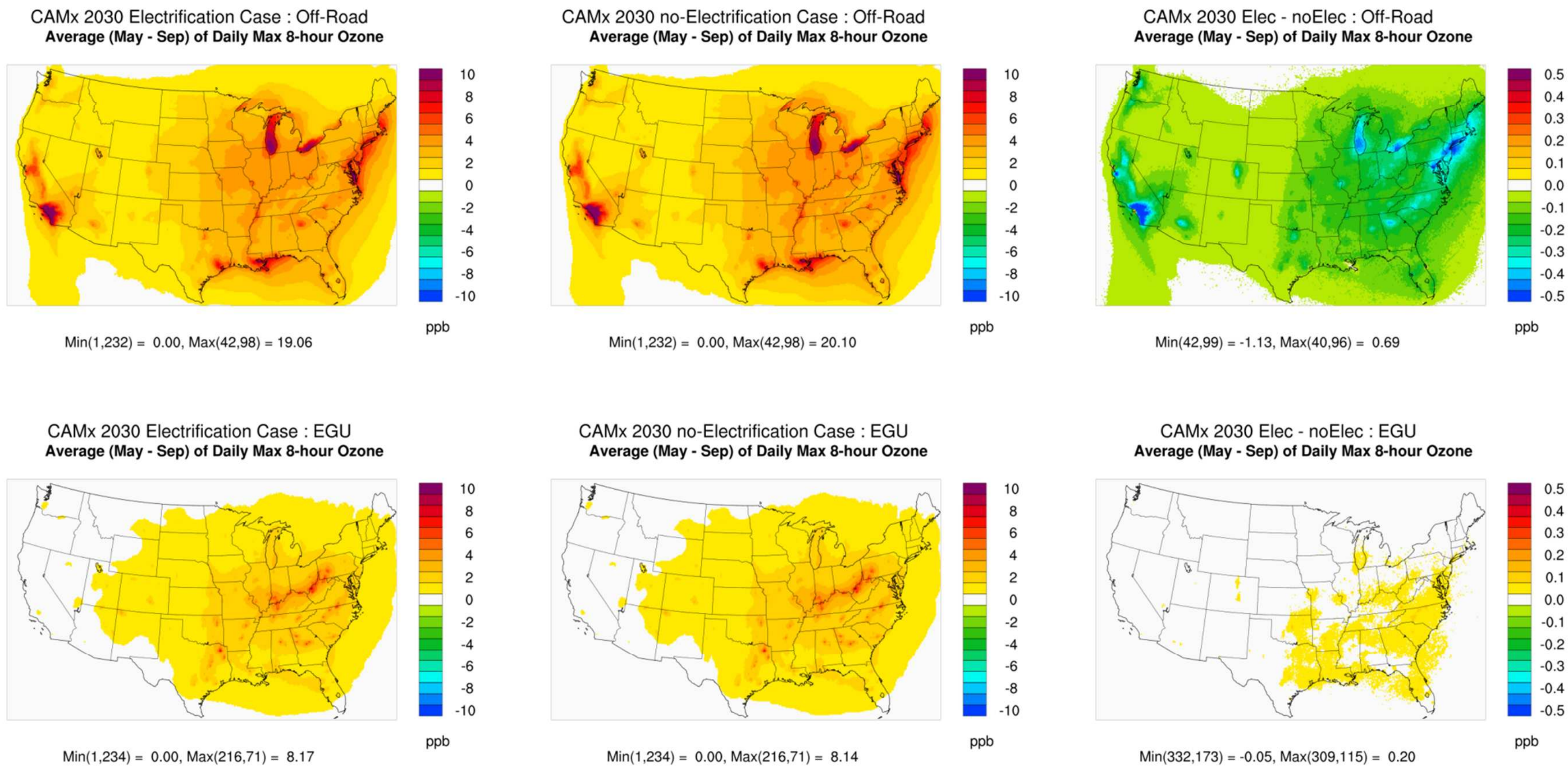

Figure S14. Source contributions to summer average daily maximum 8-hour ozone concentrations for the electrification scenario (left), the base case (middle), and difference between electrification scenario and base case (right) (Continued from previous page).

