Supporting Information

Marginal Emissions Factors for Electricity Generation in the Midcontinent ISO

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Sections:

1) Regional MISO analysis
2) State analysis
3) Utility analysis
4) Generator analysis
5) Variation of share of average and average marginal generation and AEFs and AMEFs by system demand
6) Temporal analysis

No. of pages = 16

No. of figures = 21

No. of tables = 7

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1. Regional MISO analysis

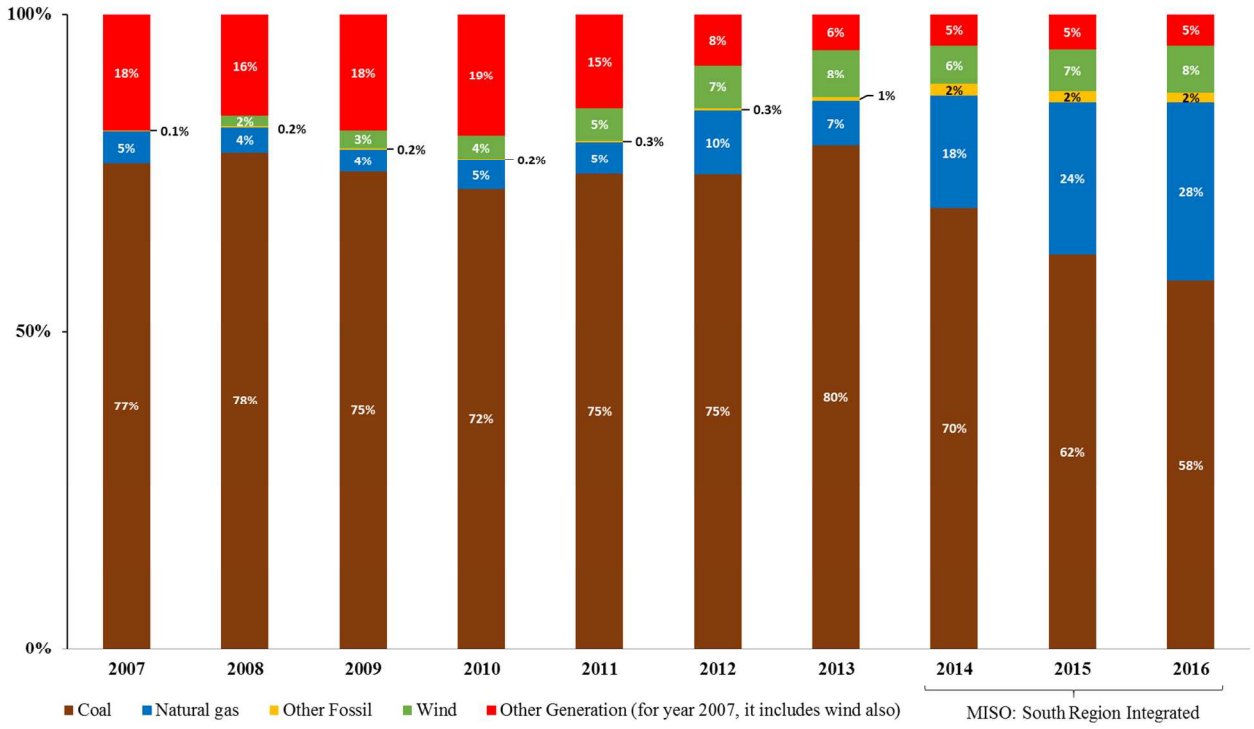
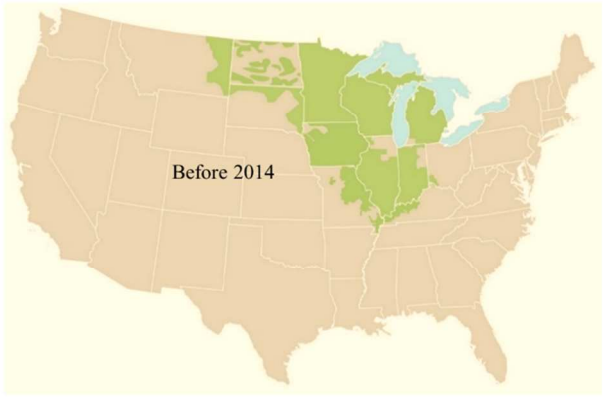


Figure S1. Generation statistics of MISO (Other generation includes nuclear, hydro and other renewables. For the year 2007, 'Other generation' includes wind as well because MISO wind data for year 2007 is not available).



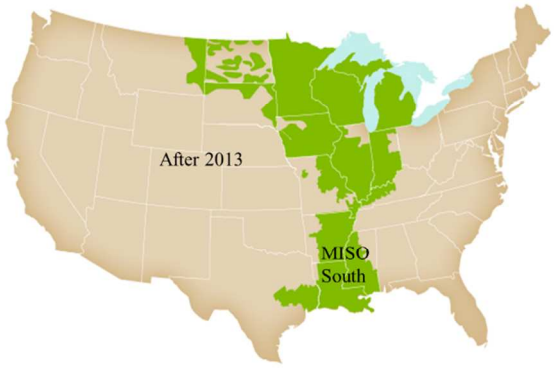


Figure S2. Midcontinent ISO footprint (Source: https://www.misoenergy.org/Planning/InterregionalCoordination/PublishingImages/IPSAC_MISO_Map.png)

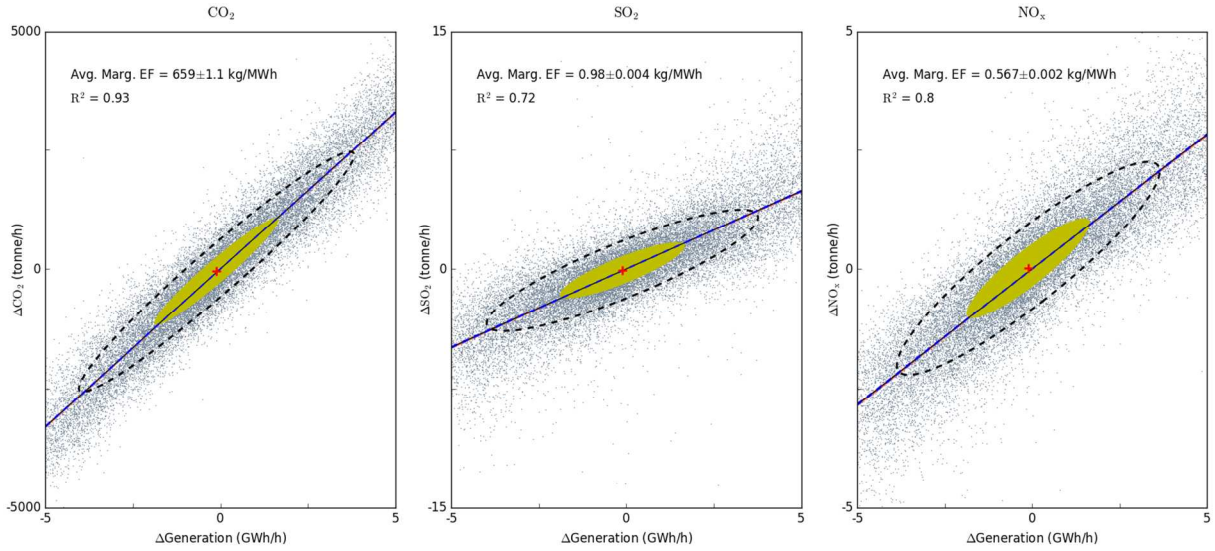


Figure S3. Linear regression for hourly changes in power generation and pollutant emissions, for Midcontinent ISO, years-2014 through 2016, after south region was integrated to Midwest ISO.

