From Cradle to Junkyard: Assessing the life cycle Greenhouse Gas Benefits of Electric Vehicles*

Online Appendix

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A Appendix

A.1 Calculating Marginal Electricity Emissions

As described in Section 2.1.2, accurately computing the change in overall emissions from replacing an EV with an ICE requires an understanding of how electricity generation responds to the *marginal* change in demand induced by EV charging. We employ methods similar to Graff-Zivin et al. [2014] which estimates the marginal change in CO_2 emissions resulting from changes in fossil fuel generation load. Additionally, we follow Holland et al. [2015] in using net load data from FERC Form 714 compute non-fossil fuel generation, which are excluded from the analysis in Graff-Zivin et al..

Contrary to previous work, we compute the impact of a marginal change in electricity generation on full life cycle CO_2e emissions, including fuel extraction, processing, transport, and combustion. These calculations require determining the probability that each fuel type is supplying the marginal megawatt then multiplying by the life cycle CO_2e emissions for that fuel. Additionally, we account for seasonal heterogeneity in the composition of the marginal generation fuel, allowing the parameters to vary by quarter of year. These calculations are described the the following sections.

A.1.1 Marginal Fuel Use Calculations

Let E^R_{rit} be the quantity of electricity (measured in MWh) consumed in NERC region r on interconnection i at time t and E^{I-R}_{rit} be the quantity of electricity consumed by all NERC regions other than r on interconnection i at time t.[1] Likewise, let C^I_{it}, G^I_{it}, P^I_{it}, and R^I_{it} be

[1] For WECC and TRE, NERC Regions which form their own interconnections, $E^{I-R}_{rit} = 0 \ \forall t$ since there are no other NERC regions on the interconnection.

the corresponding quantities (measured in million BTU) of coal, natural gas, petroleum, and non-fossil fuel[2] resources deployed on interconnection i at time t to generate that electricity.

For each NERC Region r, on interconnection i, in quarter of year q, and hour of day h electricity generation should follow the relationship:[3]

$$E_t^R = a^c C_t^I + a^g G_t^I + a^p P_t^I + a^r R_t^I + E_t^{I-R} + \lambda_m^a + \nu_t \tag{1}$$

Our parameter of interest is the marginal change in fuel consumption given an increase in electricity demand, or e.g., $\frac{\partial \Delta_t C}{\partial \Delta_t E}$. If one were to estimate (1) the marginal effect $b^c = \frac{\partial \Delta_t E}{\partial \Delta_t C}$, is not the effect of interest. Moreover, one cannot extract the desired marginal effect using the inverse function theorem since (1) is an equilibrium relationship. In equilibrium, changes in natural gas consumption are correlated with changes in coal consumption.

Instead, we estimate the marginal effect of interest by considering fuel consumed as the dependent variable. This leads to a system of equations:

$$\begin{aligned}
C_{riqht}^I &= \alpha + \alpha^E E_t^R + \alpha^{E-I} E_t^{I-R} + \alpha^g G_t^I + \alpha^p P_t^I + \alpha^r R_t^I + \lambda_m^C + \varepsilon_t^C \\
G_t^I &= \beta + \beta^E E_t^R + \beta^{E-I} E_t^{I-R} + \beta^c C_t^I + \beta^p P_t^I + \beta^r R_t^I + \lambda_m^G + \varepsilon_t^G \\
P_{riqht}^I &= \gamma + \gamma^E E_t^R + \gamma^{E-I} E_t^{I-R} + \gamma^c C_t^I + \gamma^g G_t^I + \gamma^r R_t^I + \lambda_m^P + \varepsilon_t^P \\
R_{ht}^I &= \delta + \delta^E E_t^R + \delta^{E-I} E_t^{I-R} + \delta^c C_t^I + \delta^g G_t^I + \beta^p P_t^I + \lambda_m^R + \varepsilon_t^R
\end{aligned} \tag{2}$$

For each NERC region, quarter of year, and hour of day, we are interested in the equilibrium change in, e.g., C_t^I given a one unit change in E_t^R. Noting C_t^I, G_t^I, P_t^I, R_t^I are co-determined

[2]Non-fossil fuel generation includes all resources generating electricity without the combustion of carbon-based fuels. This includes renewables such as wind, solar, and geothermal, traditional hydroelectric, pumped hyrdo storage, and nuclear sources. We measure non-fossil fuel generation as the mean BTU of fossil fuel needed to replace non-fossil fuel generation in each NERC region.

[3]We estimate these parameters separately for each NERC region, quarter of year, and hour of day. λ_m^a is a month fixed effect.

with $E_t^R$and decomposing E_t^I into E_t^R and E_t^{I-R}, taking the derivative the expectation with respect to E^R in each equation gives the expected marginal effects:[4]

$$\begin{aligned}
E\left[\frac{\partial C_t^I}{\partial E_t^R}\right] &= \alpha^E + \alpha^g E\left[\frac{\partial G_t^I}{\partial E_t^R}\right] + \alpha^p E\left[\frac{\partial P_t^I}{\partial E_t^R}\right] + \alpha^r E\left[\frac{\partial R_t^I}{\partial E_t^R}\right] \\
E\left[\frac{\partial G_t^I}{\partial E_t^R}\right] &= \beta^E + \beta^c E\left[\frac{\partial C_t^I}{\partial E_t^R}\right] + \beta^p E\left[\frac{\partial P_t^I}{\partial E_t^R}\right] + \beta^r E\left[\frac{\partial R_t^I}{\partial E_t^R}\right] \\
E\left[\frac{\partial P_t^I}{\partial E_t^R}\right] &= \gamma^E + \gamma^c E\left[\frac{\partial C_t^I}{\partial E_t^R}\right] + \gamma^g E\left[\frac{\partial G_t^I}{\partial E_t^R}\right] + \gamma^r E\left[\frac{\partial R_t^I}{\partial E_t^R}\right] \\
E\left[\frac{\partial R_t^I}{\partial E_t^R}\right] &= \delta^E + \delta^c E\left[\frac{\partial C_t^I}{\partial E_t^R}\right] + \delta^g E\left[\frac{\partial G_t^I}{\partial E_t^R}\right] + \delta^p E\left[\frac{\partial P_t^I}{\partial E_t^R}\right]
\end{aligned} \tag{3}$$

In matrix form, for each r, i, q, h this is:

$$\begin{bmatrix} 1 & -\alpha^g & -\alpha^p & -\alpha^r \\ -\beta^c & 1 & -\beta^p & -\beta^r \\ -\gamma^c & -\gamma^g & 1 & -\gamma^r \\ -\delta^c & -\delta^g & -\delta^p & 1 \end{bmatrix} \begin{bmatrix} E\left[\frac{\partial C_t^I}{\partial E_t^R}\right] \\ E\left[\frac{\partial G_t^I}{\partial E_t^R}\right] \\ E\left[\frac{\partial P_t^I}{\partial E_t^R}\right] \\ E\left[\frac{\partial R_t^I}{\partial E_t^R}\right] \end{bmatrix} = \begin{bmatrix} \alpha^E \\ \beta^E \\ \gamma^E \\ \delta^E \end{bmatrix} \tag{4}$$

Thus, the expected marginal fuel in each NERC region, quarter of year, and hour of day for each type consumed resulting from an increase of 1 MW in generation is expressed as:

$$\begin{bmatrix} E\left[\frac{\partial C_t^I}{\partial E_t^R}\right] \\ E\left[\frac{\partial G_t^I}{\partial E_t^R}\right] \\ E\left[\frac{\partial P_t^I}{\partial E_t^R}\right] \\ E\left[\frac{\partial R_t^I}{\partial E_t^R}\right] \end{bmatrix} = \begin{bmatrix} 1 & -\alpha^g & -\alpha^p & -\alpha^r \\ -\beta^c & 1 & -\beta^p & -\beta^r \\ -\gamma^c & -\gamma^g & 1 & -\gamma^r \\ -\delta^c & -\delta^g & -\delta^p & 1 \end{bmatrix}^{-1} \begin{bmatrix} \alpha^E \\ \beta^E \\ \gamma^E \\ \delta^E \end{bmatrix} \tag{5}$$

Non-Fossil Fuel Generation is Endogenous. The idiosyncratic error includes changes in consumption in NERC region r that are unexplained by fuel consumption and non-fossil fuel generation. This highlights a potential simultaneity bias. Unobserved changes in the

[4]We assume $E\left[\frac{\partial E_t^{I-R}}{\partial E_t^R}\right] = 0$ or, in equilibrium, an increase of 1 MW of load in one NERC region does not have any affect on the load in other NERC regions on the same interconnection.

efficiency of converting fossil fuels into electricity are included in ν. If these changes in efficiency are correlated with ν then the regression coefficients may be biased. For example, fossil-fuel generation technologies are generally less efficient during the ramp-up phase. Renewable generation technologies, such as solar and wind power, have output that is a function of environmental parameters which can vary unpredictably. If, for example, clouds move to cover a solar array total renewable generation will fall. Consequently, new fossil fuel generation must be ramped up to meet demand. Thus, idiosyncratic changes to non-fossil fuel generation will be correlated with the efficiency of fossil fuel generation. To address this concern, we instrument for non-fossil fuel generation using lagged values of non-fossil fuel generation.[5]

Estimation of Marginal Fuel Consumption. We construct hourly measures of fuel consumption by type at NERC region level using the CEMS dataset. CEMS reports only fossil-fuel powered electricity generating units. Electricity generated from e.g., wind, solar, geothermal, traditional hydro, pumped hydro storage, and nuclear are excluded. Using data from FERC Form 714 we compute hourly total load in each NERC region. Hourly generation by non-fossil fuel sources is the difference between total load in each NERC region and total net electricity generation by fossil fuel-powered generating units in that NERC region.[6,7]

Using our dataset of hourly load and emissions, we estimate the system of equations in (2) using two-stage least squares for each NERC region, quarter of year and hour of day. We then solve the system of equations specified in Equation (4) using the singular value

[5] After conditioning on hour by month fixed effects, unobserved changes in grid efficiency should be uncorrelated with lagged renewable generation.

[6] CEMS excludes any fossil fuel-powered generating units with a peak capacity of less than 50 MW. These small peaker plants comprise a small portion of total fossil fuel generation and are marginal only during periods of extreme demand. We do not believe these units would materially alter our estimates of marginal or average fuel use. However, our estimate of non-fossil fuel generation includes these small peaker plants and is an overstatement of total non-fossil fuel generation.

[7] Since load in one NERC region may be served by generation in another this method may misassign some non-fossil fuel generation to the wrong NERC region. Our empirical specification, however, allows electricity to flow between NERC regions so any misassignment should not bias our results on aggregate.

decomposition method. There is a discontinuity in the solution to this system at points where the matrix of coefficients is singular. If the estimated matrix of coefficients is ill-conditioned then the solution will be highly sensitive to estimation error in the regression coefficients. Our reported coefficients are bootstrapped over 200 replications clustering at the week level.[8]

Marginal Direct CO_2 Emissions. Following Graff-Zivin et al. [2014] we model direct CO_2 emissions (EM_t) as a function of total fossil fuel electricity generation (E_t) at time t. Similar to marginal fuel consumption, we separately estimate the following relationship for each NERC region, quarter of year, and hour of day where ξ_m is a month fixed effect:

$$EM_t^I = \zeta^R \ E_t^R + \zeta^I \ E_t^I + \xi_m + \varepsilon_t^{EM} \tag{6}$$

Assuming CO_2 emissions, conditional on generation load, are uncorrleated with emissions at time $\tau \neq t$, taking the derivative with respect to electricity generated at time t in each NERC region, quarter of year, and hour of day:

$$\frac{\partial EM_t^I}{\partial E_t^R} = \zeta^R \tag{7}$$

Thus, ζ^R identifies the marginal change in CO_2 emissions from an change in electricity. Using hourly CO_2 emissions and electricity generation by NERC region and hour from the CEMS data we estimate marginal CO_2 emissions for each NERC region and quarter of year using Equation 6.[9]

[8] We estimate a marginal consumption rate for each fuel type (coal, natural gas, petroleum, and non-fossil fuel), each hour of day, each quarter of year, and each NERC region, or 3072 parameters, not including fixed effects. These estimates are available upon request.

[9] We estimate a marginal CO_2 emissions rate for each hour of day, each quarter of year, and each NERC region, or 768 parameters, not including fixed effects. These estimates are available upon request.

CEMS data only reports combustion-related CO_2 emissions, and does not represent the total life cycle emissions. life cycle emissions were added based on electricity fuel production and delivery emissions reported in GREETnet (Wang 2014a) for average coal for U.S. electricity, residual oil used in electricity, and North American natural gas from shale and regular recovery for electricity. The fuel production and delivery emissions for these fuels on a grams of CO_2e per MMBtu basis are 6200, 11800 and 14600 for coal, natural gas, and gasoline, respectively.[10]

For both ICEs and EVs we compute fuel demand and, ultimately, emissions as a function of VMT. Gasoline demand for ICEs are a direct function of EPA-estimated fuel economy and VMT demand. Charging an EV generates emissions through additional demand on the electrical grid. The additional marginal emissions from that demand depend on the fuel mix when the vehicle is charged on the interconnect supplying electricity to the vehicle. Graff-Zivin et al. [2014] note, and our regression results confirm, that the time of day in which EVs are charged can have a significant impact on charging emissions. We consider two charging scenarios: "Day" charging assumes EVs draw current from the grid charge with uniform probability between 9 AM and 5 PM and zero probability at other times. This scenario is consistent with charging an EV while at work. "Night" charging assumes EVs charge with uniform probability between 8 PM and 4 AM and zero probability otherwise. This is consistent with households charging vehicles at home overnight. Marginal emissions under the day and night charging scenarios by quarter are shown in Figures A.9 and A.10, respectively.

