nature energy

Article

https://doi.org/10.1038/s41560-023-01241-8

Nuclear power generation phase-outs redistribute US air quality and climate-related mortality risk

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1 Supplementary Methods

As described in the Methods and Materials Section, the United States Energy Grid Optimization model (US-EGO) uses data from the National Electric Energy Data System (NEEDS) to perform a cost optimization to meet energy demand in every one of 64 NEEDS regions at every hour of the year. There is transmission between regions, and we have isolated the Texas (ERCOT), Eastern and Western Interconnections in order to represent the limitation on transmission between these regions in the real world [1], meaning that there is no transmission between these regions. We limit hydro-power to maximum capacity factors based on region (Southwest at 56%, Midwest at 68%, Southeast at 49% and Northeast at 73%) [2], aside from the Northwest, for which the model underpredicts hydro-power generation, so we allow it to use 100% of available hydro-power. Finally, we adjust the fuel price of refined coal to be $3 less than the listed price in order to better match refined coal use in the real-world data (based on the fact that refined coal is subsidized [3]).

Constraints for generation in the optimization are:

$$gen_{solar} - capacity_{solar} * pattern_{solar} \leq 0 \tag{1}$$

$$gen_{wind} - capacity_{wind} * pattern_{wind} * 0.85 \leq 0 \tag{2}$$

$$gen_{nuclear} - capacity_{nuclear} * 0.95 \leq 0 \tag{3}$$

and for all other fuel types:

$$gen_{fuel} - capacity_{fuel} \leq 0 \tag{4}$$

Where gen is generation, $capacity$ is the maximum capacity of the EGU, and the $pattern_{solar}$ and $pattern_{wind}$ are the renewable capacity pattern for solar and wind, respectively, taken from NEEDS. For simplicity, we use the pattern of solar capacity for only one region, ERC-REST (South-Eastern Texas), and apply it across every region– this has annual and diurnal patterns that fall in the middle of all 64 regions.

Constraints setting $generation + imports = load + exports$ for region i at time t are:

$$\left(\sum gen_i + \sum_{to\ i} trans - \sum_{from\ i} trans - load \geq 0\right)_t \tag{5}$$

Constraints on transmission are:

$$trans_i - trans_{capacity} \leq 0 \tag{6}$$

We evaluate US-EGO by comparing our generation and emissions output from our 2016 baseline (Base) US-EGO scenario to the generation and emissions data from our eGRID scenario. To evaluate the model, we use annual mean generation and emissions for SO_2, NO, NO_2, and CO_2 by fuel type (biomass, coal, fossil waste, geothermal, hydro, landfill gas, municipal solid waste, natural gas, non-fossil waste, nuclear, oil, petroleum coke, solar, waste coal, and wind) and NEEDS region (64 regions) [4], as seen in Supplementary Figure 1. We calculate the Pearson correlation coefficient between the annual model generation and eGRID generation across both region and fuel types, which are between 0.82 and 1.0. These correlations show that our Base US-EGO scenario captures the existing structure of the energy grid as measured by the correlation with eGRID. We do not evaluate methane (CH_4) emissions in our paper because the model largely underestimates the emissions by region and fuel type (see Supplementary Figure 1e). Many oil and gas plants that are the highest emitters have little to no generation in our Base and No Nuclear scenarios– this is consistent with the generation for these specific EGUs in the eGRID generation data. The majority of the high emissions plants in the Base scenario have annual generation within a 200 MWh range of eGRID, and a few have larger or smaller generation.

In two of the shutdown scenarios, No Nuclear and No Nuclear + No Coal, the demand in various regions exceeds possible supply at certain points in the year. In the nuclear shutdown, the demand in the NEEDS' ERC-REST region, located in southeastern Texas, exceeds possible supply for a total of 20 hours in the month of May. Almost 20% of Texas' energy supply is from nuclear power, and we have constrained transmission to stay within the Texas Interconnection (ERCOT), which limits the ability of transmission to take on the shortage. In No Nuclear + No Coal, 35 regions have demand that exceeds supply throughout various times of the year. We close these gaps by adding generators that have prohibitive costs such that they are only utilized when the optimization cannot match demand constraints. The generators have zero emissions so they do not impact our estimated changes in emissions.

Our multi-system model uses EGU-specific data for explicit interpretation of spatial and temporal variation. However, our choice to use EGU-specific data introduces some tradeoffs relative to more complex energy grid models. We do not include ramp up or reserves for generation, and we do not account for investment into new electricity generation, beyond including emissions-free generators without specific locations or limitations on capacity. More complex models incorporate quantification of where this type of investment would occur. The lack of ramp up and reserves have an impact on the amount of generation capacity and the speed with which new plants come on and offline, reducing the amount of capacity available when nuclear and coal power are shut down. This reduces the impact of estimations of future build out on our results. Future research could explore related questions combining chemical transport models with capacity expansion models.