Table S1. Comparison between AEF and AMEF at regional scale for years 2014-2016

Pollutant	AEF (Kg/MWh)	AMEF (Kg/MWh)	EFs % Difference
CO_2	704	659	-6.4%
SO_2	0.953	0.984	3%
NO_x	0.521	0.567	9%

Table S2. MISO Regional AEF and AMEFs differences by year

Year	CO_2 AEF	CO_2 AMEF	CO_2 AMEF R^2	CO_2 AMEF -AEF	SO_2 AEF	SO_2 AMEF	SO_2 AMEF R^2	SO_2 AMEF -AEF	NO_x AEF	NO_x AMEF	NO_x AMEF R^2	NO_x AMEF -AEF
2007	747	576	0.87	-23%	2.71	2.18	0.71	-20%	0.963	0.691	0.63	-28%
2008	756	590	0.84	-22%	2.48	1.96	0.70	-21%	0.936	0.691	0.74	-26%
2009	722	585	0.89	-19%	2.06	1.82	0.80	-12%	0.678	0.565	0.76	-17%
2010	703	545	0.88	-22%	1.83	1.44	0.73	-21%	0.618	0.481	0.77	-22%
2011	732	602	0.88	-18%	1.68	1.49	0.70	-11%	0.626	0.537	0.76	-14%
2012	745	659	0.90	-12%	1.44	1.38	0.78	-4%	0.616	0.547	0.77	-11%
2013	772	628	0.88	-19%	1.43	1.28	0.72	-10%	0.628	0.513	0.73	-18%
All years	739	597	0.88	-19%	1.97	1.63	0.71	-17%	0.727	0.567	0.72	-22%

Table S3. MISO Regional AEF and AMEFs by fuel type for years 2007 through 2013

Coal-fired EGUs				
	AEF	AMEF	AMEF R^2	AMEF - AEF
CO_2	712	511 ± 1.085	0.78	-28%
SO_2	1.96	1.61 ± 0.0042	0.70	-18%
NO_x	0.708	0.518 ± 0.0015	0.67	-27%
Natural gas-fired EGUs				
	AEF	AMEF	AMEF R^2	AMEF - AEF
CO2	22.9	85.7 ± 0.391	0.44	274%
SO2	0.0096	0.017 ± 0.0003	0.06	78%
NOx	0.016	0.046 ± 0.0003	0.24	182%

*% difference is calculated as ((AMEF – AEF)/AEF) *100

Table S4. MISO Regional AEF and AMEFs for coal fleet by year

Year	CO_2 AEF	CO_2 AMEF	CO_2 AMEF R^2	CO_2 AMEF -AEF	SO_2 AEF	SO_2 AMEF	SO_2 AMEF R^2	SO_2 AMEF -AEF	NO_x AEF	NO_x AMEF	NO_x AMEF R^2	NO_x AMEF -AEF
2007	720	450	0.71	-37%	2.68	2.10	0.68	-21%	0.927	0.619	0.56	-33%
2008	737	507	0.73	-31%	2.46	1.91	0.69	-22%	0.908	0.632	0.70	-30%
2009	704	530	0.83	-25%	2.06	1.81	0.79	-12%	0.668	0.533	0.73	-20%
2010	680	467	0.78	-31%	1.83	1.43	0.73	-22%	0.605	0.432	0.71	-29%
2011	706	526	0.80	-25%	1.68	1.49	0.70	-11%	0.612	0.494	0.71	-19%
2012	702	557	0.83	-21%	1.44	1.38	0.78	-4%	0.596	0.496	0.72	-17%
2013	740	538	0.79	-27%	1.42	1.28	0.72	-10%	0.614	0.471	0.68	-23%
All years	712	511	0.78	-28%	1.96	1.61	0.70	-18%	0.708	0.518	0.67	-27%

Table S5. MISO Regional AEF and AMEFs for natural gas fleet by year

Year	CO_2 AEF	CO_2 AMEF	CO_2 AMEF R^2	CO_2 AMEF -AEF	SO_2 AEF	SO_2 AMEF	SO_2 AMEF R^2	SO_2 AMEF -AEF	NO_x AEF	NO_x AMEF	NO_x AMEF R^2	NO_x AMEF -AEF
2007	26.4	126	0.53	375%	0.034	0.075	0.22	118%	0.034	0.071	0.34	106%
2008	16.9	82.6	0.42	389%	0.024	0.044	0.15	84%	0.024	0.052	0.21	114%
2009	14.5	54.8	0.39	278%	0.002	0.007	0.05	220%	0.008	0.028	0.15	275%
2010	19.2	78.3	0.41	307%	0.002	0.006	0.08	219%	0.010	0.045	0.28	341%
2011	20.8	75.7	0.41	265%	0.001	0.002	0.03	52%	0.010	0.040	0.26	291%
2012	38.2	102	0.52	167%	0.0003	0.001	0.03	149%	0.016	0.048	0.31	208%
2013	26.6	89.3	0.47	235%	0.0002	0.001	0.14	256%	0.010	0.040	0.19	303%
All years	22.9	85.7	0.44	274%	0.0096	0.017	0.06	78%	0.016	0.046	0.24	182%