[10] There are presumably indirect GHG emissions from non-fossil fuel generation. These emissions fall into two categories, first those associated with building the capital stock for generating sites. All capital investments are sunk at the time of generation and do not impact marginal GHG emissions. The second are indirect fuel procurement emissions, for example, mining of uranium for nuclear thermal generators. The GHG emissions per MW of these activities are minute and would not substantially alter our qualitative or quantitative conclusions.

A.2 Robustness Scenarios

We conduct a number of additional tests of the robustness of our results from Section 3.

Vehicle Life and Range Limitations: Our primary specification assumes both ICEs and EVs are used for similar trips and operate for 257,000 km and are then scrapped. As alternatives, we assume both EVs and ICEs have a fixed life with scrappage occurring after either 12 or 16 years. Additionally, these scenarios also consider the limited rage of EVs compared to ICEs. If a potential trip falls outside of the range of an EV a household may chose to make the trip in an ICE, modify the trip route, or to not take the trip at all. Not only is the maximum range on an EV on a single charge shorter than the range of a typical ICE on a single tank of gasoline, but the range of an EV depends critically on environmental conditions. As described further in Section 2.4, EVs may expend additional energy for each kilometer driven when operating in cold or hot temperatures, depleting the batter faster, and reducing range. As a component of this test of robustness, we compute the probability that any trip in the NHTS would fall within the range of our prototype EV within that NERC Region and quarter given climate conditions in that region and downweight the probability of any trip occurring by the probability it is within the range of the EV.[11] These adjustments to our preferred scenario do not alter our qualitative conclusions.

The results are shown in Table A.3. EVs tend to have larger manufacturing emissions than ICEs, thus increasing the life of the vehicle spreads those emissions over more VMT, improving EVs relative to ICEs. Direct combustion emissions account for the majority of

[11] This assumes households will substitute VMT in an ICE for VMT in an EV when the trip length exceeds the range of the EV. If households reduced VMT in response to range restrictions we understate the emissions benefits of EVs. However, if households instead respond to reduced range by making more, shorter trips (for example, returning home to charge in what would be the middle of a trip absent range restrictions and then resuming the trip later) EV emissions benefits would be overstated. It is important to note, as we describe in Section 2.1.1, since EVs have lower marginal costs of operation than ICEs a household that chooses not to make a trip in an EV when they would have made the trip in an ICE suffers a welfare loss.

life cycle emissions and the effect of the lifespan assumption is small. The components of EV emissions benefits over ICEs are shown by NERC region in Figure A.15.

Accelerated Battery Wear: Finally, there is strong evidence that prolonged exposure to high temperatures can substantially shorten the life of EV batteries. However, our review of the literature has not found research that estimates the calendar life of batteries under real-world high-heat conditions. As a test of robustness, we compute life cycle CO_2e emissions assuming each EV would require three, as opposed to two, battery replacements during its lifetime. This implies an expected 85,000 km life for each battery. The results are shown in Table A.3. Additional battery replacements have small impacts on life cycle CO_2e emissions, on the order of 0.08 tons per year. Table A.8 shows average manufacturing, fuel production, and fuel combustion emissions for EVs and ICEs in each NERC region under this scenario (VMT rebound, cold weather battery effects, and additional battery replacement). Changes in life cycle CO_2e emissions are driven only by vehicle manufacturing but the change is generally small in comparison to the fuel procurement and combustion-related reductions in CO_2e emissions.

VMT Rebound: Our primary specification assumes households have a price elasticity of VMT of -0.2. Electric vehicles have lower marginal costs of operation than gasoline-powered ICEs, so rebound will tend to reduce the GHG benefits of EVs. As a test of robustness, we consider VMT rebound elasticities of zero (no rebound) and -0.4 as well, consistent with the range of elasticities identified in the literature by Gillingham et al. [2014]. The results are shown in Table A.4. These robustness tests have the expected effect on the quantitative output of the simulation; EVs, with lower marginal costs of operation tend to increase emissions more than ICEs when the rebound elasticity is larger. However, under the range of rebound elasticities consistent with the literature our qualitative results are unchanged.

Average Grid Emissions: Other research examining the emissions benefits of EVs have considered average and not marginal emissions from electricity generation. While the relevant metric when considering the benefits of replacing an ICE with an EV is marginal change in GHG emissions from charging, in Table A.5 we present emissions benefits computed using average grid emissions for comparison. Note that, since wind, solar, and nuclear generation are generally inframarginal, the GHG benefits of EVs are generally larger when considering average emissions. This is not always the case, however. For example, the bulk of daytime generation in MRO is coal, but natural gas generation is often marginal. Here considering average emissions reduces the benefits EVs compared to ICEs.

A.3 Distribution of Emissions Benefits

The micro-level resolution of the NHTS allows us to investigate the distribution of impacts from replacing a midsize ICE with an EV, accounting for all considerations in our Complete Effects scenario. There is substantial heterogeneity both within and across geography in miles traveled per year, and it translates into heterogeneity in the potential benefits from adoption of an electric vehicle. Figure A.16 shows the difference in expected reduction in annualized life cycle emissions for replacing an ICE with an EV in each NERC regions and Californoa. It is important to note, while in expectation replacing an ICE with an EV in the MRO NERC region would lead to an emissions increase, there is some mass of households for which there are emissions gains. Conversely, in the WECC NERC region, where an EV is expected to deliver emissions benefits over ICEs, some portion of households would see increased life cycle CO_2 emissions by adopting an EV over an ICE.

Appendix Tables and Figures

Table A.1: Summary Stats for Electricity Generation, Emissions, and Fuel Consumption

Grid Interconnection	Houly Fuel Consumed Coal (mmBTU)	Natural Gas (mmBTU)	Petroleum (mmBTU)	Non-Fossil Fuel (mmBTU equiv.)	Hourly CO_2 (ton)	Hourly Gross Load (MWh)
FRCC	30,829	79,683	8,100	109,744	8,430	25,365
	(8,234)	(21,978)	(5,997)	(31,096)	(2,159)	(6,643)
MRO	159,415	7,953	54	9,491	17,472	16,340
	(27,324)	(12,546)	(212)	(14,503)	(3,198)	(2,623)
NPCC	14,360	96,985	9,386	174,852	7,903	33,253
	(11,065)	(29,296)	(10,087)	(23,687)	(2,869)	(6,391)
RFC	674,486	127,179	7,490	66,831	77,285	86,698
	(136,493)	(63,783)	(10,144)	(54,889)	(16,454)	(16,574)
SERC	430,181	244,185	1,831	234,137	58,850	94,991
	(105,780)	(87,714)	(4,732)	(49,425)	(14,545)	(18,918)
SPP	191,202	90,621	5,417	136,980	25,910	41,829
	(32,661)	(45,116)	(3,973)	(29,063)	(5,510)	(9,248)
TRE	157,518	135,947	48	66,923	24,750	37,612
	(31,647)	(62,274)	(288)	(19,826)	(6,129)	(9,562)
WECC	231,973	145,851	0	412,839	32,744	82,915
	(36,626)	(60,448)	(0)	(69,584)	(6,552)	(12,632)
US	1,889,771	928,334	32,324	1,211,699	253,320	418,967
	(342,285)	(334,184)	(25,736)	(138,649)	(50,811)	(74,007)

Mean fuel consumed, CO_2 emitted, and electricity generated per hour by fossil fuel-fired electricity generation units 50 MW and larger. Standard errors shown in parentheses. CEMS reports fuel consumption in millions of BTU. Analysis limited to electricity generation in 2011 and 2012.

Table A.2: GHG Emissions benefits of replacing a midsize ICE with an EV, accelerated battery wear

Region	Preferred Specification	Preferred Specification	Robustness Inc. Battery Wear	Robustness Inc. Battery Wear
FRCC	1.20	0.99	1.11	0.90
	[0.27 - 1.64]	[0.32 - 1.35]	[0.22 - 1.53]	[0.26 - 1.26]
MRO	0.01	-1.27	-0.07	-1.36
	[0.01 - 0.67]	[-1.56 - -0.11]	[-0.05 - 0.58]	[-1.67 - -0.21]
NPCC	0.20	0.70	0.13	0.62
	[-0.18 - 0.58]	[0.04 - 1.23]	[-0.24 - 0.50]	[0.00 - 1.15]
RFC	-0.18	-0.23	-0.26	-0.31
	[-0.45 - 0.09]	[-0.50 - 0.08]	[-0.50 - 0.03]	[-0.58 - 0.01]
SERC	0.32	0.11	0.23	0.02
	[0.03 - 0.50]	[-0.03 - 0.18]	[-0.02 - 0.40]	[-0.10 - 0.10]
SPP	0.29	-0.54	0.22	-0.61
	[-0.07 - 0.80]	[-0.71 - -0.14]	[-0.08 - 0.69]	[-0.82 - -0.18]
TRE	1.19	1.03	1.10	0.93
	[0.57 - 1.53]	[0.49 - 1.33]	[0.53 - 1.42]	[0.44 - 1.21]
WECC w/o CA	0.93	0.56	0.84	0.48
	[0.37 - 1.22]	[0.20 - 0.69]	[0.32 - 1.11]	[0.15 - 0.61]
CA	1.18	0.84	1.09	0.75
	[0.54 - 1.47]	[0.34 - 1.04]	[0.49 - 1.36]	[0.29 - 0.95]
US	0.41	0.18	0.33	0.09
	[0.01 - 0.76]	[-0.09 - 0.48]	[-0.04 - 0.68]	[-0.15 - 0.40]
Charge Time	Day	Night	Day	Night
Climate Effects	Yes	Yes	Yes	Yes
Battery Replacements	2	2	3	3
Rebound Elasticity	-.2	-.2	-.2	-.2
Emissions Calculation	Marginal	Marginal	Marginal	Marginal
Assumed Vehicle Life	257k km	257k km	257k km	257k km
Forecast Model	N/A	N/A	N/A	N/A
Foreast Year				

Expected life cycle tons of CO_2e avoided per year by replacing a midsized ICE with an EV. Day charging assumes EV charging is uniformly distributed from 9 AM to 5 PM. Night Charging assumes EV charging is uniformly distributed from 8 PM to 4 AM. Effects for the 25th and 75th percentile of the VMT distribution from NHTS shown in square brackets. Complete Effects Scenario assumed VMT rebound elasticity of -0.2, consistent with previous empirical estimates and accounts for reduced EV efficiency in cold weather. Battery Deterioration assumes EV batteries are, on average, replaced after 85,000 km, instead of 127,000 km in the Preferred specification.

Table A.3: GHG Emissions benefits of replacing a midsize ICE with an EV, Range limitations and alternative vehicle life assumptions

Region	257k km Vehicle Life	257k km Vehicle Life	16-year Vehicle Life	16-year Vehicle Life	12-year Vehicle Life	12-year Vehicle Life
FRCC	1.20	0.99	1.29	1.08	1.22	1.01
	[0.27 - 1.64]	[0.32 - 1.35]	[0.28 - 1.85]	[0.30 - 1.51]	[0.22 - 1.78]	[0.24 - 1.45]
MRO	0.01	-1.27	0.16	-1.10	0.09	-1.16
	[0.01 - 0.67]	[-1.56 - -0.11]	[-0.09 - 0.76]	[-1.33 - -0.23]	[-0.20 - 0.69]	[-1.40 - -0.31]
NPCC	0.20	0.70	0.28	0.77	0.21	0.70
	[-0.18 - 0.58]	[0.04 - 1.23]	[-0.18 - 0.68]	[-0.08 - 1.37]	[-0.25 - 0.60]	[-0.15 - 1.29]
RFC	-0.18	-0.23	-0.07	-0.11	-0.14	-0.19
	[-0.45 - 0.09]	[-0.50 - 0.08]	[-0.33 - 0.19]	[-0.36 - 0.17]	[-0.40 - 0.12]	[-0.42 - 0.10]
SERC	0.32	0.11	0.49	0.29	0.40	0.21
	[0.03 - 0.50]	[-0.03 - 0.18]	[0.04 - 0.74]	[-0.05 - 0.45]	[-0.05 - 0.64]	[-0.11 - 0.36]
SPP	0.29	-0.54	0.47	-0.41	0.31	-0.55
	[-0.07 - 0.80]	[-0.71 - -0.14]	[-0.24 - 0.93]	[-0.55 - -0.18]	[-0.51 - 0.86]	[-0.77 - -0.25]
TRE	1.19	1.03	1.34	1.18	1.28	1.11
	[0.57 - 1.53]	[0.49 - 1.33]	[0.54 - 1.78]	[0.45 - 1.57]	[0.47 - 1.71]	[0.39 - 1.51]
WECC w/o CA	0.93	0.56	1.04	0.69	1.01	0.65
	[0.37 - 1.22]	[0.20 - 0.69]	[0.25 - 1.42]	[0.12 - 1.00]	[0.27 - 1.35]	[0.09 - 0.94]
CA	1.18	0.84	1.27	0.94	1.20	0.87
	[0.54 - 1.47]	[0.34 - 1.04]	[0.51 - 1.64]	[0.32 - 1.25]	[0.44 - 1.57]	[0.25 - 1.18]
US	0.41	0.18	0.54	0.31	0.46	0.24
	[0.01 - 0.76]	[-0.09 - 0.48]	[-0.07 - 0.91]	[-0.15 - 0.67]	[-0.14 - 0.84]	[-0.22 - 0.59]
Charge Time	Day	Night	Day	Night	Day	Night
Climate Effects	Yes	Yes	Yes	Yes	Yes	Yes
Battery Replacements	2	2	2	2	2	2
Rebound Elasticity	-.2	-.2	-.2	-.2	-.2	-.2
Emissions Calculation	Marginal	Marginal	Marginal	Marginal	Marginal	Marginal
Assumed Vehicle Life	257k km	257k km	16 yr	16 yr	12 yr	12 yr
Forecast Model	N/A	N/A	N/A	N/A	N/A	N/A
Foreast Year						

Expected life cycle tons of CO_2e avoided per year by replacing a midsized ICE with an EV. Night Charging assumes EV charging is uniformly distributed from 8 PM to 4 AM. Effects for the 25th and 75th percentile of the VMT distribution from NHTS shown in square brackets. Complete Effects Scenario assumes both EVs and ICEs last for 257,000 km and are then replaced. Vehicle Life scenarios instead assume EVs and ICEs last 16 and 12 years, respectively, before replacement. EV trips are downweighted by the probability they are within the range of the EV given region/quarter climate conditions.