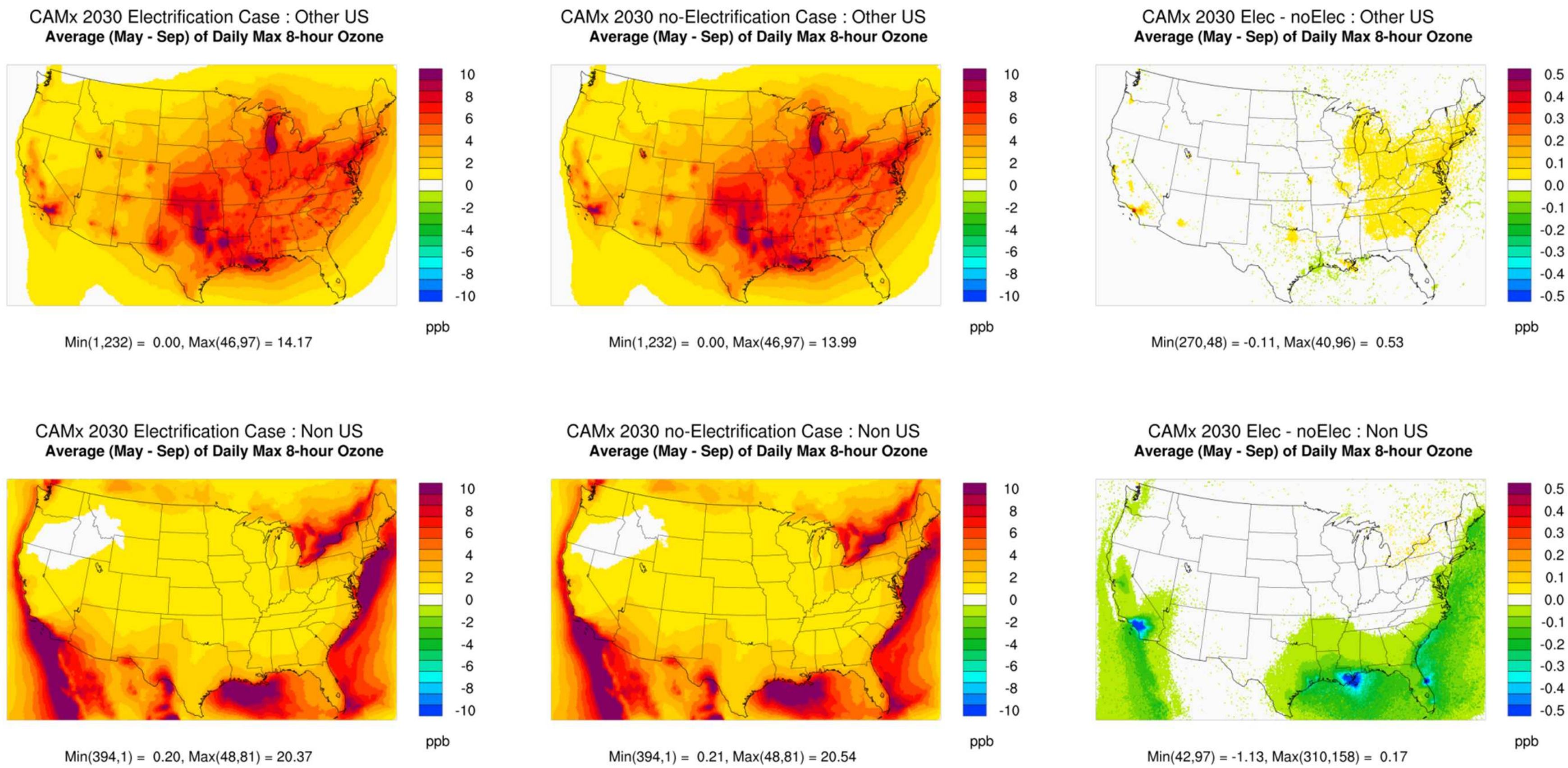

Figure S14. Source contributions to summer average daily maximum 8-hour ozone concentrations for the electrification scenario (left), the base case (middle), and difference between electrification scenario and base case (right) (Continued from previous page).