2) State analysis

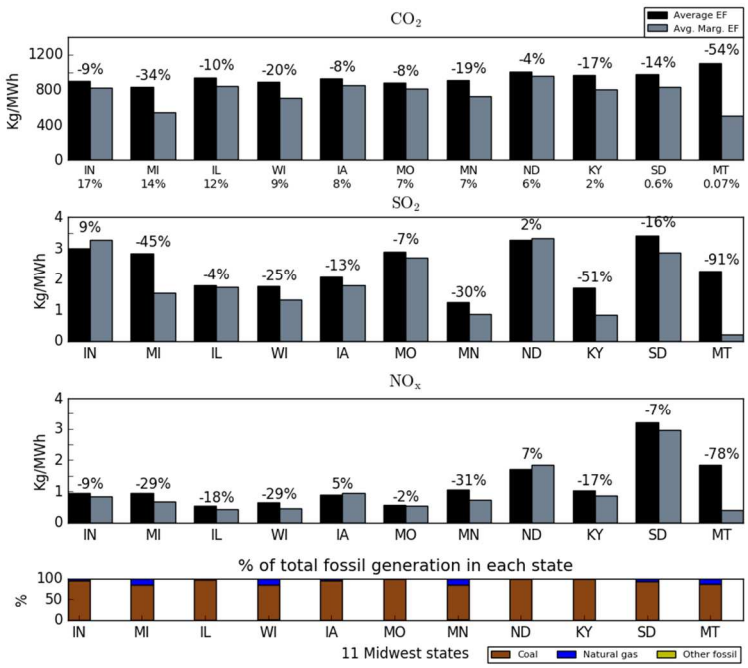
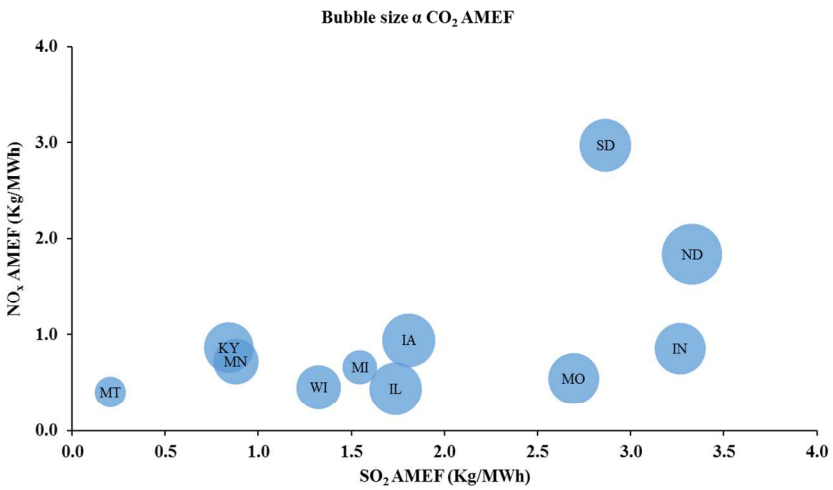


Figure S4. State wise AEF and AMEF for three pollutants from year 2007 through 2013. Percentages at top of bars show the difference between AEF and AMEF. States are sorted by increasing % share of total MISO generation (shown at bottom of x-axis for CO2 plot, sum of percentages ~83%). Bottommost plot shows % generation by fuel in each state.

(A.)



B.)

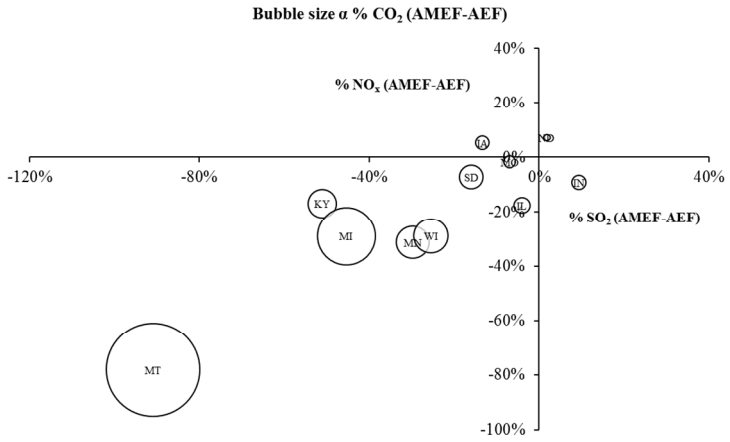


Figure S5. (A) Plots showing inter-relation between three variables: CO_2 AMEF, SO_2 AMEF and NO_x AMEF. (B) Plot showing inter-relation between % difference between AEF and AMEF for three pollutants.

Plot (A) shows low correlation between NO_x AMEF and SO_2 AMEF with insignificant change in CO_2 AMEF

3) Utility Analysis

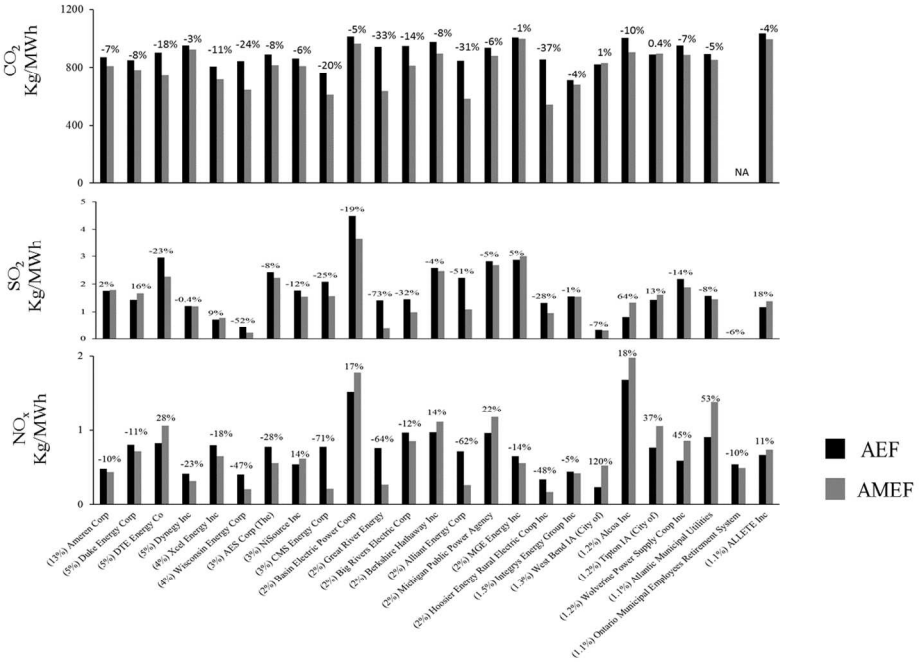


Figure S6. AEFs and AMEFs for utilities bidding in MISO in the year 2012 (having generation share > 1%). Percentages shown at top of bars are difference between AEF and AMEF. Utilities are sorted by decreasing % generation share of total generation (shown in brackets on x-axis).