Table A.4: Emissions benefits of replacing a midsize ICE with an EV, robustness to VMT rebound

Region	Robustness No Rebound	Robustness No Rebound	Preferred Specification	Preferred Specification	Robustness Strong Rebound	Robustness Strong Rebound
FRCC	1.81	1.63	1.20	0.99	0.58	0.35
	[0.70 - 2.39]	[0.73 - 2.11]	[0.27 - 1.64]	[0.32 - 1.35]	[-0.03 - 0.91]	[-0.20 - 0.76]
MRO	0.84	-0.31	0.01	-1.27	-0.82	-2.24
	[0.19 - 1.50]	[-0.41 - 0.03]	[0.01 - 0.67]	[-1.56 - -0.11]	[-0.84 - 0.06]	[-2.68 - -0.74]
NPCC	0.79	1.25	0.20	0.70	-0.38	0.15
	[0.13 - 1.15]	[0.34 - 1.73]	[-0.18 - 0.58]	[0.04 - 1.23]	[-0.81 - 0.12]	[-0.49 - 0.74]
RFC	0.56	0.51	-0.18	-0.23	-0.92	-0.97
	[0.11 - 0.81]	[0.04 - 0.80]	[-0.45 - 0.09]	[-0.50 - 0.08]	[-1.25 - -0.35]	[-1.33 - -0.37]
SERC	1.16	0.97	0.32	0.11	-0.52	-0.75
	[0.48 - 1.57]	[0.43 - 1.30]	[0.03 - 0.50]	[-0.03 - 0.18]	[-0.72 - -0.14]	[-1.03 - -0.30]
SPP	0.97	0.22	0.29	-0.54	-0.38	-1.30
	[0.21 - 1.56]	[-0.02 - 0.48]	[-0.07 - 0.80]	[-0.71 - -0.14]	[-0.39 - -0.03]	[-1.92 - -0.41]
TRE	1.93	1.78	1.19	1.03	0.45	0.27
	[0.93 - 2.48]	[0.85 - 2.28]	[0.57 - 1.53]	[0.49 - 1.33]	[0.19 - 0.58]	[0.07 - 0.36]
WECC w/o CA	1.65	1.33	0.93	0.56	0.20	-0.21
	[0.74 - 2.00]	[0.60 - 1.62]	[0.37 - 1.22]	[0.20 - 0.69]	[-0.03 - 0.31]	[-0.39 - -0.02]
CA	1.77	1.46	1.18	0.84	0.59	0.22
	[0.89 - 2.21]	[0.73 - 1.86]	[0.54 - 1.47]	[0.34 - 1.04]	[0.17 - 0.71]	[-0.09 - 0.37]
US	1.14	0.94	0.41	0.18	-0.32	-0.58
	[0.33 - 1.57]	[0.24 - 1.35]	[0.01 - 0.76]	[-0.09 - 0.48]	[-0.69 - 0.16]	[-0.94 - -0.03]
Charge Time	Day	Night	Day	Night	Day	Night
Climate Effects	Yes	Yes	Yes	Yes	Yes	Yes
Battery Replacements	2	2	2	2	2	2
Rebound Elasticity	0	0	-.2	-.2	-.4	-.4
Emissions Calculation	Marginal	Marginal	Marginal	Marginal	Marginal	Marginal
Assumed Vehicle Life	257k km	257k km	257k km	257k km	257k km	257k km
Forecast Model	N/A	N/A	N/A	N/A	N/A	N/A
Foreast Year						

Expected life cycle tons of CO_2e avoided per year by replacing a midsized ICE with an EV. Day charging assumes EV charging is uniformly distributed from 9 AM to 5 PM. Night Charging assumes EV charging is uniformly distributed from 8 PM to 4 AM. Effects for the 25th and 75th percentile of the VMT distribution from NHTS shown in square brackets. Preferred scenario assumed VMT rebound elasticity of -0.2, consistent with previous empirical estimates and accounts for impact of climate on vehicle operating efficiency. Low Rebound and High Rebound scenarios assume VMT rebound elasticities of -0.1 and -0.4, respectively, consistent with the range of empirical estimates in the literature.

Table A.5: GHG Emissions benefits of replacing a midsize ICE with an EV, Average grid emissions

Region	Preferred Specification	Preferred Specification	Robustness Average Emissions
FRCC	1.20	0.99	2.55
	[0.27 - 1.64]	[0.32 - 1.35]	[1.21 - 3.26]
MRO	0.01	-1.27	-1.93
	[0.01 - 0.67]	[-1.56 - -0.11]	[-2.34 - -0.68]
NPCC	0.20	0.70	2.89
	[-0.18 - 0.58]	[0.04 - 1.23]	[1.53 - 3.61]
RFC	-0.18	-0.23	-0.75
	[-0.45 - 0.09]	[-0.50 - 0.08]	[-1.00 - -0.31]
SERC	0.32	0.11	1.02
	[0.03 - 0.50]	[-0.03 - 0.18]	[0.42 - 1.38]
SPP	0.29	-0.54	0.80
	[-0.07 - 0.80]	[-0.71 - -0.14]	[0.32 - 1.11]
TRE	1.19	1.03	0.91
	[0.57 - 1.53]	[0.49 - 1.33]	[0.42 - 1.20]
WECC w/o CA	0.93	0.56	2.20
	[0.37 - 1.22]	[0.20 - 0.69]	[1.12 - 2.77]
CA	1.18	0.84	2.39
	[0.54 - 1.47]	[0.34 - 1.04]	[1.15 - 2.99]
US	0.41	0.18	0.87
	[0.01 - 0.76]	[-0.09 - 0.48]	[-0.33 - 1.79]
Charge Time	Day	Night	Avg
Climate Effects	Yes	Yes	Yes
Battery Replacements	2	2	3
Rebound Elasticity	-.2	-.2	-.2
Emissions Calculation	Marginal	Marginal	Average
Assumed Vehicle Life	257k km	257k km	257k km
Forecast Model	N/A	N/A	N/A
Foreast Year			

Expected life cycle tons of CO_2e avoided per year by replacing a midsized ICE with an EV. Night Charging assumes EV charging is uniformly distributed from 8 PM to 4 AM. Effects for the 25th and 75th percentile of the VMT distribution from NHTS shown in square brackets. Preferred scenario assumes both EVs and ICEs last for 257,000 km and are then replaced.

Table A.6: life cycle emissions by source, VMT Rebound Scenario

Interconnect	Technology	Vehicle Manufacturing	Fuel Production	Fuel Combustion	Total
	EV	0.85	0.36	2.85	4.06
FRCC	*ICE*	0.53	0.95	3.67	5.14
	Difference	0.33	-0.58	-0.82	-1.08
	EV	0.85	0.37	4.19	5.40
MRO	*ICE*	0.52	0.93	3.61	5.05
	Difference	0.33	-0.56	0.58	0.35
	EV	0.78	0.32	2.54	3.64
NPCC	*ICE*	0.49	0.89	3.44	4.81
	Difference	0.29	-0.57	-0.89	-1.17
	EV	0.83	0.37	3.43	4.62
RFC	*ICE*	0.51	0.92	3.56	4.99
	Difference	0.32	-0.55	-0.13	-0.37
	EV	0.94	0.30	3.85	5.09
SERC	*ICE*	0.57	1.03	3.99	5.59
	Difference	0.37	-0.73	-0.14	-0.50
	EV	0.85	0.21	4.09	5.15
SPP	*ICE*	0.52	0.93	3.62	5.07
	Difference	0.33	-0.72	0.46	0.07
	EV	0.95	0.40	3.19	4.55
TRE	*ICE*	0.58	1.05	4.08	5.71
	Difference	0.37	-0.65	-0.88	-1.16
	EV	0.88	0.33	3.10	4.31
WECC w/o CA	*ICE*	0.53	0.96	3.73	5.22
	Difference	0.34	-0.63	-0.63	-0.91
	EV	0.88	0.33	3.10	4.31
CA	*ICE*	0.55	0.99	3.85	5.40
	Difference	0.33	-0.66	-0.75	-1.09
	EV	0.87	0.34	3.40	4.61
US	*ICE*	0.54	0.96	3.74	5.23
	Difference	0.33	-0.63	-0.33	-0.62

Expected life cycle tons of CO_2e avoided per year by replacing a midsized ICE with an EV. Vehicle Manufacturing comprises annualized life cycle emissions from vehicle manufacture and maintenance. Fuel Production includes emissions from extracting, processing, and transporting fuel prior to combustion. Fuel Combustion accounts for all direct emissions from the combustion of fuel to power the vehicle. Assumes EV charging is uniformly distributed from 8 PM to 4 AM. VMT Rebound scenario assumes a midsize ICE is replaced with an EV and a VMT rebound elasticity of -0.2.

Table A.7: life cycle emissions by source, Climate Performance Scenario

Interconnect	Technology	Vehicle Manufacturing	Fuel Production	Fuel Combustion	Total
	EV	0.85	0.39	3.08	4.33
FRCC	*ICE*	0.53	0.98	3.81	5.31
	Difference	0.33	-0.59	-0.73	-0.99
	EV	0.85	0.47	5.31	6.63
MRO	*ICE*	0.52	0.98	3.92	5.41
	Difference	0.33	-0.51	1.40	1.22
	EV	0.78	0.40	3.31	4.50
NPCC	*ICE*	0.49	0.94	3.75	5.18
	Difference	0.29	-0.53	-0.44	-0.68
	EV	0.83	0.45	4.26	5.53
RFC	*ICE*	0.51	0.96	3.83	5.31
	Difference	0.32	-0.51	0.42	0.23
	EV	0.94	0.35	4.47	5.76
SERC	*ICE*	0.57	1.07	4.22	5.87
	Difference	0.37	-0.72	0.24	-0.11
	EV	0.85	0.26	4.81	5.92
SPP	*ICE*	0.52	0.98	3.87	5.37
	Difference	0.33	-0.72	0.94	0.55
	EV	0.95	0.45	3.57	4.97
TRE	*ICE*	0.58	1.10	4.31	6.00
	Difference	0.37	-0.65	-0.74	-1.03
	EV	0.88	0.40	3.71	4.99
WECC w/o CA	*ICE*	0.53	1.01	4.00	5.55
	Difference	0.34	-0.61	-0.29	-0.56
	EV	0.88	0.37	3.49	4.74
CA	*ICE*	0.55	1.02	4.00	5.58
	Difference	0.33	-0.65	-0.52	-0.84
	EV	0.87	0.40	4.07	5.35
US	*ICE*	0.54	1.01	3.99	5.53
	Difference	0.33	-0.61	0.09	-0.18

Expected life cycle tons of CO_2e avoided per year by replacing a midsized ICE with an EV. Vehicle Manufacturing comprises annualized life cycle emissions from vehicle manufacture and maintenance. Fuel Production includes emissions from extracting, processing, and transporting fuel prior to combustion. Fuel Combustion accounts for all direct emissions from the combustion of fuel to power the vehicle. Assumes EV charging is uniformly distributed from 8 PM to 4 AM. Battery Performance scenario assumes a midsize ICE is replaced with an EV, accounts for impact of climate on vehicle operating efficiency, and assumes a VMT rebound elasticity of -0.2.