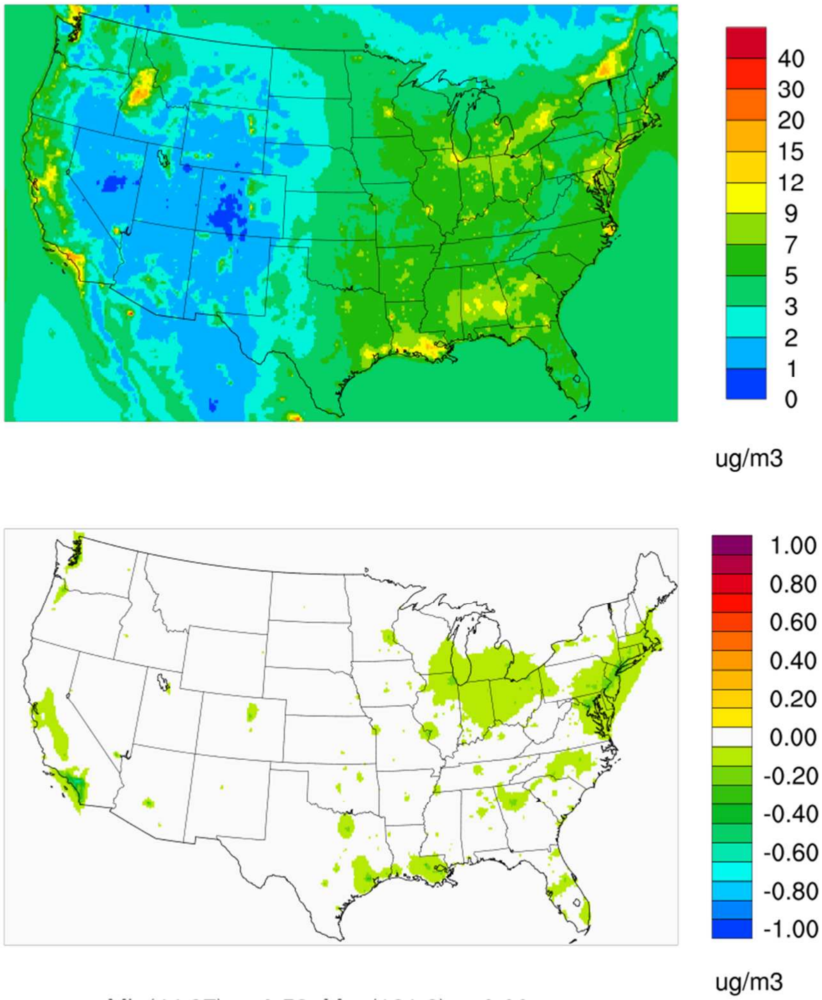

Figure S15. Annual average concentrations (µg m^{-3}) of $PM_{2.5}$ (top) and difference between Electrification Case and Base Case (bottom).

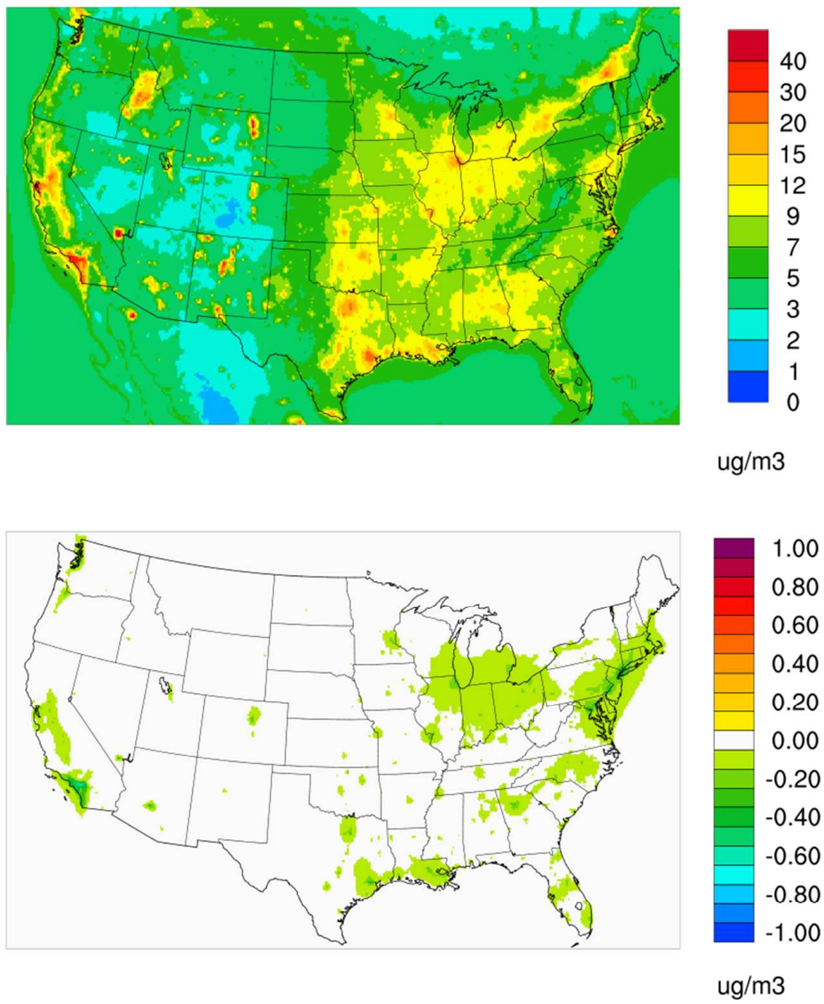

Figure S16. Annual average concentrations (μg m^{-3}) of PM_{10} (top) and difference between Electrification Case and Base Case (bottom).