4) Generator Analysis

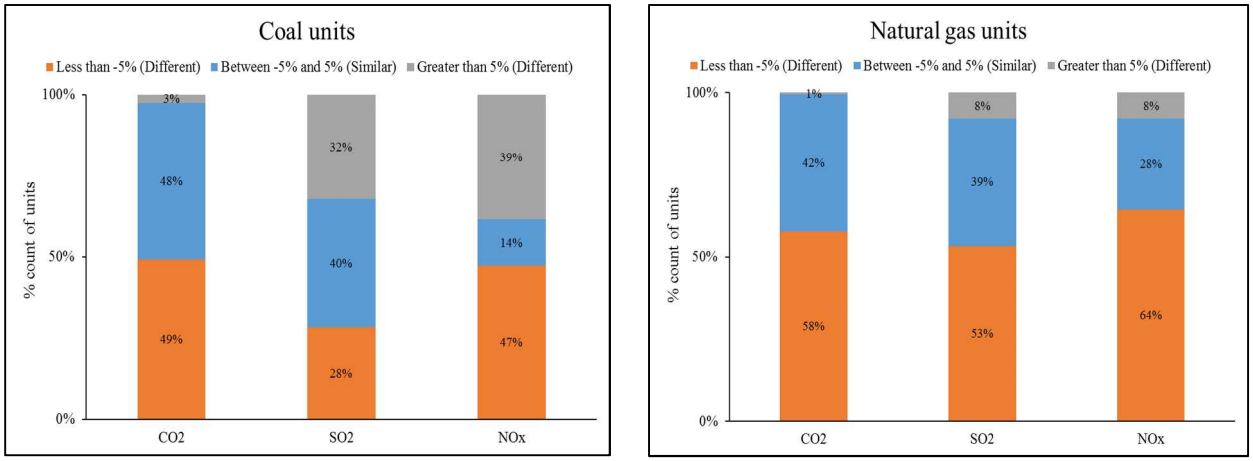


Figure S7. Figure showing significance of difference between AEF and AMEF for three pollutants among coal and natural gas units using ±5% range for all years 2007 through 2013 combined

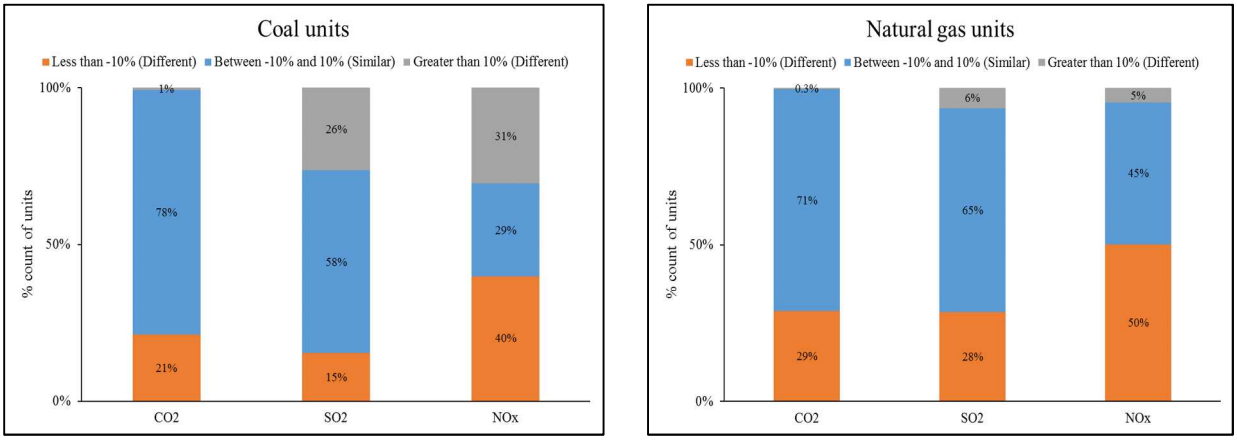


Figure S8. Figure showing significance of difference between AEF and AMEF for three pollutants among coal and natural gas units using ±10% range for all years 2007 through 2013 combined