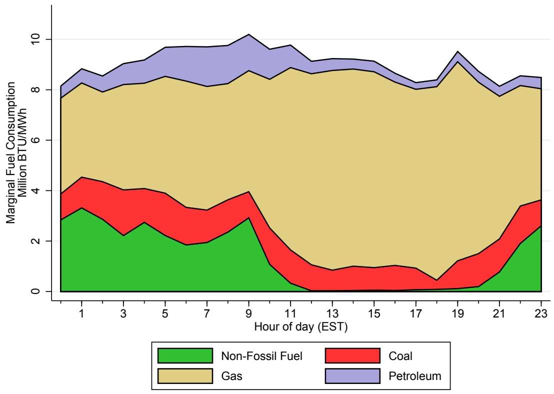
Table A.8: life cycle emissions by source, Battery Deterioration Scenario

Interconnect	Technology	Vehicle Manufacturing	Fuel Production	Fuel Combustion	Total
	EV	0.94	0.39	3.08	4.41
FRCC	*ICE*	0.53	0.98	3.81	5.31
	Difference	0.41	-0.59	-0.73	-0.90
	EV	0.93	0.47	5.31	6.71
MRO	*ICE*	0.52	0.98	3.92	5.41
	Difference	0.42	-0.51	1.40	1.30
	EV	0.85	0.40	3.31	4.57
NPCC	*ICE*	0.49	0.94	3.75	5.18
	Difference	0.36	-0.53	-0.44	-0.61
	EV	0.91	0.45	4.26	5.62
RFC	*ICE*	0.51	0.96	3.83	5.31
	Difference	0.40	-0.51	0.42	0.31
	EV	1.03	0.35	4.47	5.85
SERC	*ICE*	0.57	1.07	4.22	5.87
	Difference	0.46	-0.72	0.24	-0.02
	EV	0.93	0.26	4.81	6.01
SPP	*ICE*	0.52	0.98	3.87	5.37
	Difference	0.41	-0.72	0.94	0.64
	EV	1.05	0.45	3.57	5.07
TRE	*ICE*	0.58	1.10	4.31	6.00
	Difference	0.46	-0.65	-0.74	-0.93
	EV	0.97	0.40	3.71	5.08
WECC w/o CA	*ICE*	0.53	1.01	4.00	5.55
	Difference	0.43	-0.61	-0.29	-0.47
	EV	0.97	0.37	3.49	4.83
CA	*ICE*	0.55	1.02	4.00	5.58
	Difference	0.42	-0.65	-0.52	-0.75
	EV	0.96	0.40	4.07	5.43
US	*ICE*	0.54	1.01	3.99	5.53
	Difference	0.42	-0.61	0.09	-0.10

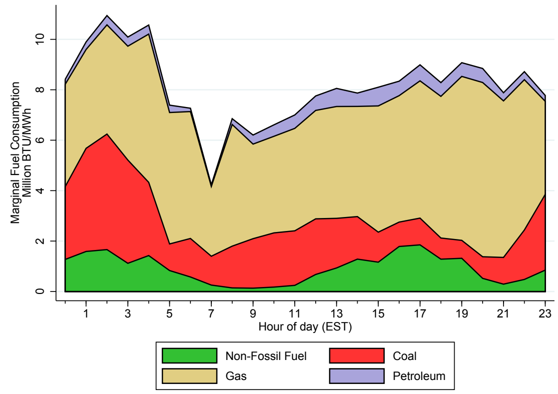
Expected life cycle tons of CO_2e avoided per year by replacing a midsized ICE with an EV. Vehicle Manufacturing comprises annualized life cycle emissions from vehicle manufacture and maintenance. Fuel Production includes emissions from extracting, processing, and transporting fuel prior to combustion. Fuel Combustion accounts for all direct emissions from the combustion of fuel to power the vehicle. Assumes EV charging is uniformly distributed from 8 PM to 4 AM. Battery Deterioration scenario assumes a midsize ICE is replaced with an EV, accounts for impact of climate on vehicle operating efficiency, a VMT rebound elasticity of -0.2, and EV batteries are replaced on average after 53,000 miles as opposed to 80,000 miles (as in the Base Scenario).

Figure A.1: Marginal Fuel Use, FRCC NERC Region

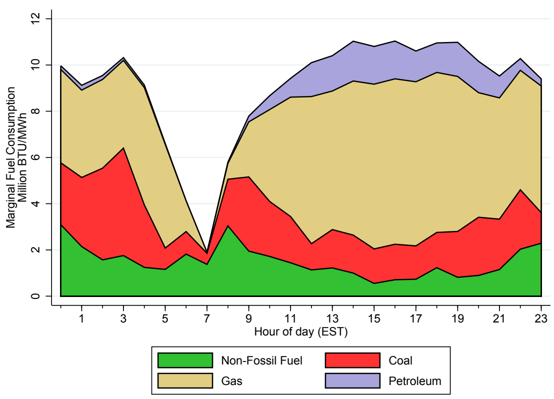
(a) January to March



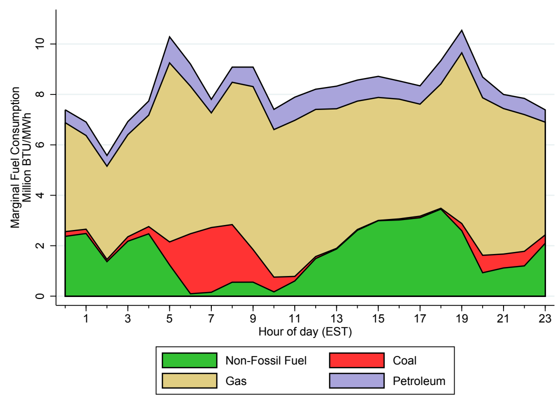
(b) April to June



(c) July to September



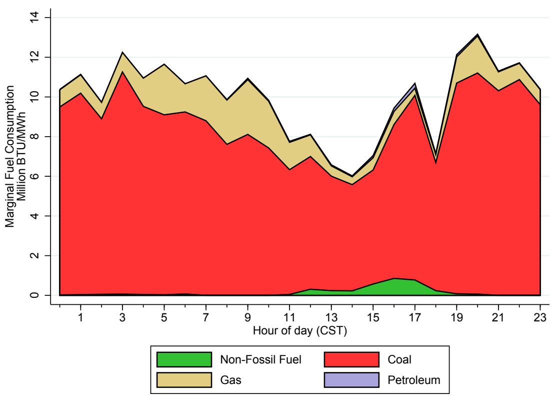
(d) October to December



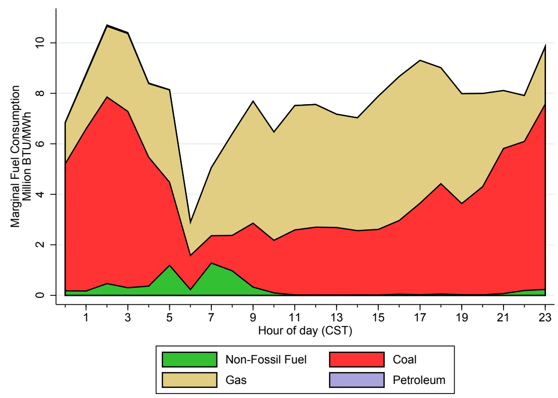
Marginal fuel use in million BTU of fuel consumed per MWh generated on the FRCC NERC region. Non-fossil fuel generation represents the quantity of fossil fuel consumption required to generate an equivalent quantity of electricity, approximately 9 mmBTU/MWh. Parameter estimates computed using weekly block bootstrap through 200 replications. Estimates include hour by month fixed effects, instrumenting for non-fossil fuel generation using lagged values, using generation and load data from in 2011 and 2012.

Figure A.2: Marginal Fuel Use, MRO NERC Region

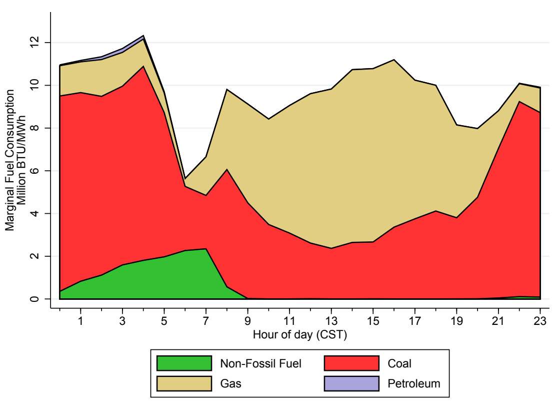
(a) January to March



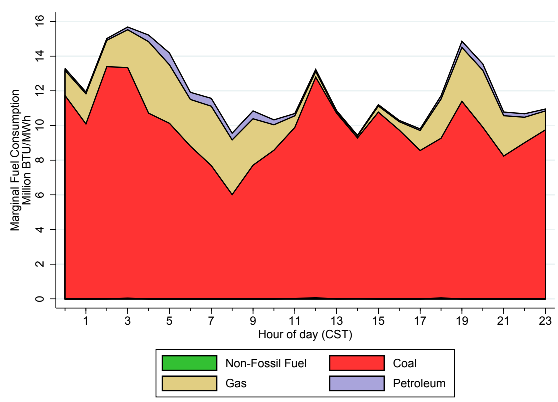
(b) April to June



(c) July to September

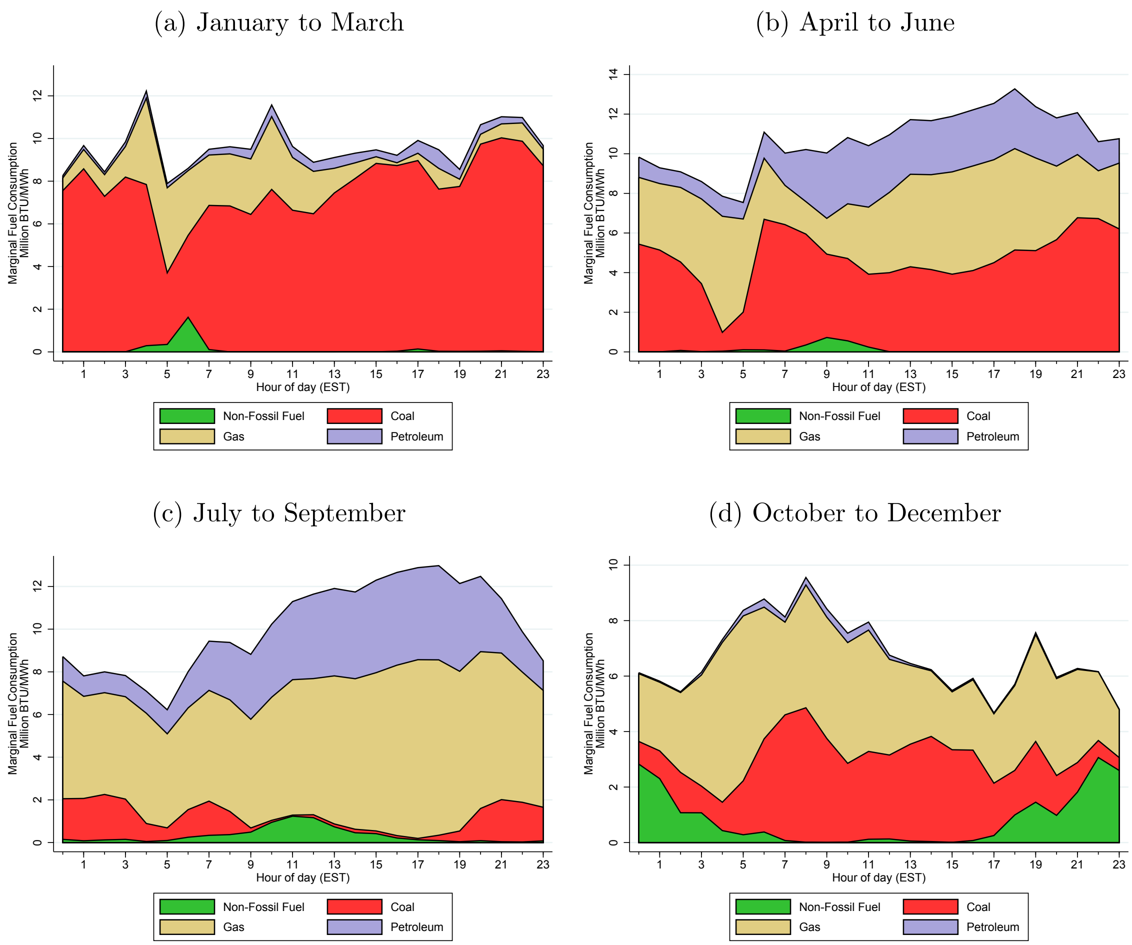


(d) October to December



Marginal fuel use in million BTU of fuel consumed per MWh generated on the MRO NERC region. Non-fossil fuel generation represents the quantity of fossil fuel consumption required to generate an equivalent quantity of electricity, approximately 9 mmBTU/MWh. Parameter estimates computed using weekly block bootstrap through 200 replications. Estimates include hour by month fixed effects, instrumenting for non-fossil fuel generation using lagged values, using generation and load data from in 2011 and 2012.