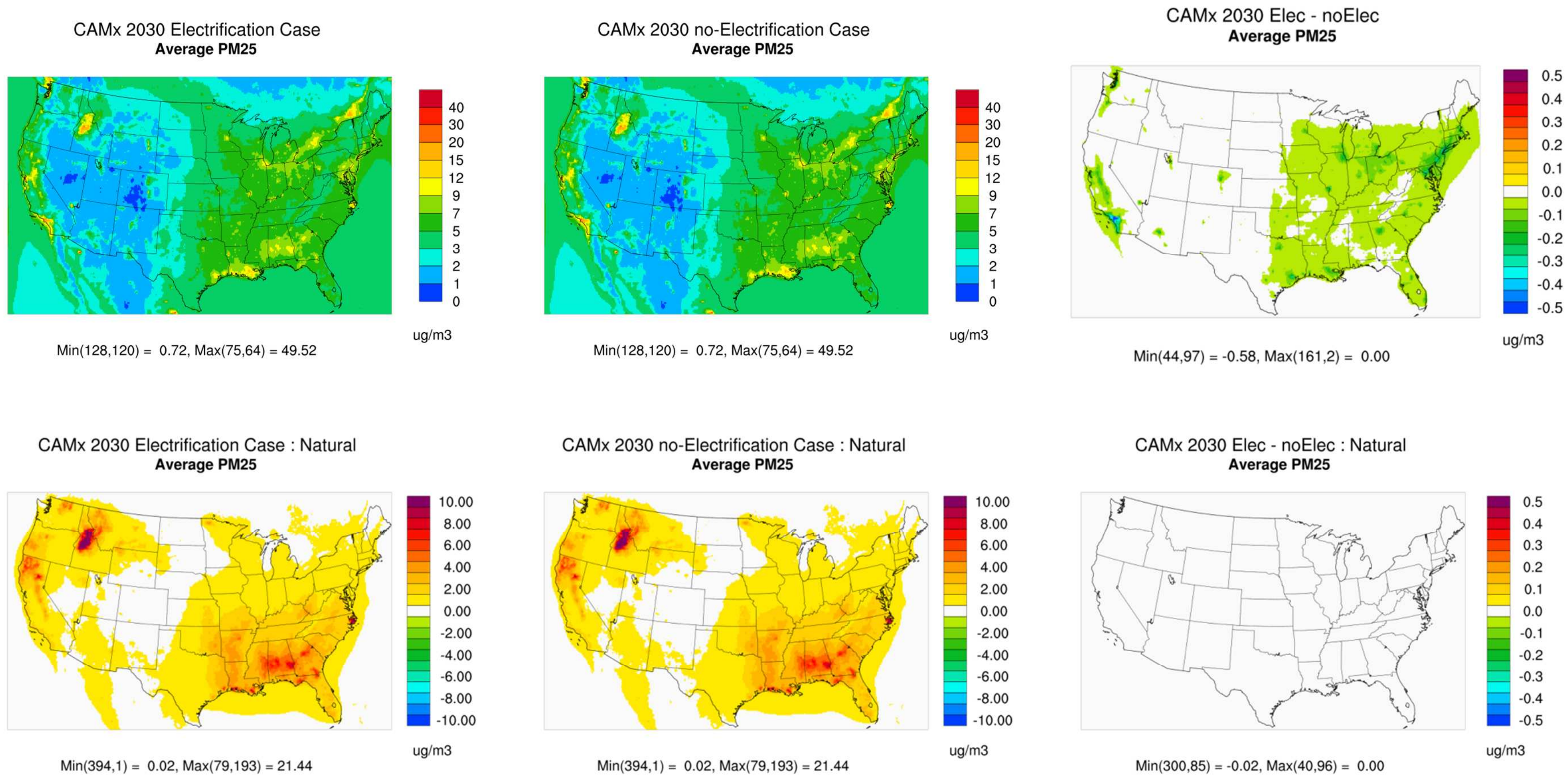

Figure S17. Source contributions annual average $PM_{2.5}$ concentrations for the electrification case (left), the base case (middle), and difference between electrification case and base case (right).