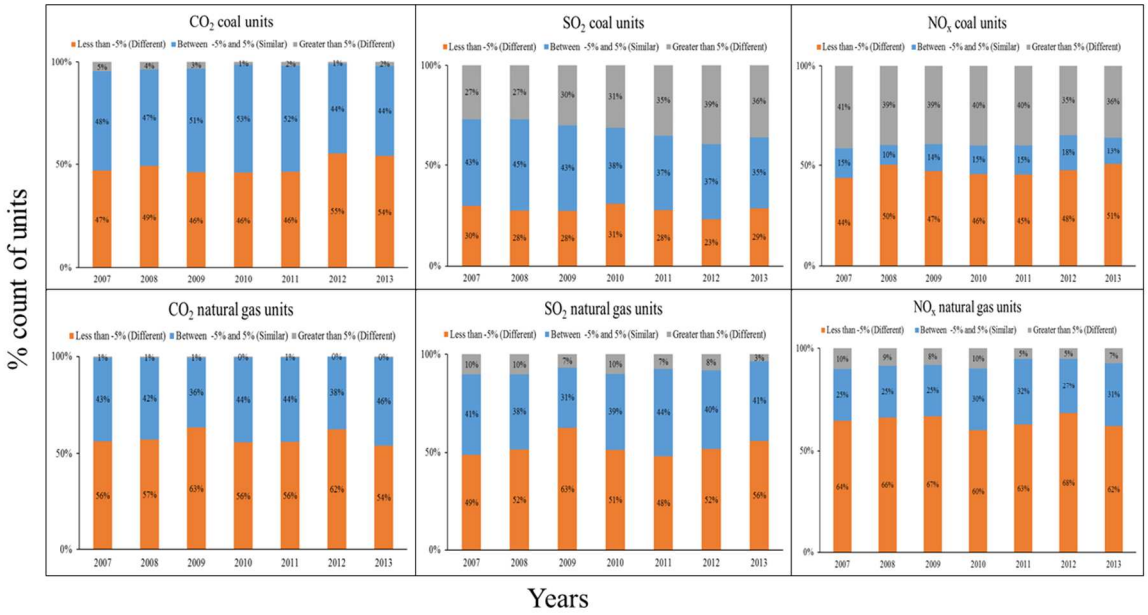


Figure S9. Significance of differences between EFs using ±5% range by year

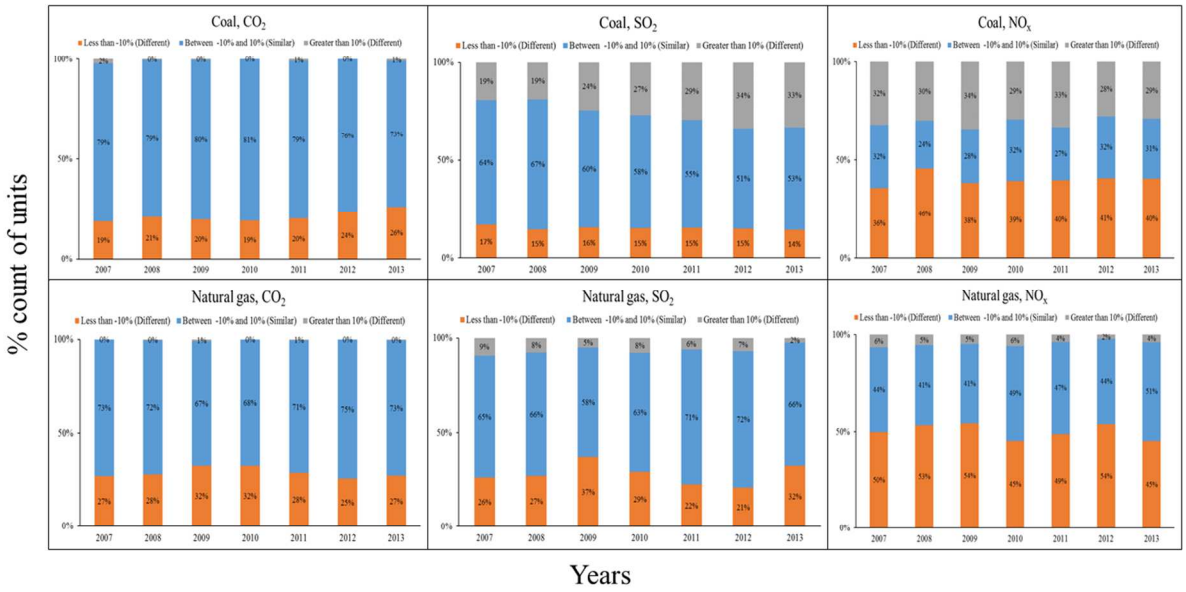


Figure S10. Significance of differences between EFs using ±10% range by year

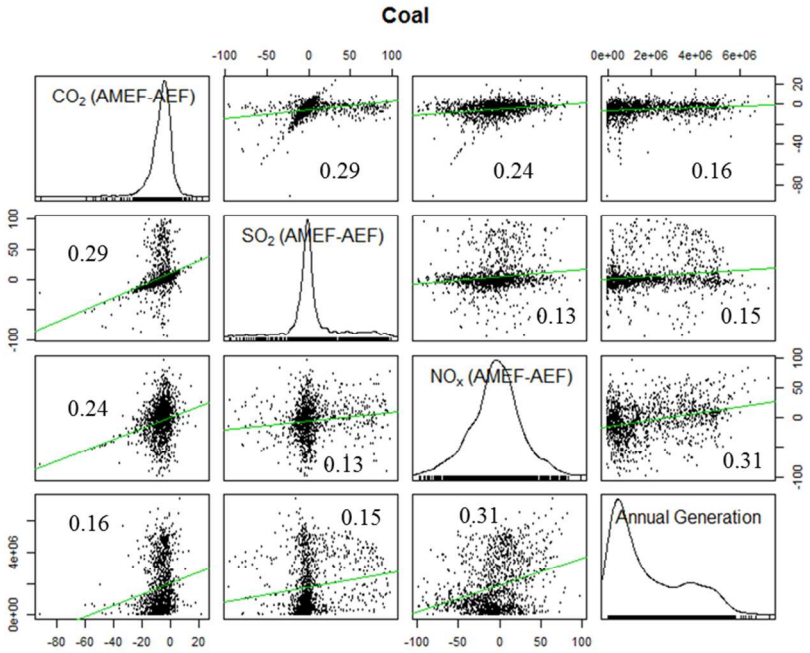


Figure S11. Scatterplot matrix showing correlation among % difference between AEF and AMEF for CO_2, SO_2 and NO_x, and Annual Generation (MWh) for coal generators. Numbers in each plot is correlation coefficient.

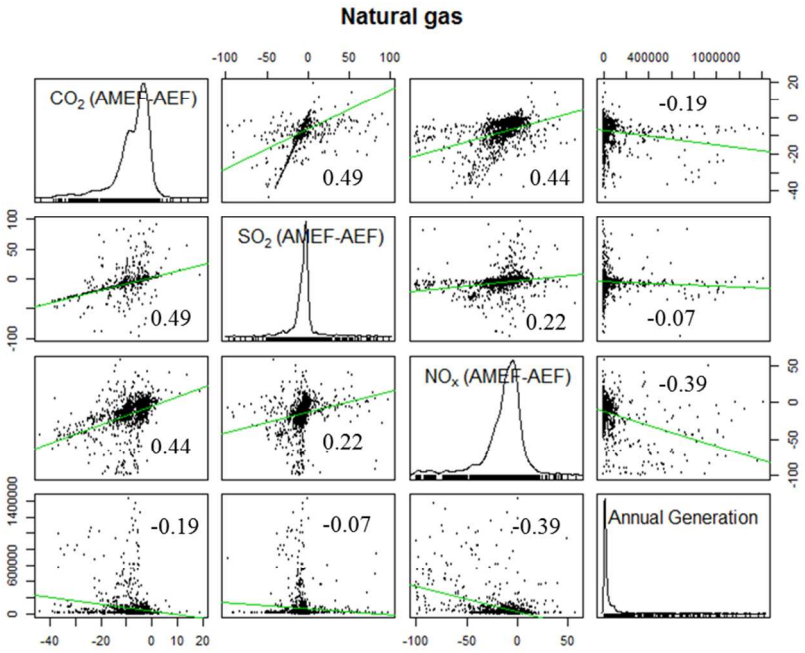


Figure S12. Scatterplot matrix showing correlation among % difference between AEF and AMEF for CO_2, SO_2 and NO_x, and Annual Generation (MWh) for natural gas generators. Numbers in each plot is correlation coefficient.

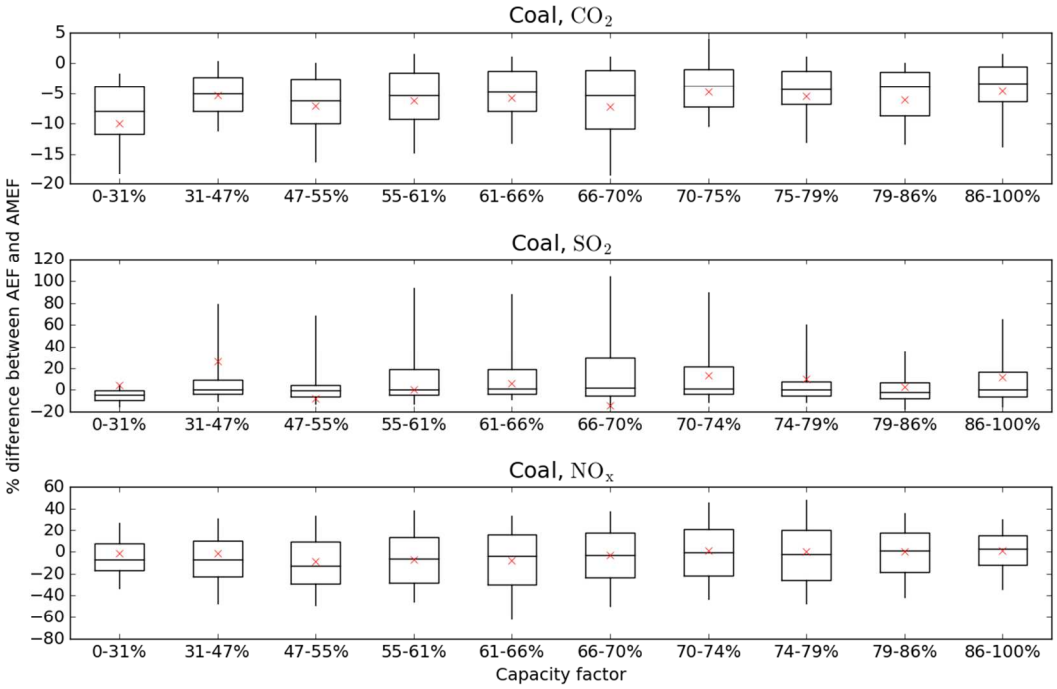


Figure S13. % difference between generator AEF and AMEF as a function of capacity factor for CO_2, SO_2 and NO_x emissions from coal units