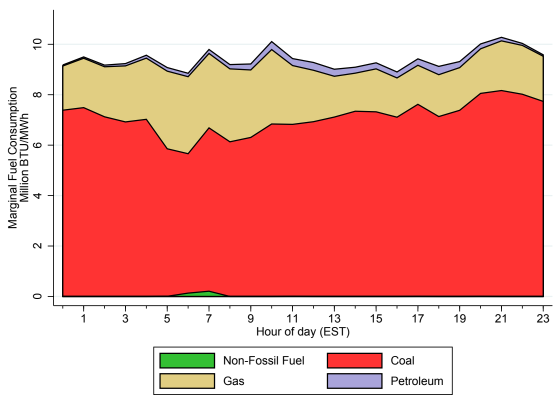
Figure A.3: Marginal Fuel Use, NPCC NERC Region



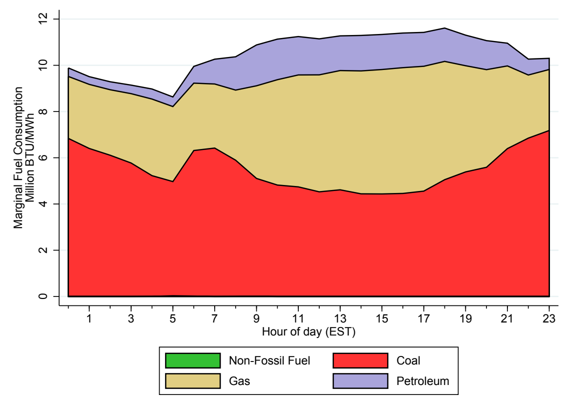
Marginal fuel use in million BTU of fuel consumed per MWh generated on the NPCC NERC region. Non-fossil fuel generation represents the quantity of fossil fuel consumption required to generate an equivalent quantity of electricity, approximately 9 mmBTU/MWh. Parameter estimates computed using weekly block bootstrap through 200 replications. Estimates include hour by month fixed effects, instrumenting for non-fossil fuel generation using lagged values, using generation and load data from in 2011 and 2012.

Figure A.4: Marginal Fuel Use, RFC NERC Region

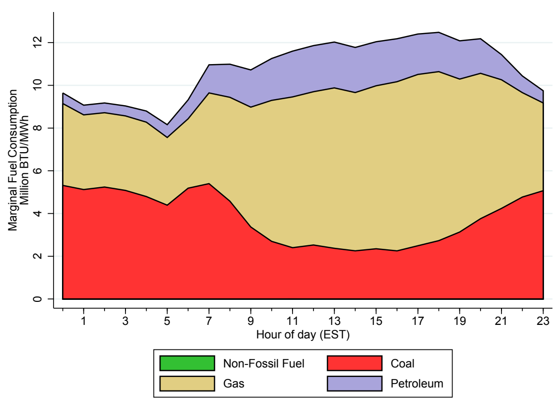
(a) January to March



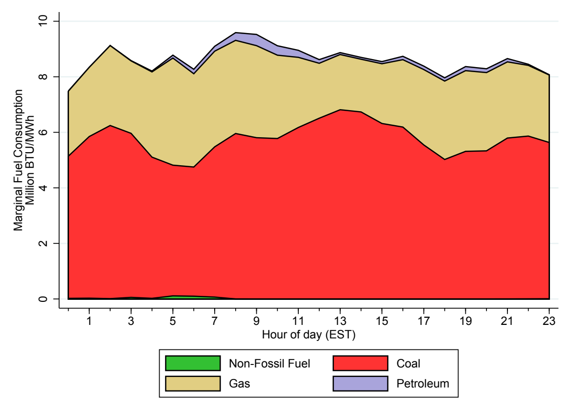
(b) April to June



(c) July to September



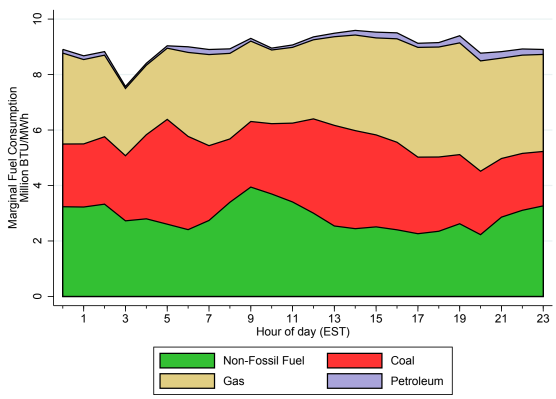
(d) October to December



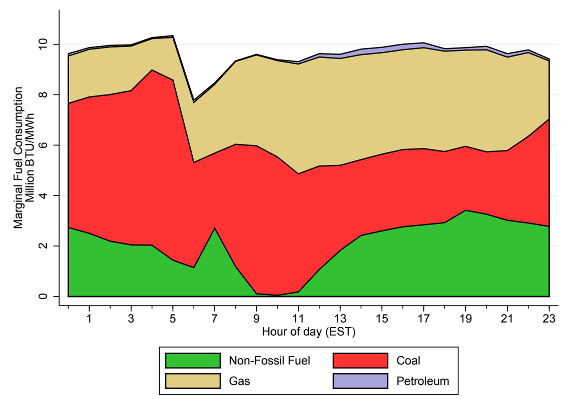
Marginal fuel use in million BTU of fuel consumed per MWh generated on the RFC NERC region. Non-fossil fuel generation represents the quantity of fossil fuel consumption required to generate an equivalent quantity of electricity, approximately 9 mmBTU/MWh. Parameter estimates computed using weekly block bootstrap through 200 replications. Estimates include hour by month fixed effects, instrumenting for non-fossil fuel generation using lagged values, using generation and load data from in 2011 and 2012.

Figure A.5: Marginal Fuel Use, SERC NERC Region

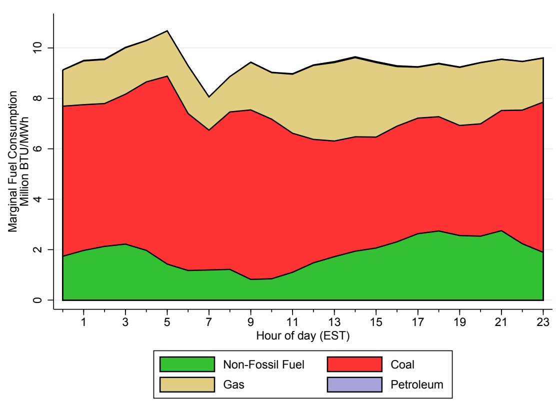
(a) January to March



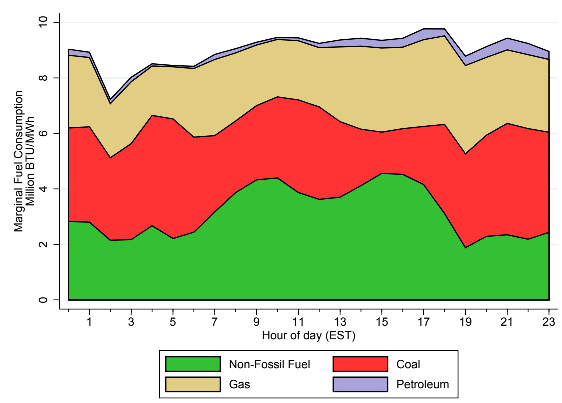
(b) April to June



(c) July to September

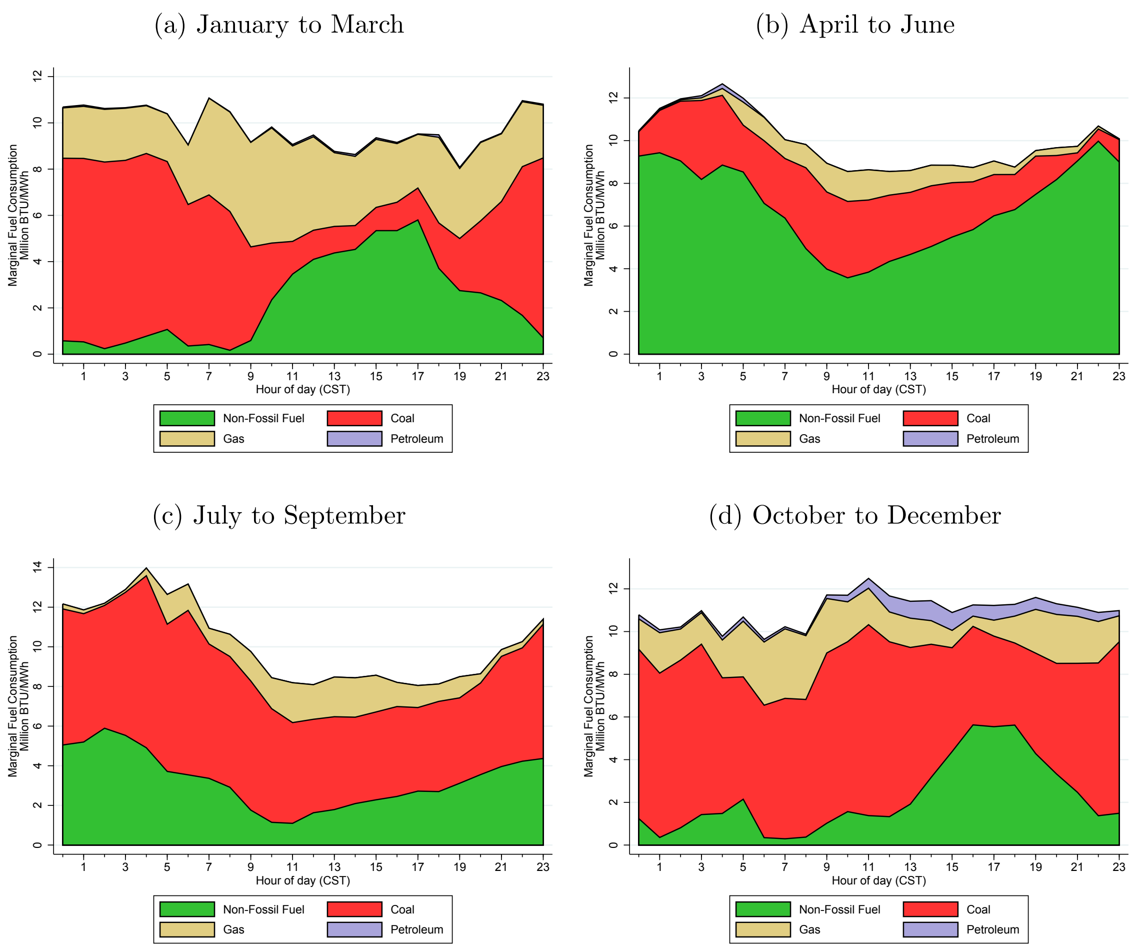


(d) October to December



Marginal fuel use in million BTU of fuel consumed per MWh generated on the SERC NERC region. Non-fossil fuel generation represents the quantity of fossil fuel consumption required to generate an equivalent quantity of electricity, approximately 9 mmBTU/MWh. Parameter estimates computed using weekly block bootstrap through 200 replications. Estimates include hour by month fixed effects, instrumenting for non-fossil fuel generation using lagged values, using generation and load data from in 2011 and 2012.

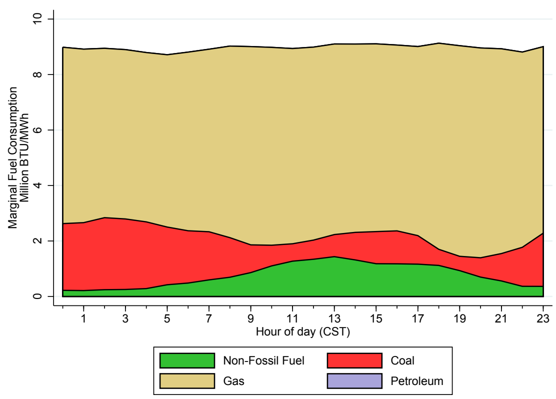
Figure A.6: Marginal Fuel Use, SPP NERC Region



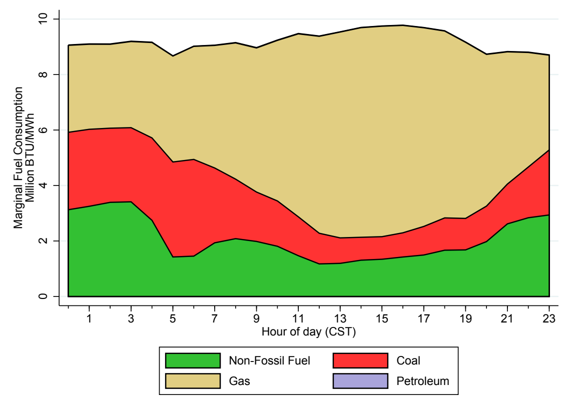
Marginal fuel use in million BTU of fuel consumed per MWh generated on the SPP NERC region. Non-fossil fuel generation represents the quantity of fossil fuel consumption required to generate an equivalent quantity of electricity, approximately 9 mmBTU/MWh. Parameter estimates computed using weekly block bootstrap through 200 replications. Estimates include hour by month fixed effects, instrumenting for non-fossil fuel generation using lagged values, using generation and load data from in 2011 and 2012.