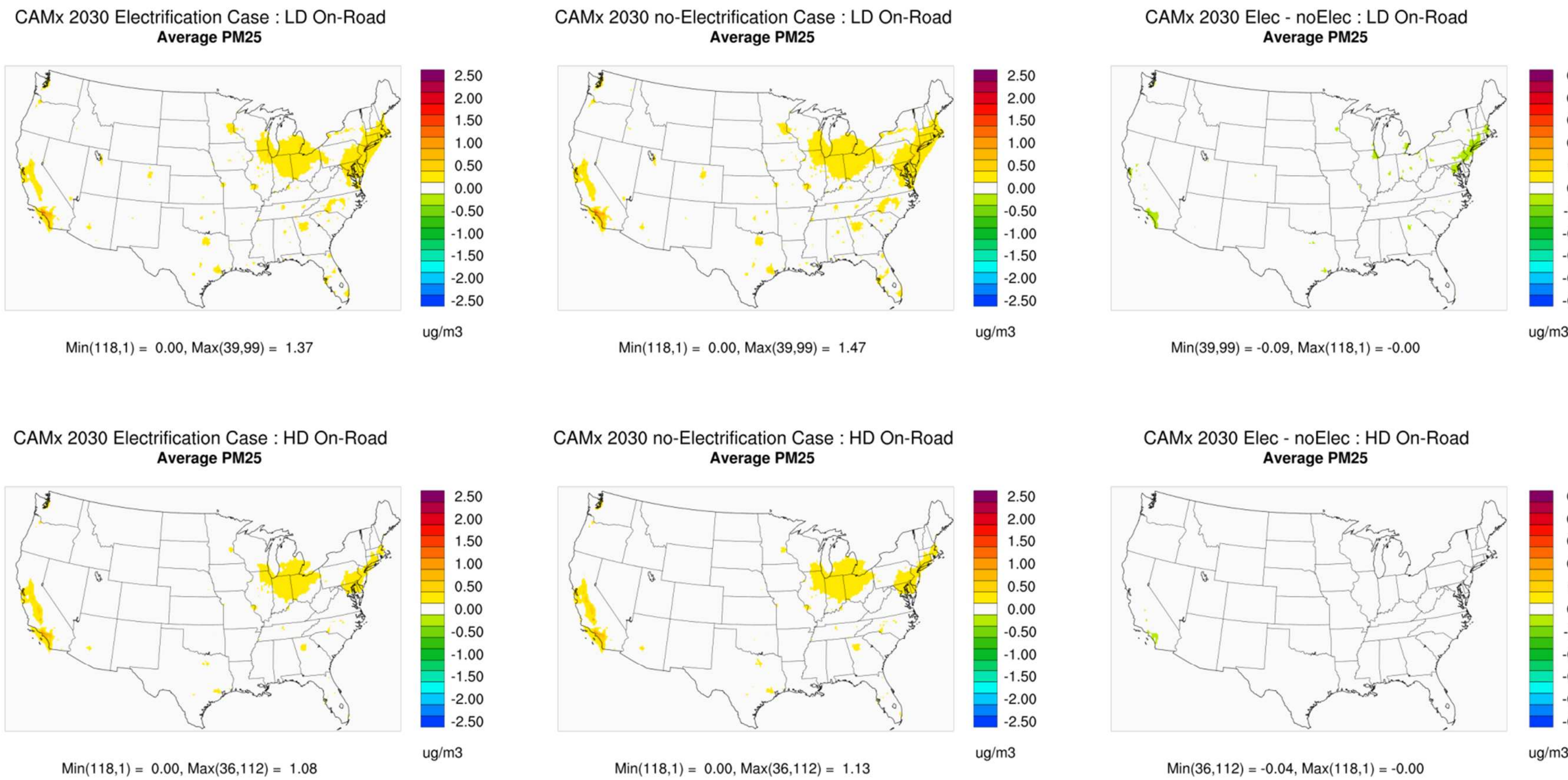

Figure S17. Source contributions annual average PM2.5 concentrations for the electrification case (left), the base case (middle), and difference between electrification case and base case (right)
(Continued from previous page)