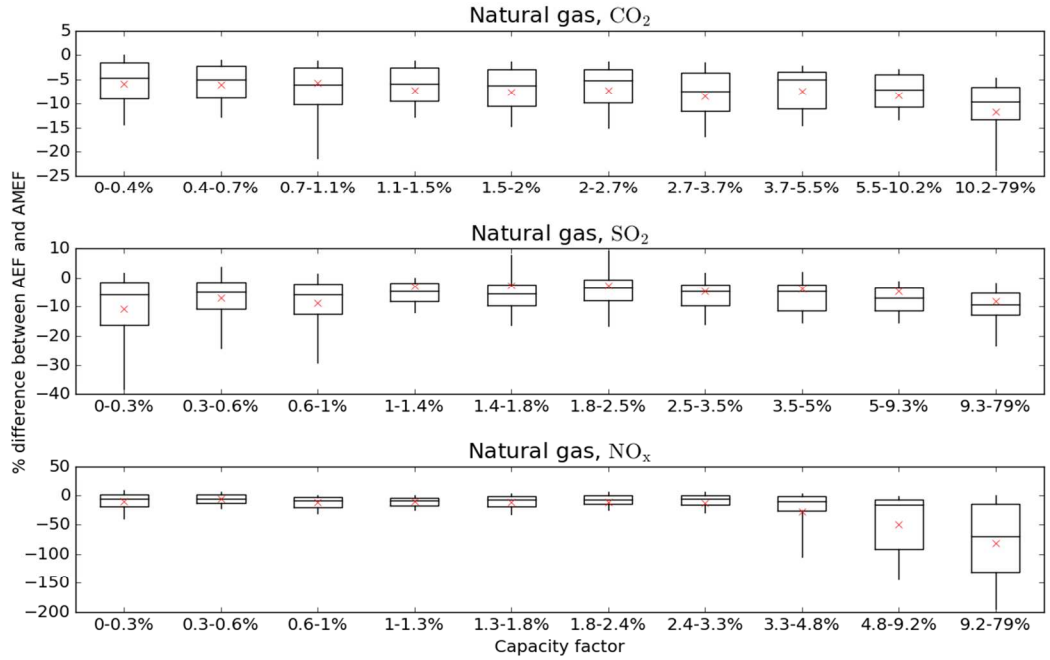


Figure S14. % difference between generator AMEF and AEF as a function of capacity factor for CO_2, SO_2, and NO_x emissions from natural gas units

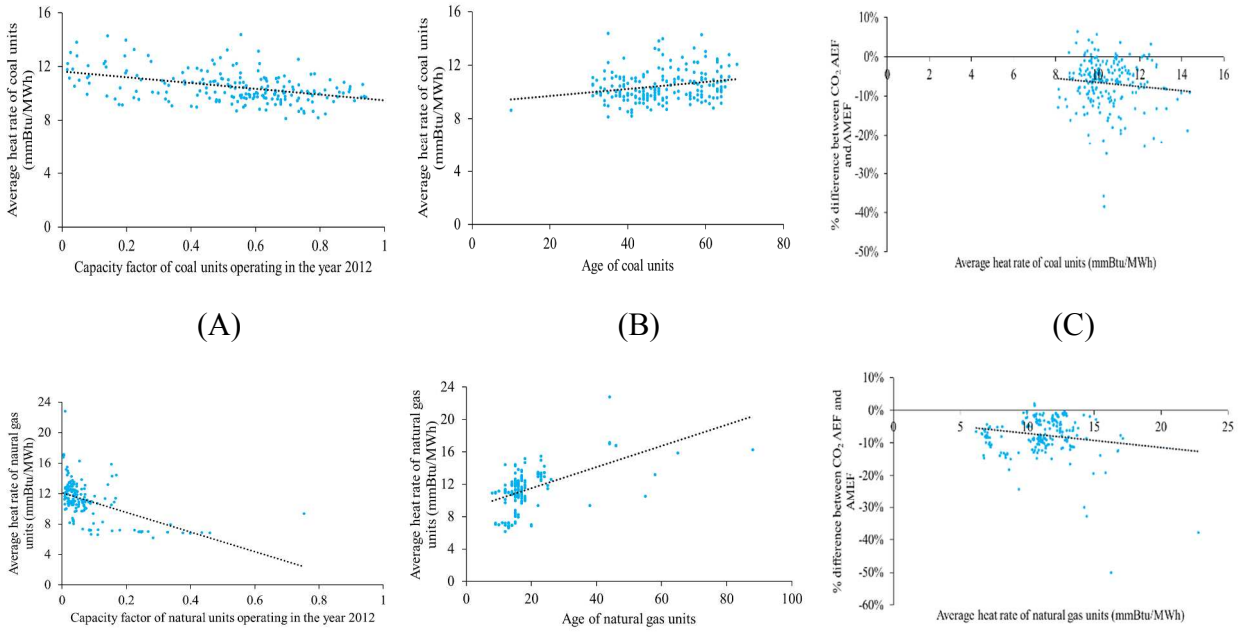


Figure S15. (A,B,C) Dependence of average heat rate of coal units operating in year 2012 on capacity factor, age of coal units; and relation between % CO_2 (AEF-AMEF) difference and average heat rate of coal units. (D,E,F) Dependence of average heat rate of natural gas units operating in year 2012 on capacity factor, age of natural gas units; and relation between % CO_2 (AEF-AMEF) difference and average heat rate of natural gas units.