Figure A.7: Marginal Fuel Use, TRE NERC Region

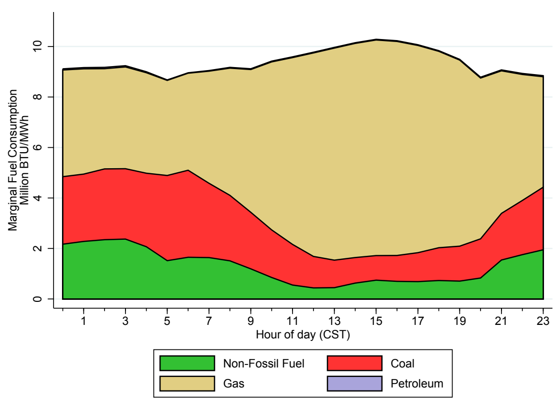
(a) January to March



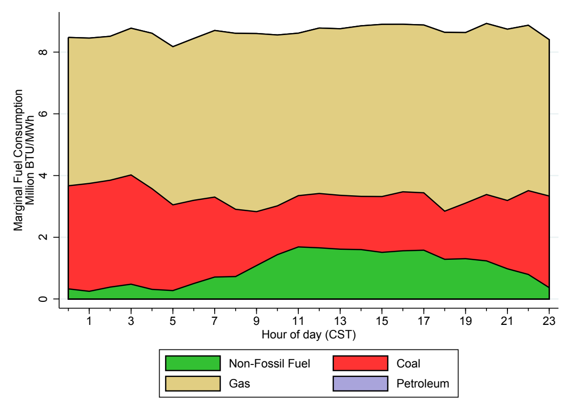
(b) April to June



(c) July to September



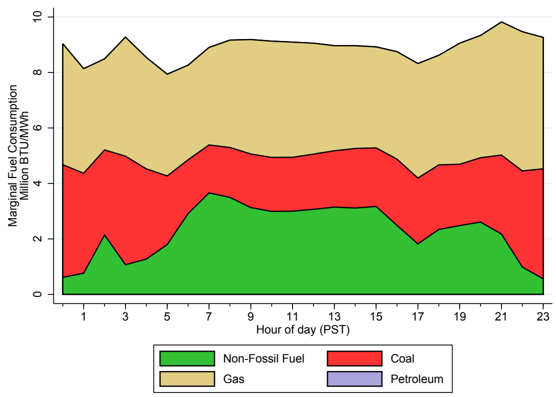
(d) October to December



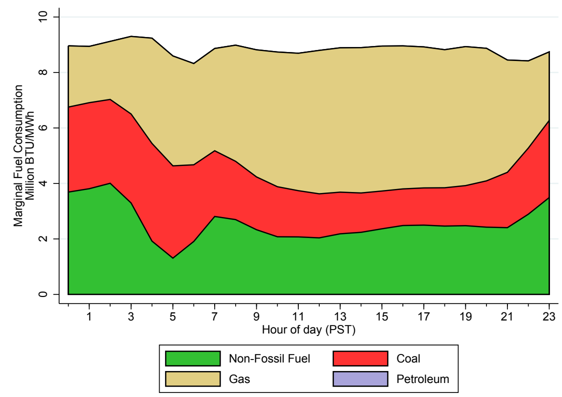
Marginal fuel use in million BTU of fuel consumed per MWh generated on the TRE NERC region. Non-fossil fuel generation represents the quantity of fossil fuel consumption required to generate an equivalent quantity of electricity, approximately 9 mmBTU/MWh. Parameter estimates computed using weekly block bootstrap through 200 replications. Estimates include hour by month fixed effects, instrumenting for non-fossil fuel generation using lagged values, using generation and load data from in 2011 and 2012.

Figure A.8: Marginal Fuel Use, WECC NERC Region

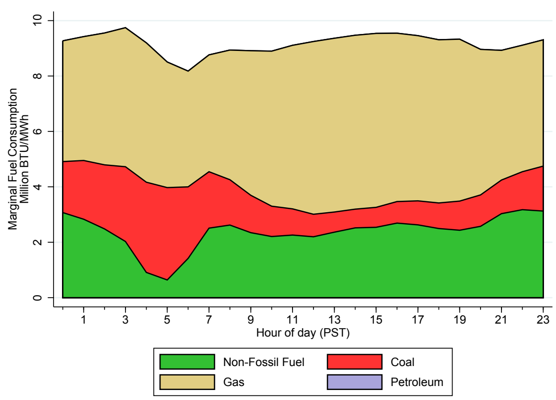
(a) January to March



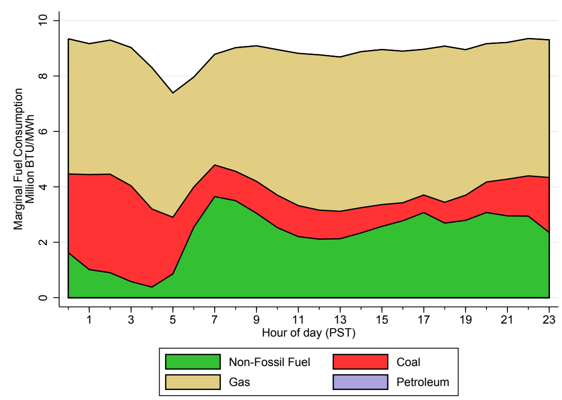
(b) April to June



(c) July to September

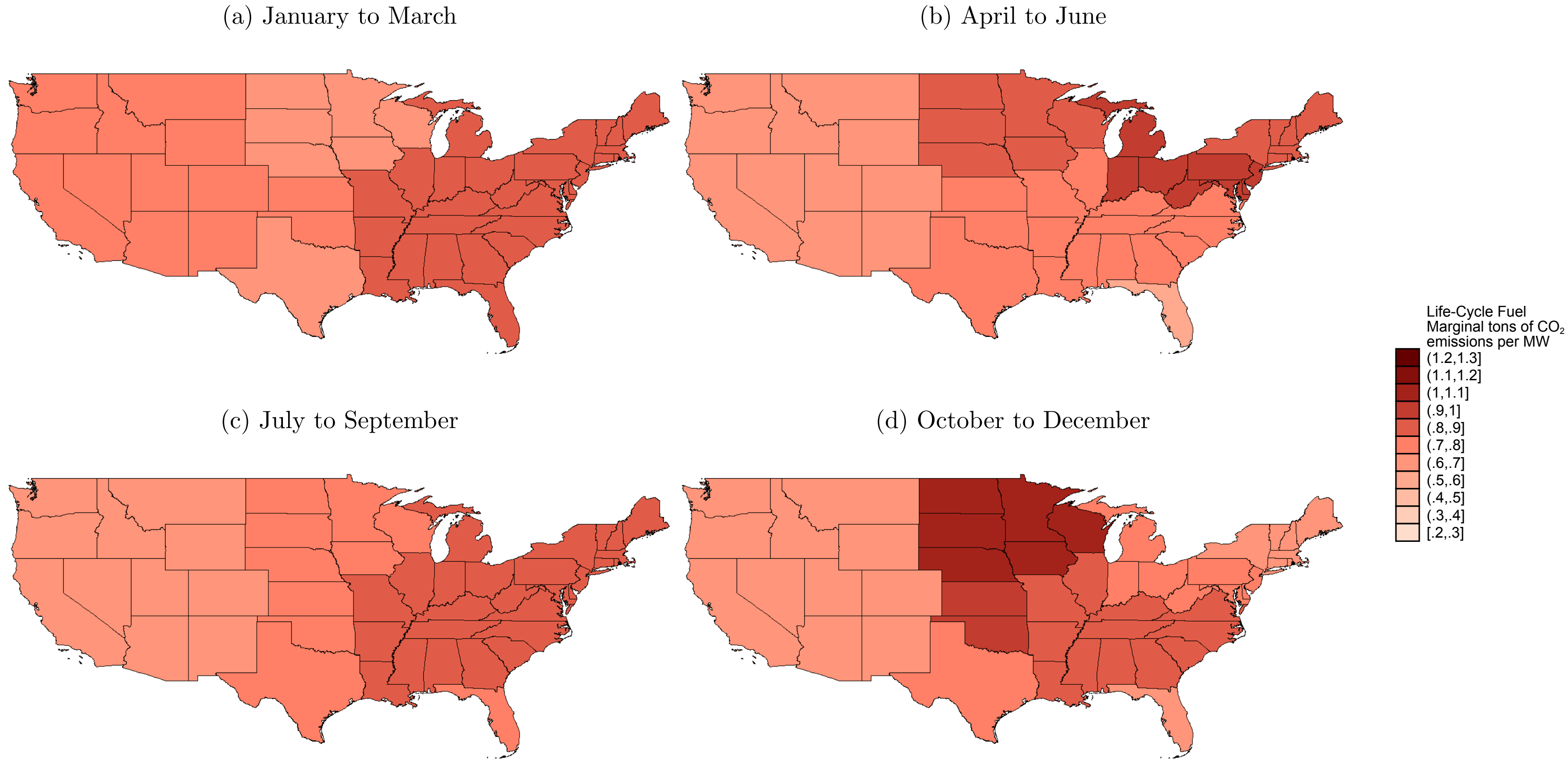


(d) October to December



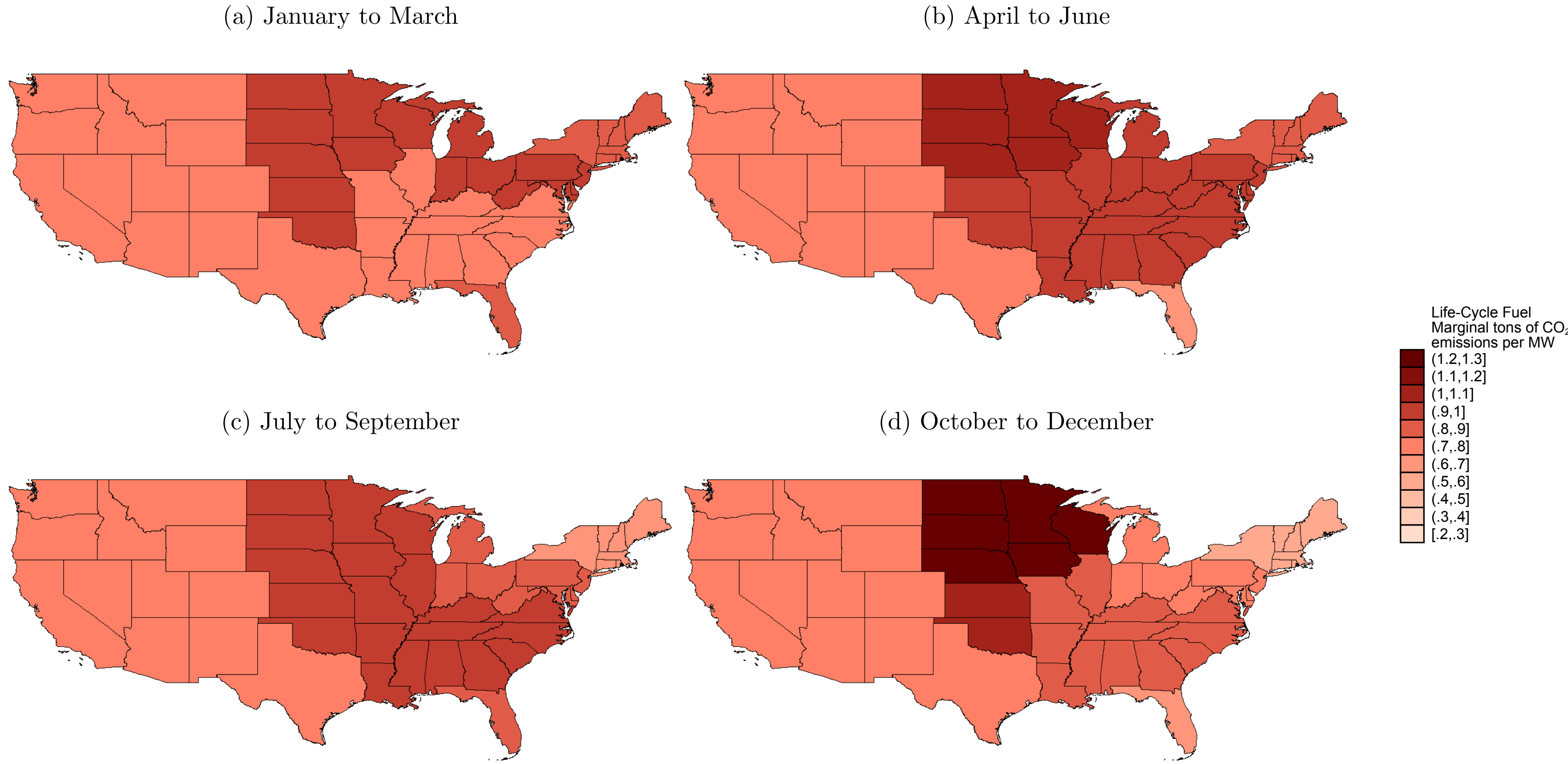
Marginal fuel use in million BTU of fuel consumed per MWh generated on the WECC NERC region. Non-fossil fuel generation represents the quantity of fossil fuel consumption required to generate an equivalent quantity of electricity, approximately 9 mmBTU/MWh. Parameter estimates computed using weekly block bootstrap through 200 replications. Estimates include hour by month fixed effects, instrumenting for non-fossil fuel generation using lagged values, using generation and load data from in 2011 and 2012.