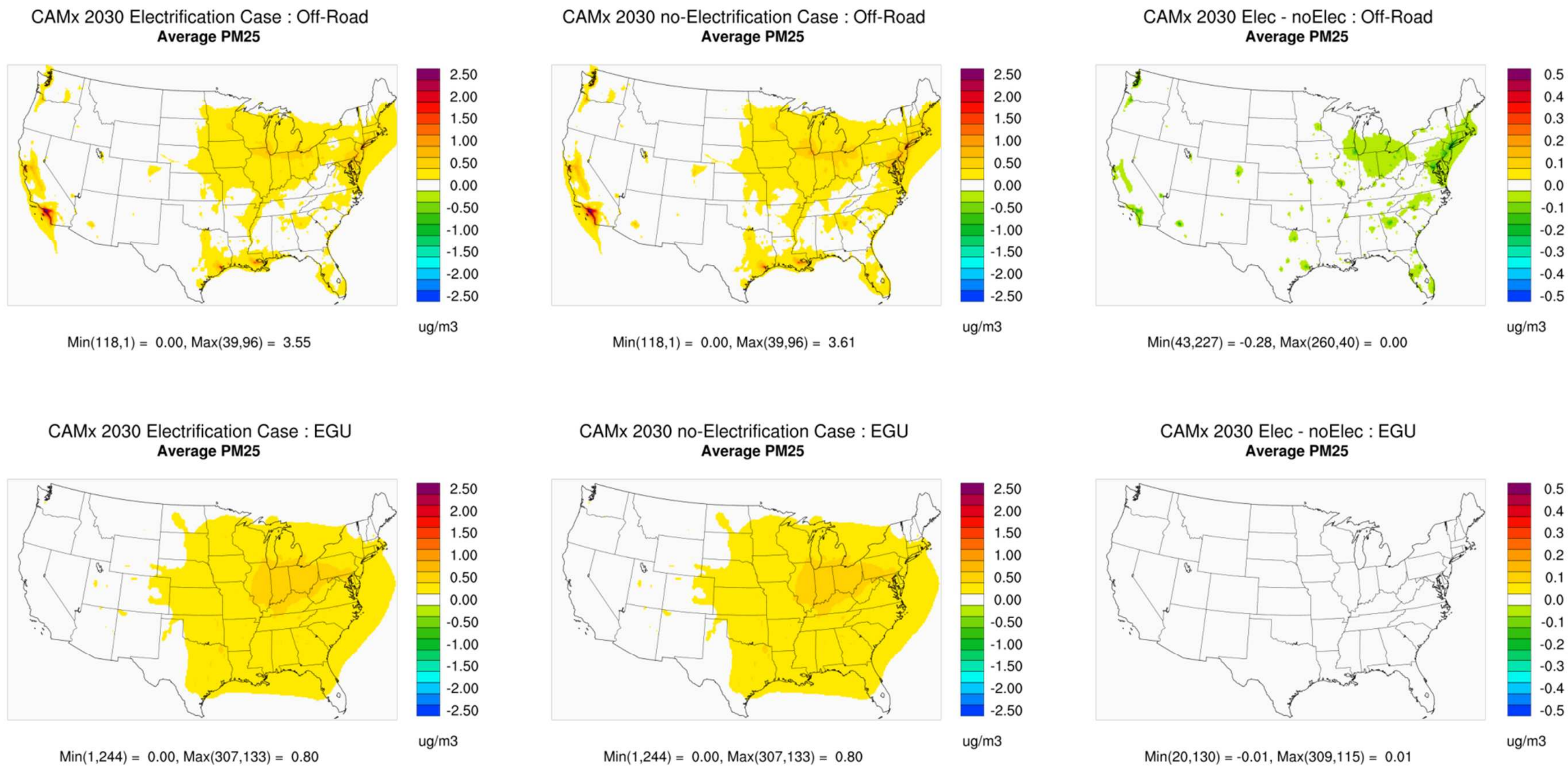

Figure S17. Source contributions annual average PM2.5 concentrations for the electrification case (left), the base case (middle), and difference between electrification case and base case (right)
(Continued from previous page)

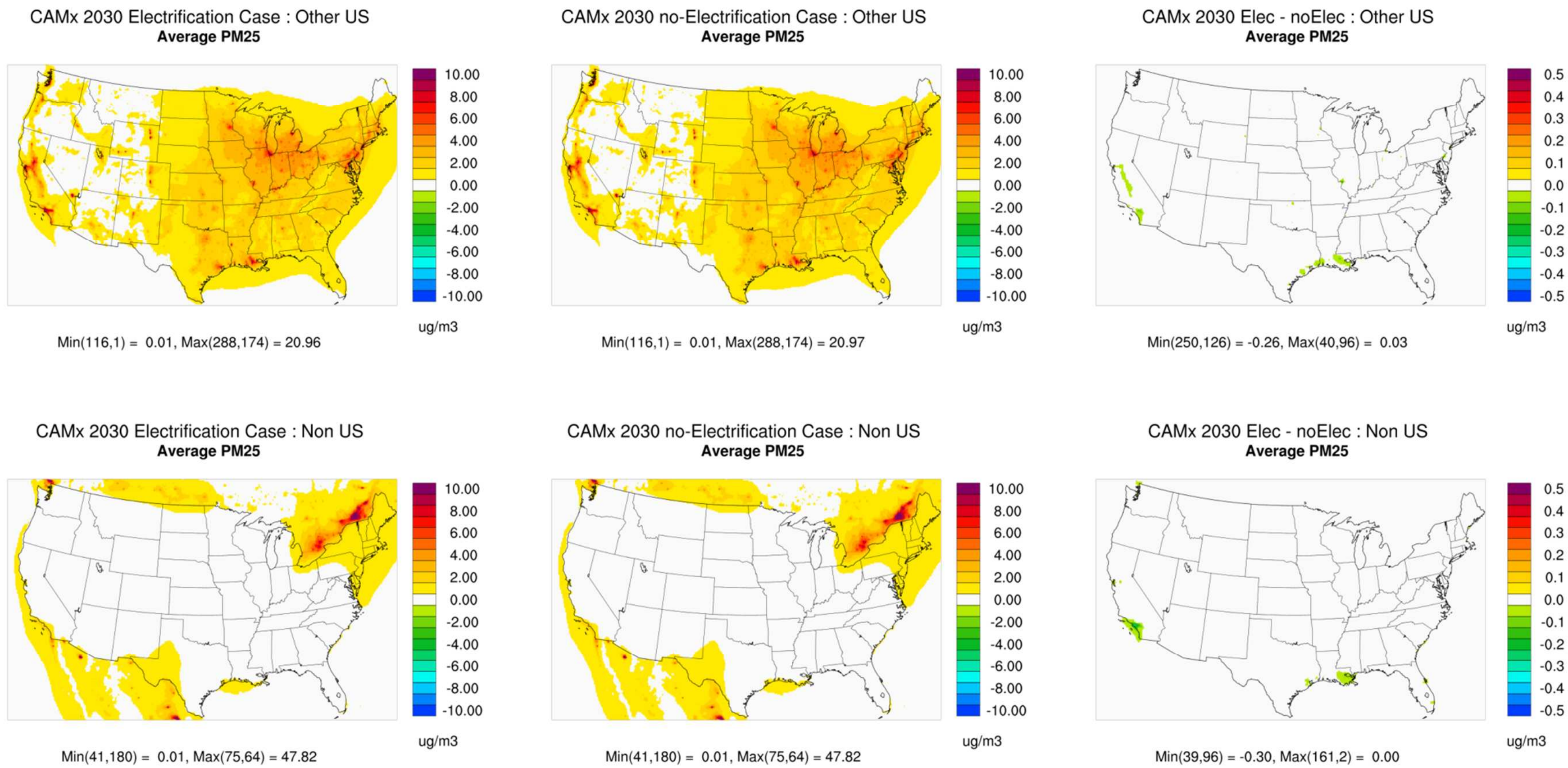

Figure S17 Source contributions annual average PM2.5 concentrations for the electrification case (left), the base case (middle), and difference between electrification case and base case (right)
(Continued from previous page)