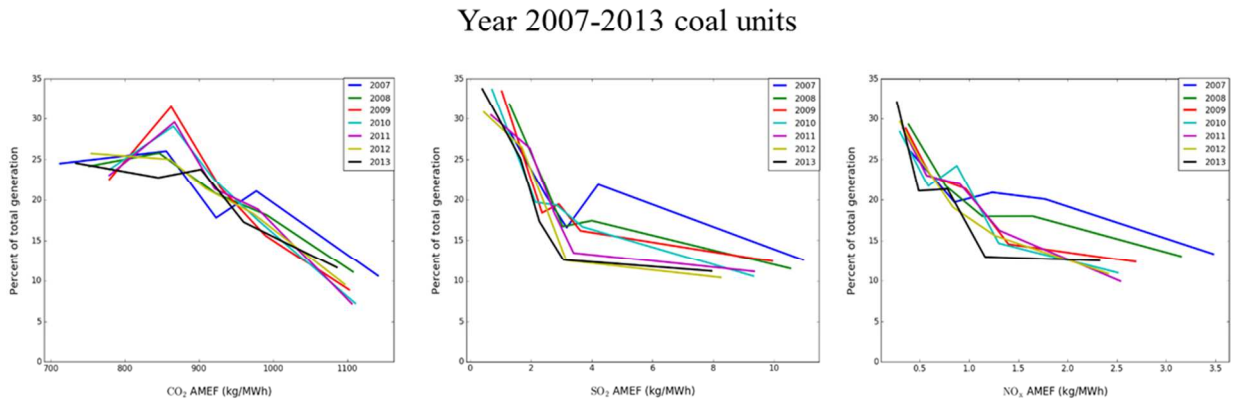


Figure S16. % of generation as a function of AMEFs for coal units

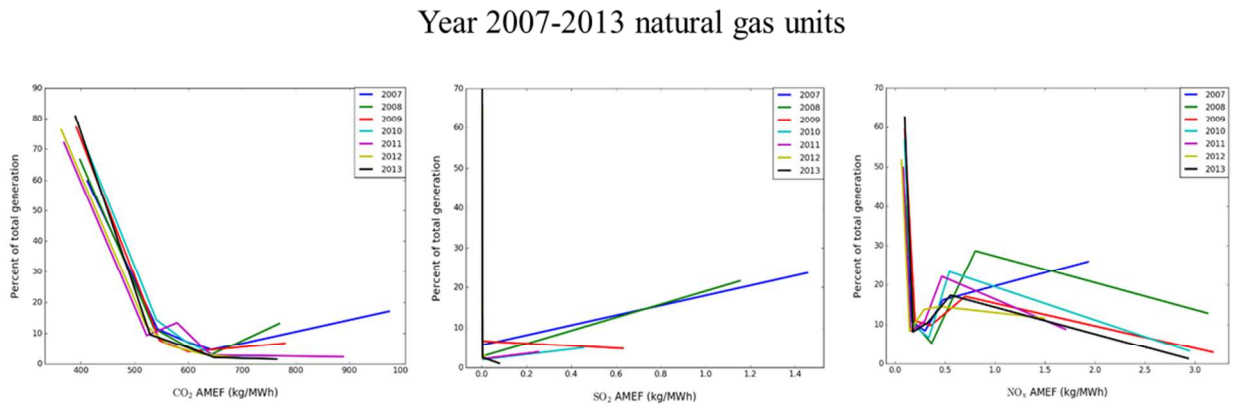
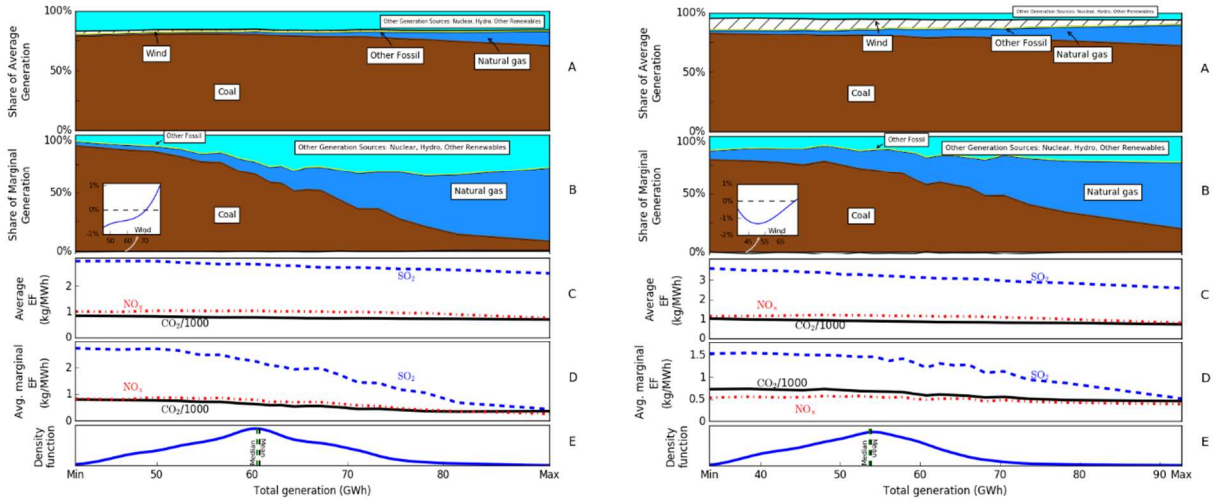


Figure S17. % of generation as a function of AMEFs for natural gas units

5. Variation of share of average and average marginal generation and AEFs and AMEFs by system demand



(I) 2008 (II) 2013

Figure S18. Results by total generation for MISO for year 2008 (I) and 2013 (II). (A) Average generation by fuel. (B) Average marginal generation by fuel. (C) AEFs as a function of total generation (D) AMEFs as a function of total generation. (E) Kernel density distribution for total generation.

6. Temporal analysis

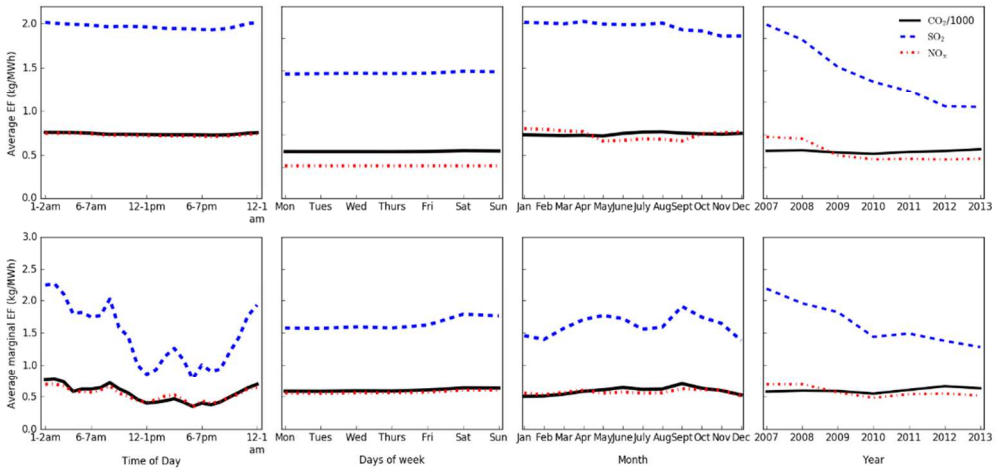


Figure S19. Comparison of time of day, days of week, monthly and yearly trends in AEF and AMEFs for MISO from year 2007 through 2013

CO_2 AMEF is ~64% higher at low demand hours than at high demand hours, because coal is the dominant marginal fuel at low demand hours. Similarly, AMEF for SO_2 is 84% higher (for NO_x: 38% higher) at low demand hours than at high demand hours.