Figure A.9: Marginal Emissions from Day Charging



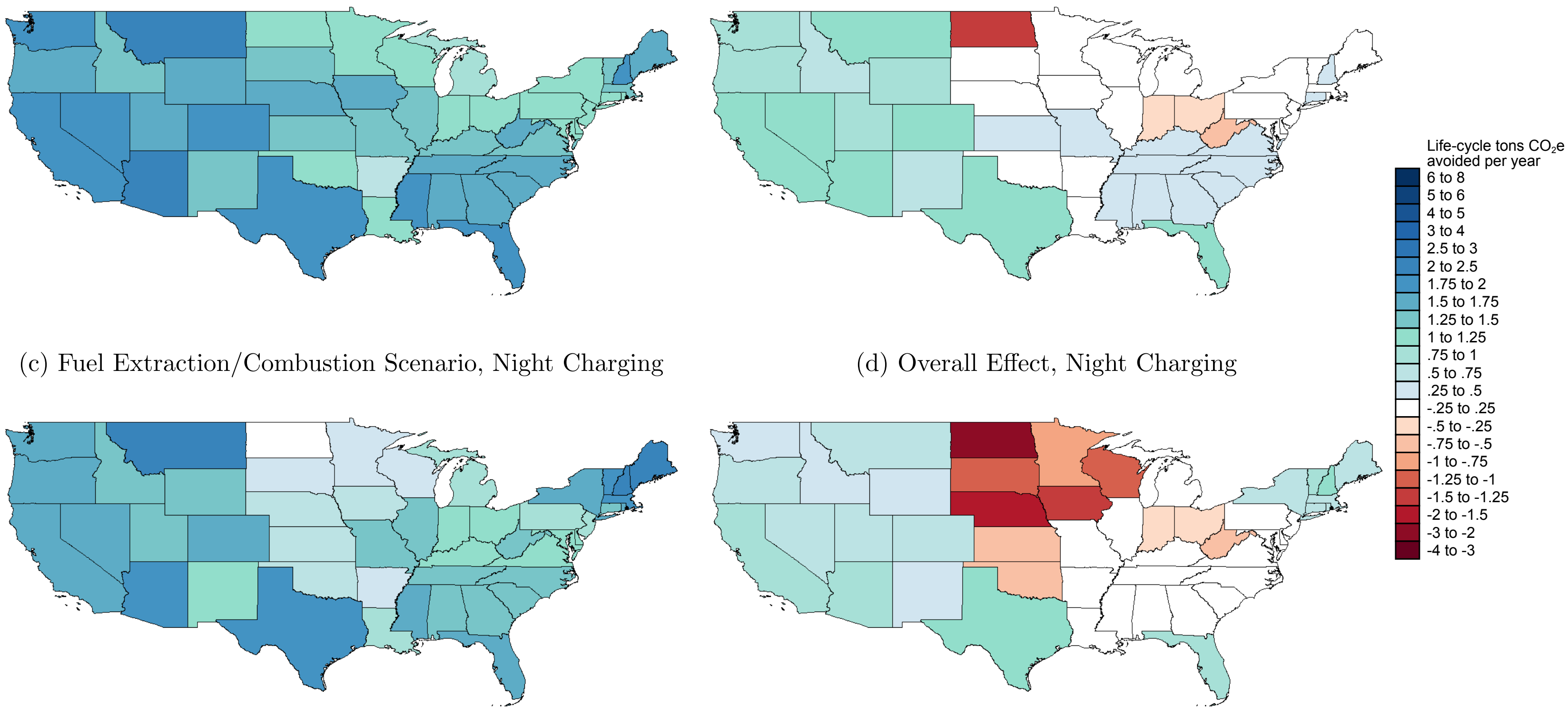
Expected marginal emissions in tons of CO_2e by grid NERC region from direct fuel combustion and indirect GHG emissions per MWh of EV charging. Estimated using CEMS and FERC Form 714 data from 2011 and 2012. Color scales are identical across quarters and darker colors indicate higher emissions. Night charging assumes uniform probability of charging from 9 AM until 4 PM and zero probability otherwise.

Figure A.10: Marginal Emissions from Night Charging



Expected marginal emissions in tons of CO_2e by grid NERC region from direct fuel combustion and indirect GHG emissions per MWh of EV charging. Estimated using CEMS and FERC Form 714 data from 2011 and 2012. Color scales are identical across quarters and darker colors indicate higher emissions. Night charging assumes uniform probability of charging from 8 PM until 4 AM and zero probability otherwise.

Figure A.11: Expected annual CO_2e emissions from replacing an ICE with an EV, Night Charging



(a) Fuel Extraction/Combustion Scenario, Day Charging

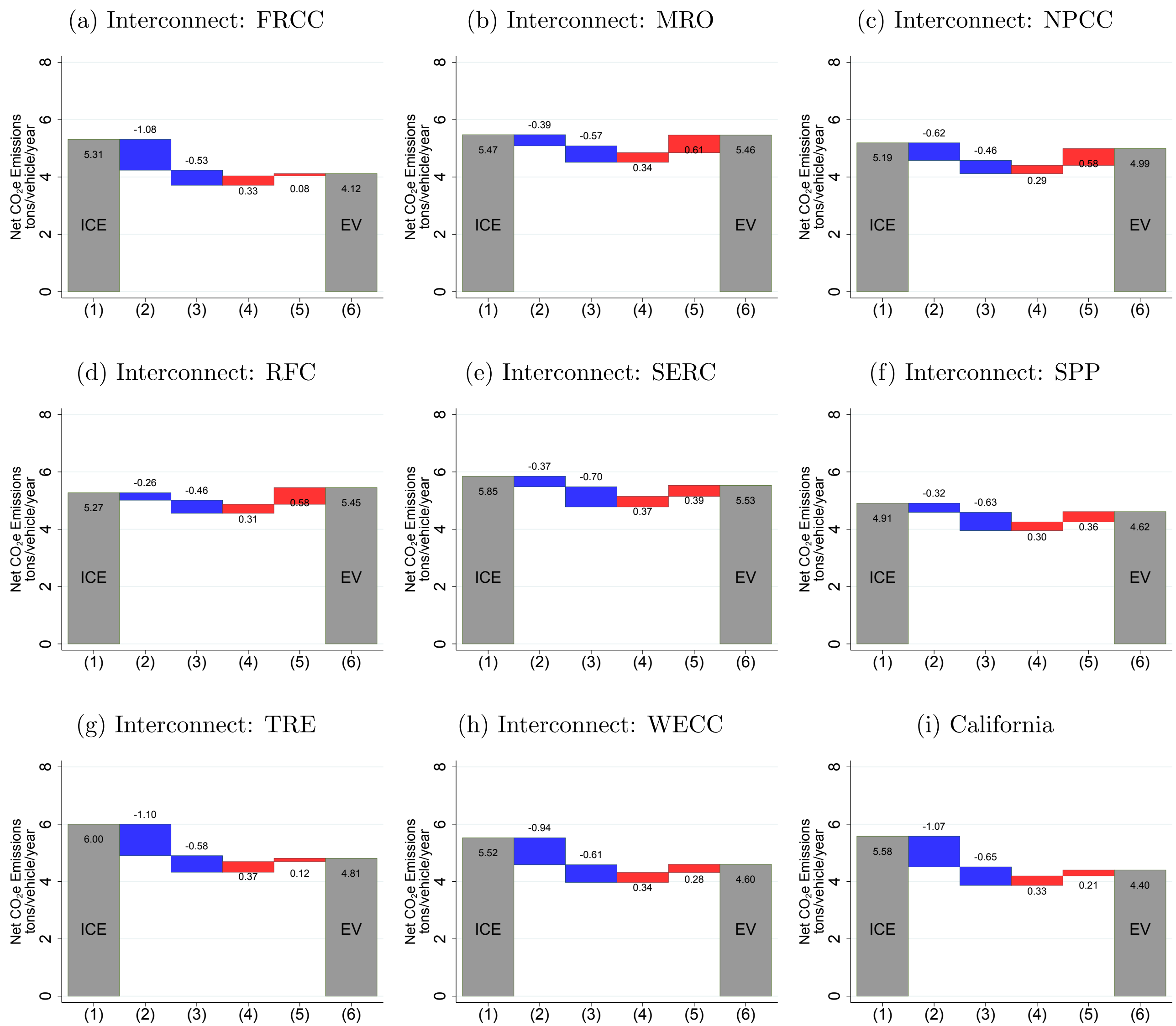
(b) Overall Effect, Day Charging

(c) Fuel Extraction/Combustion Scenario, Night Charging

(d) Overall Effect, Night Charging

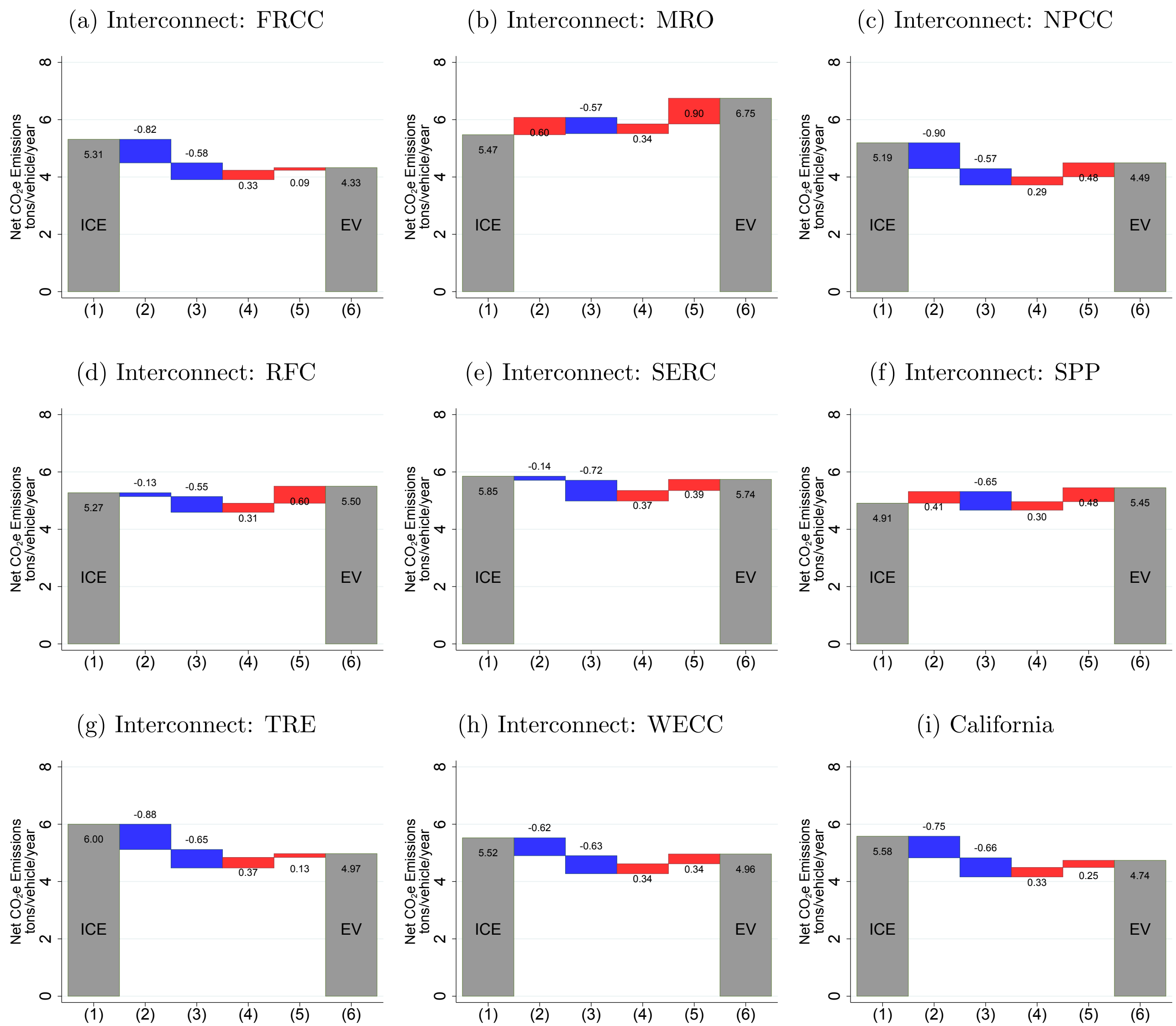
Expected emissions reduction in tons of CO_2e per year from replacing a midsized ICE with an EV. Color scales are identical across maps. Day charging assumes vehicles are charged between 9 AM and 5 PM. Night charging assumes vehicles are charged between 8 PM and 4 AM. Overall Effects scenarios assume a VMT rebound elasticity of -0.2 and for impact of climate on vehicle operating efficiency.