2.3. Human-exposure analysis

Population exposure metrics are useful to convey the information relevant to the public health effects by providing an estimate of public exposure to pollutant levels. There are different methods for calculating exposure metrics. Population exposure metrics exist that have no concentration threshold (i.e., absolute exposure), which is useful if there is no threshold for health effects. However, there may be pollution levels below which human health effects do not occur or pollution levels that cannot be attained due to limits imposed by natural or background conditions. For these reasons, calculating exposure metric above a certain ozone threshold is widely practiced. However, the selection of the threshold value is often a subject of much debate. Rather than choose an arbitrary threshold, we present exposure in terms of population based on the design value (DV) of the pollutant of concern, i.e. the value for which the National Ambient Air Quality Standard (NAAQS) is defined. For example, the 8-hour-average ozone design value is based on the 99th percentile of observed mixing ratios which is tantamount to the 4th highest observed 8-hour-average ozone mixing ratio. We use histograms to demonstrate number of population exposed to a range of DV.

The population exposure for ozone is presented in Figure S18. The ozone exposure results based on the ozone design value are consistent with current air quality management practices in the United States that aim to reduce exposure to high ozone concentrations, and these results show that electrifications of mobile sources reduce over 13 million people (3.8% of total populations projected for 2030) exposed to 4th highest 8-hour ozone concentration exceeding 65 ppb.

The population exposure results for $PM_{2.5}$ based on the 98th percentile 24-hour metric mimic the ozone results (Figure S19). The electrification scenario reduces the exposure to the high 24-hour $PM_{2.5}$ exceeding 15 µg m^{-3} by 4.7 million people (1.3% of total populations). The population exposure results for annual average concentrations of $PM_{2.5}$ are shown in Figure S20. Electrifications reduce the exposure to the annual average $PM_{2.5}$ exceeding 7 µg m^{-3} by 8.2 million people (2.3% of total populations).

These population exposure results may be understated due to our modeling grid resolution (12 km). The exposure metrics can be strongly affected by small-scale spatial variability, such as strong concentration gradients of $PM_{2.5}$ near road way. It is more common to use high-resolution air pollution fields (e.g., 1 km) to calculate these metrics.

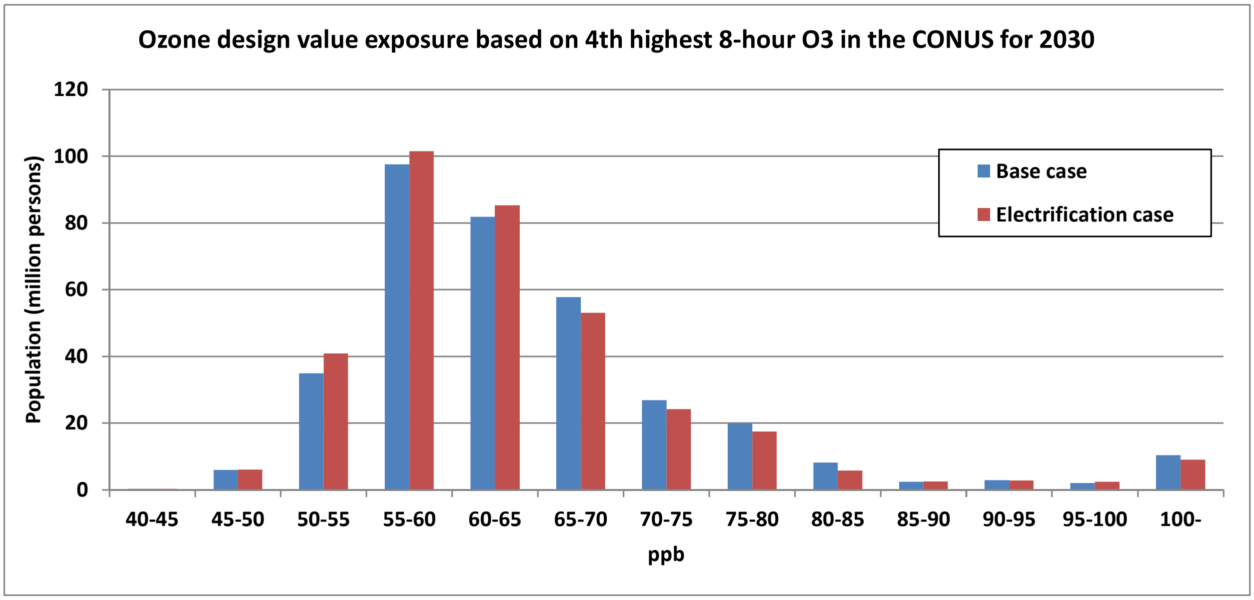

Figure S18 Histogram showing population exposed to the 4th Highest 8-Hour-Average Ozone for Base Case and Electrification Case