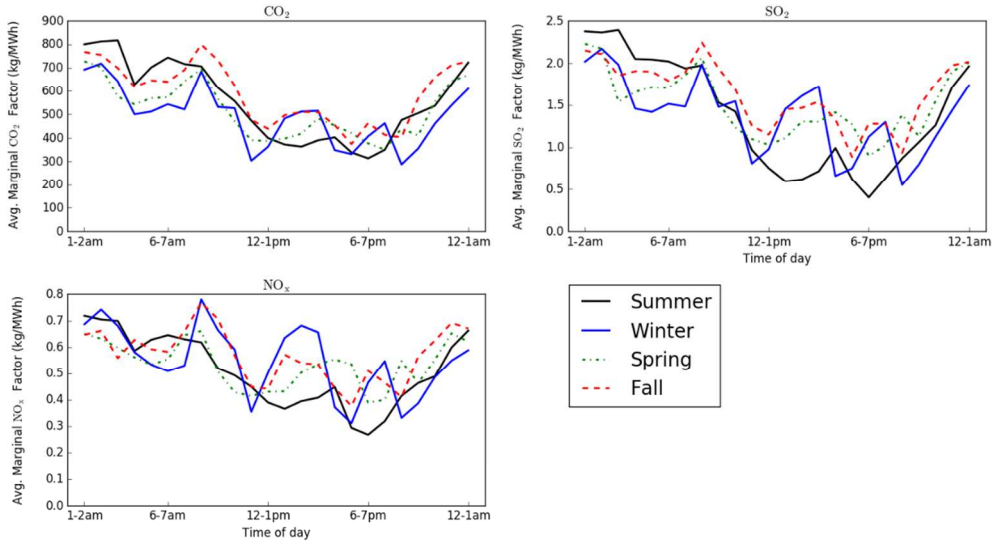


Figure S20. AMEFs by season for combined all years, 2007-2013

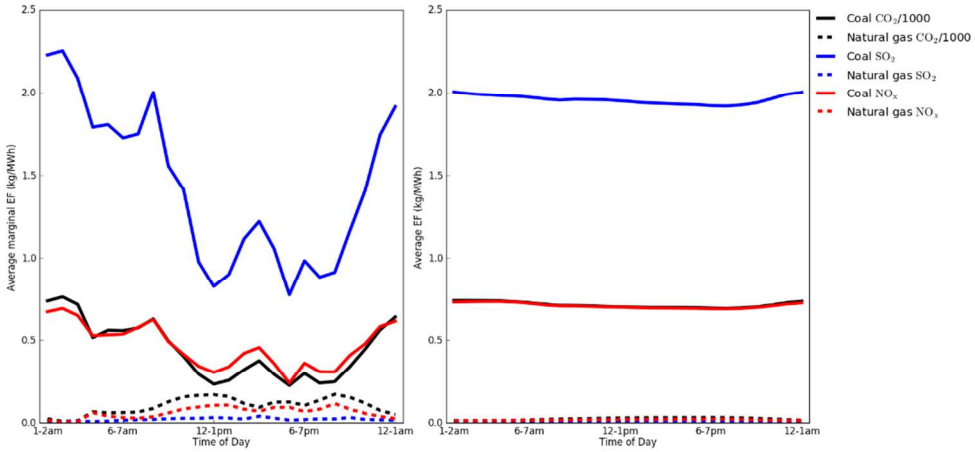


Figure S21. AMEF and AEFs by time of day and fuel source: coal and natural gas (2007-2013)

Table S6. Percent difference between system (MISO region) AEF and AMEF by time of day for all fuels, coal-specific and natural-gas specific emissions

	System (all fuel) AEF/AMEF % difference			Coal-specific system AEF/AMEF % difference			Natural gas-specific system AEF/AMEF % difference		
Time/Pollutants	CO_2	SO_2	NO_x	CO_2	SO_2	NO_x	CO_2	SO_2	NO_x
1 AM	0.45%	11%	-8%	-0.4%	11%	-8%	79%	10%	31%
2 AM	2%	13%	-7%	3%	13%	-6%	-43%	-53%	-74%
3 AM	-4%	5%	-12%	-3%	5%	-12%	-13%	4%	-40%
4 AM	-23%	-10%	-22%	-30%	-10%	-28%	401%	-20%	407%
5 AM	-18%	-9%	-23%	-24%	-9%	-27%	310%	3%	209%
6 AM	-17%	-12%	-23%	-23%	-13%	-26%	270%	75%	111%
7 AM	-14%	-10%	-17%	-20%	-11%	-19%	235%	100%	70%
8 AM	-3%	3%	-9%	-12%	2%	-12%	306%	100%	128%
9 AM	-16%	-20%	-24%	-30%	-21%	-31%	448%	152%	253%
10 AM	-24%	-27%	-31%	-43%	-28%	-41%	530%	162%	384%
11 AM	-38%	-49%	-39%	-59%	-50%	-52%	523%	152%	424%
12 PM	-46%	-56%	-43%	-67%	-58%	-57%	507%	190%	464%
1 PM	-44%	-53%	-38%	-64%	-54%	-52%	447%	158%	457%
2 PM	-41%	-42%	-29%	-54%	-42%	-40%	292%	98%	316%
3 PM	-36%	-35%	-27%	-46%	-37%	-35%	209%	256%	254%
4 PM	-44%	-44%	-37%	-59%	-45%	-49%	314%	149%	365%
5 PM	-52%	-59%	-53%	-68%	-60%	-66%	315%	35%	363%
6 PM	-45%	-48%	-40%	-57%	-49%	-48%	240%	66%	228%
7 PM	-49%	-53%	-45%	-66%	-54%	-56%	355%	112%	304%
8 PM	-43%	-52%	-40%	-65%	-53%	-56%	507%	109%	515%
9 PM	-33%	-39%	-32%	-52%	-40%	-42%	489%	202%	375%
10 PM	-24%	-28%	-26%	-38%	-28%	-33%	430%	90%	269%
11 PM	-15%	-12%	-15%	-23%	-12%	-19%	319%	80%	185%
12 AM	-9%	-4%	-14%	-13%	-4%	-15%	236%	62%	108%

Table S7. MISO-wide daytime and nighttime AMEFs for years 2007 through 2013. Column 2 and 3 represents AMEF considering daytime (8am to 5pm everyday) and nighttime hours (7pm to 7am everyday). Column 4 and 5 represents AMEF and AEF not accounting for temporal differences. Daytime and Nighttime AMEFs are calculated by regressing hourly changes in emissions during respective times over hourly changes in generation during respective times.

	Daytime AMEF	Nighttime AMEF	System AMEF	System AEF
CO_2 (Kg/MWh)	557	618	597	739
SO_2 (Kg/MWh)	1.44	1.71	1.63	1.97
NO_x (Kg/MWh)	0.526	0.585	0.567	0.727