Figure A.12: Net impact on CO_2e emissions by source, day charging



Blue (red) bars represent net CO_2e emissions reduction (increase) in tons per year by replacing (1) a midsize ICE with (6) an EV. Assumes a VMT rebound elasticity of -0.2. EV batteries are assumed to be replaced twice during the life of the vehicle, after about 80,000 miles. Emissions sources are categorized as follows: (2) Fuel Combustion - direct emissions from combustion of fuel to power ICEs or electricity generation; (3) Fuel Production - other emissions associated with the extraction, processing, transport, and storage of fossil fuels for combustion; (4) Manufacturing Emissions - emissions associated with manufacturing and maintenance of the vehicle over its lifetime; (5) Climate - emissions attributable to the impact of climate on the efficient operation of EVs and ICEs

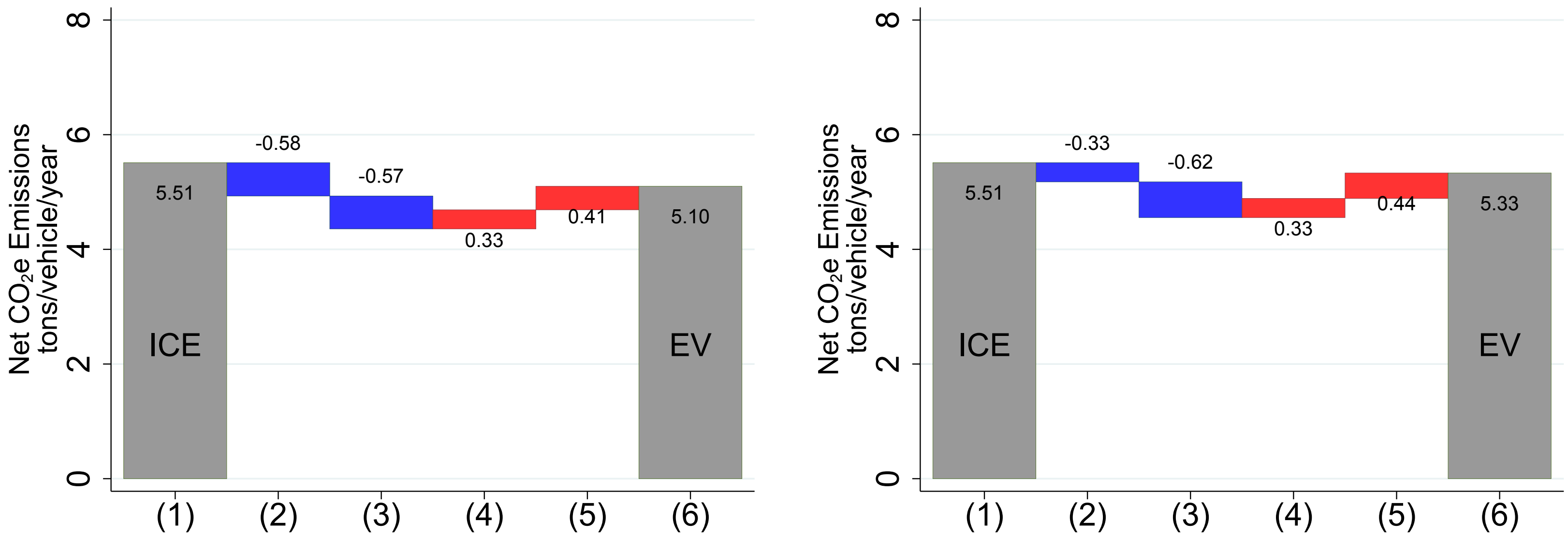
Figure A.13: Net impact on CO_2e emissions by source, night charging



Blue (red) bars represent net CO_2e emissions reduction (increase) in tons per year by replacing (1) a midsize ICE with (6) an EV. Assumes a VMT rebound elasticity of -0.2. EV batteries are assumed to be replaced twice during the life of the vehicle, after about 80,000 miles. Emissions sources are categorized as follows: (2) Fuel Combustion - direct emissions from combustion of fuel to power ICEs or electricity generation; (3) Fuel Production - other emissions associated with the extraction, processing, transport, and storage of fossil fuels for combustion; (4) Manufacturing Emissions - emissions associated with manufacturing and maintenance of the vehicle over its lifetime; (5) Climate - emissions attributable to the impact of climate on the efficient operation of EVs and ICEs

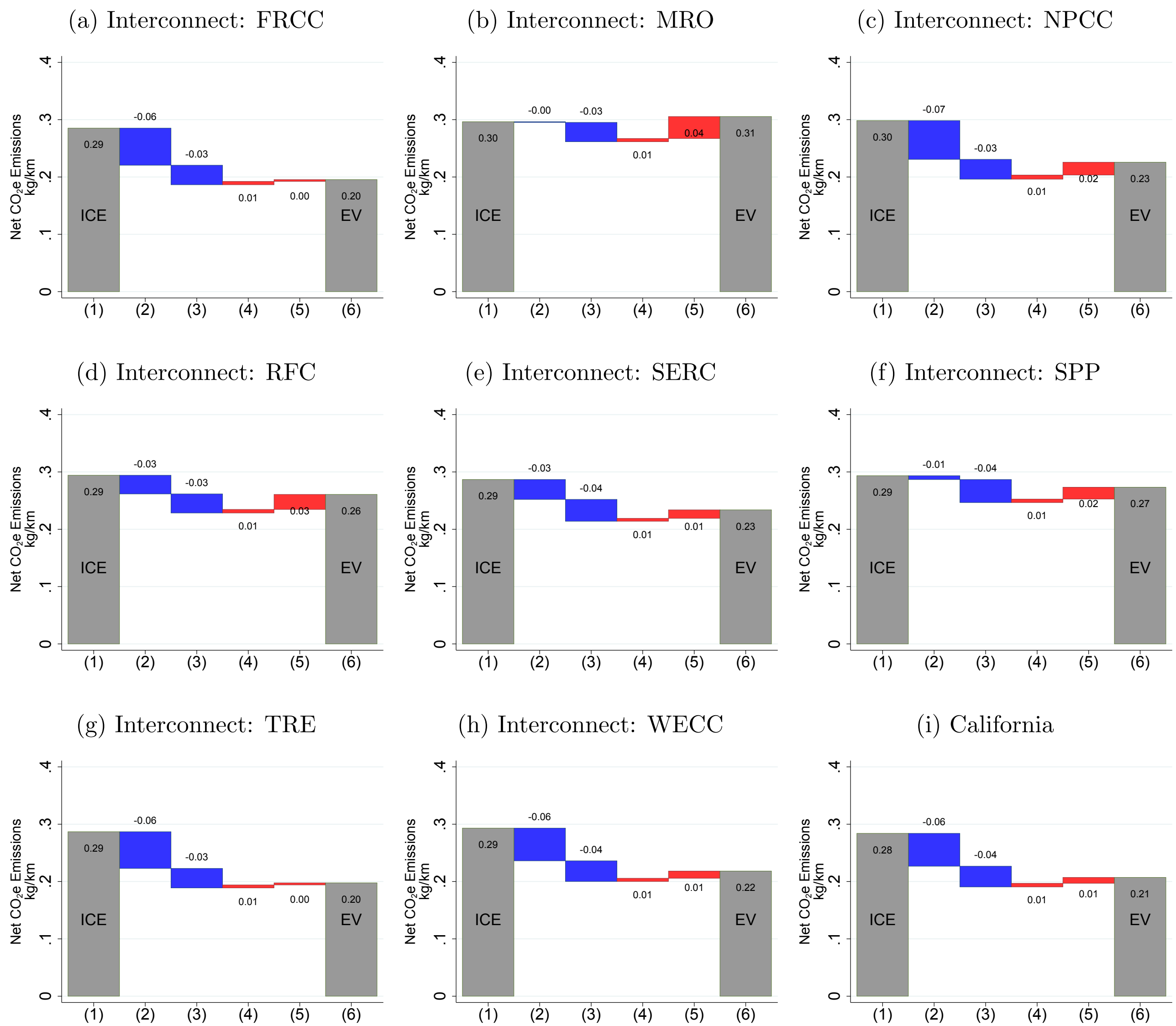
Figure A.14: Net impact on CO_2e emissions by source, United States

(a) Day Charging (b) Night Charging



Blue (red) bars represent net CO_2e emissions reduction (increase) in tons per year by replacing (1) a midsize ICE with (6) an EV. Assumes a VMT rebound elasticity of -0.2. EV batteries are assumed to be replaced twice during the life of the vehicle, after about 80,000 miles. Emissions sources are categorized as follows: (2) Fuel Combustion - direct emissions from combustion of fuel to power ICEs or electricity generation; (3) Fuel Production - other emissions associated with the extraction, processing, transport, and storage of fossil fuels for combustion; (4) Manufacturing Emissions - emissions associated with manufacturing and maintenance of the vehicle over its lifetime; (5) Climate - emissions attributable to the impact of climate on the efficient operation of EVs and ICEs.

Figure A.15: Net impact on CO_2e emissions by source, assuming 16-year Vehicle Life

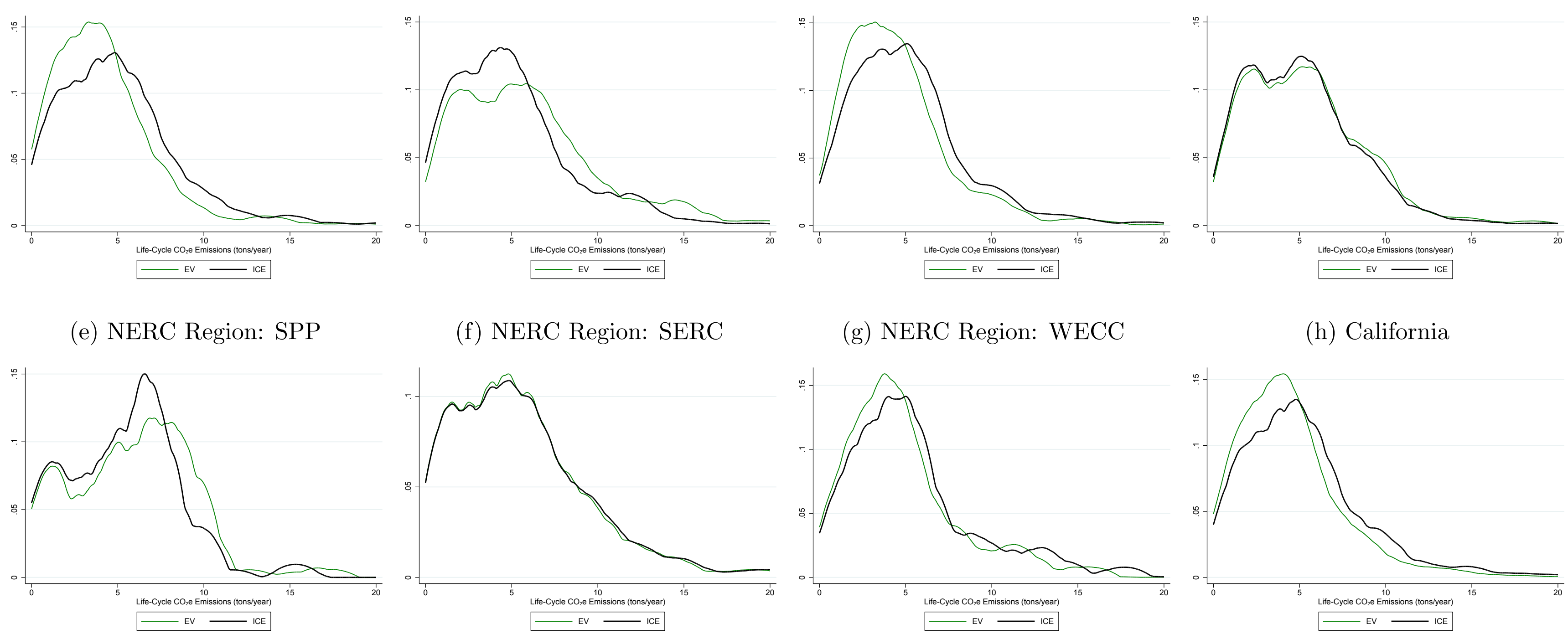


Blue (red) bars represent net CO_2e emissions reduction (increase) in tons per year by replacing (1) a midsize ICE with (6) an EV. Assumes a VMT rebound elasticity of -0.2. EV batteries are assumed to be replaced twice during the life of the vehicle, after about 80,000 miles. Emissions sources are categorized as follows: (2) Fuel Combustion - direct emissions from combustion of fuel to power ICEs or electricity generation; (3) Fuel Production - other emissions associated with the extraction, processing, transport, and storage of fossil fuels for combustion; (4) Manufacturing Emissions - emissions associated with manufacturing and maintenance of the vehicle over its lifetime; (5) Climate - emissions attributable to the impact of climate on the efficient operation of EVs and ICEs

Figure A.16: Probability distribution of annualized life cycle CO_2e emissions benefits

(a) NERC Region: FRCC (b) NERC Region: MRO (c) NERC Region: NPCC (d) NERC Region: RFC

(e) NERC Region: SPP (f) NERC Region: SERC (g) NERC Region: WECC (h) California



Kernel density estimate of the distribution in annualized reduction in life cycle CO_2e emissions from replacing a midsized ICE with an EV. Assumes EVs are charged between 8 PM and 4 AM, assumes a VMT rebound elasticity of -0.2, and accounts for the reduced performance of EVs in cold weather. Estimates use the Epanechnikov kernel with bandwidth 0.5.