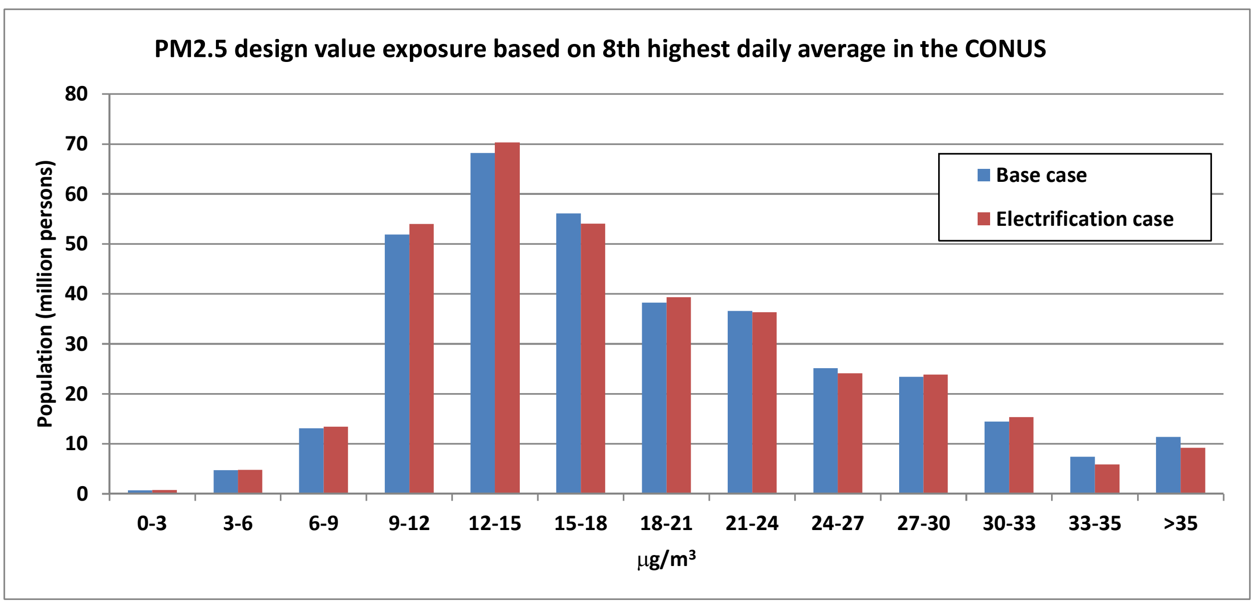

Figure S19 Histogram showing population exposed to the 98th percentile 24-hour average $PM_{2.5}$ for Base Case and Electrification Case

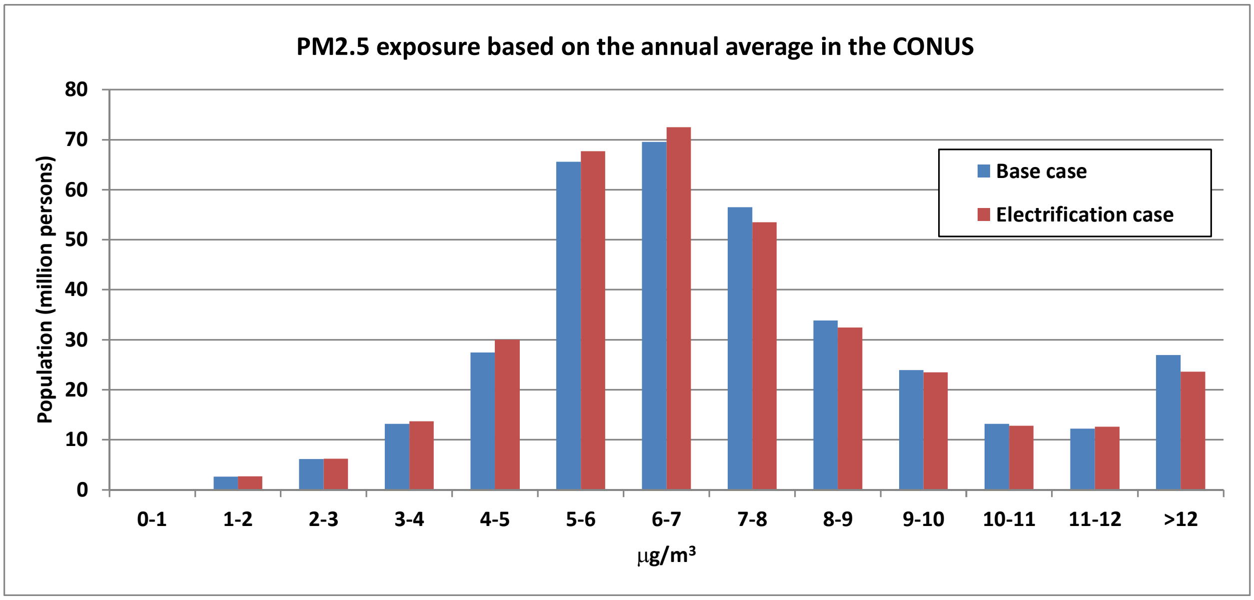

Figure S20 Histogram showing population exposed to annual average $PM_{2.5}$ for Base Case and Electrification Case

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