We compare 2016 observational data from the IMPROVE network [5] and the EPA's Air Quality System (AQS) monitoring network [6] to our base model, NEI 2011, NEI 2016 and eGRID GEOS Chem output. We use AQS daily average observations for $PM_{2.5}$, NO_2, SO_2 and ozone and IMPROVE observations for $PM_{2.5}$, sulfate, and nitrate. We interpolate our model data onto the locations of monitors using xarray's nearest method [7]. We calculate the R-value based on interpolated values of our model runs compared to the observations from IMPROVE and AQS (Supplementary Figures 5 and 6). We also calculate the normalized mean bias (NMB) of ozone and $PM_{2.5}$ for our base model and the observations. The NMB is calculated as $\frac{\sum(M_i - O_i)}{\sum(O_i)} \times 100\%$, where i denotes the seasonal mean at each observational site. The results can be seen in Supplementary Tables 1 and 2. For ozone, our largest bias shows that the model is high compared to observations during the summer months in the Midwest, Northeast, and Southeast. For $PM_{2.5}$, we find biases during the winter in the Northeast and Southeast (where the model is biased high), and the Northwest, and Southwest (where the model is biased low), as well as being biased low during the summer in the Southwest. Our NMB and R-values are of similar magnitude to previous work [8, 9, 10, 11]. In Supplemental Figure 4, we compare the observational data for each of our pollutants with the model output by regional annual mean. The resulting concentrations from our Base and eGRID scenarios are within a similar range of the observational data as the typical GEOS-Chem emissions inventory, the NEI 2011 scenario, which shows again that US-EGO does capture similar ranges of pollutant concentrations.

We calculate a proxy to estimate whether or not a region is NO_x abundant, limited, or transitional by using the formaldehyde CH_2O:NO_2 ratio [12]. We define CH_2O:NO_2 of less than .5 as VOC limited, between .5 and .8 as transitional, and as greater than .8 as NO_x limited. Supplementary Figure 8 shows differences between the regimes for the nuclear shutdown and the coal and nuclear shutdown, particularly during the summer, which lead to differences in ozone formation. There is also a shift between VOC limited regimes dominating during the wintertime and NO_x limited regimes dominating during summertime.

2 Supplementary Discussion

Similar to No Nuclear, in No Nuclear + No Coal, there is a gap between production and demand. This gap occurs across 35 National Electric Energy Data System (NEEDS) regions (see the user guide in [4] for a map of the regions). The gap is regionally dependent, but in the majority of these regions, the largest gap is during the summer (see Methods for how this gap is filled). Under No Nuclear + No Coal, there is more reliance on oil and gas plants that have high NO_x emissions factors, and less reliance on the higher SO_2 and CO_2 emitting EGUs. In the U.S., there are 29 EGUs with emissions factors that emit one standard deviation more than the national mean of CO_2, 16 for NO_x, and 19 for SO_2. The majority of these high emitting plants are oil and gas plants, many of which have no generation under No Nuclear and the Base, and are only needed under No Nuclear + No Coal. These plants also account for a higher fraction of the national total electricity generation under No Nuclear + No Coal, as well as a much higher fraction of the overall emissions of each pollutant. For example, 43% of the national NO_x emissions are from these 15 EGUs under No Nuclear + No Coal, while only one of these plants is used in Base and it accounts for 0.2% of national NO_x emissions. All 15 of these high NO_x EGUs in No Nuclear + No Coal are oil and gas plants, while the one used in the Base is a biomass plant. A similar picture is seen for SO_2, where 50% of the national SO_2 emissions come from the 15 high SO_2 emitting EGUs, but they provide less than 0.1% of nationwide electricity generation.

$PM_{2.5}$ is lower in some locations and higher in others under No Nuclear + No Coal. This leads to an annual average increase in mortalities of 3800 (95% CI 2900-4600), which are concentrated in the Southeast and the Great Lakes region. Apr.-Sept. MDA8 ozone increases in most of the U.S., aside from some small decreases in Eastern Texas and Appalachia.

For No Nuclear + No Coal there are \$62 billion in damages due to changes in mortalities from shutting down both nuclear and coal power plants (\$33 billion due to ozone and \$29 billion due to $PM_{2.5}$). Costs due to one year of higher CO_2 emissions in No Nuclear + No Coal are between \$1.4 and \$24.3 billion (for discount rates of 5% and 1.5%, respectively), compared to the Base. Overall, one year of emissions from No Nuclear + No Coal leads to costs between \$63.4 and \$86.3 billion.

In No Nuclear + No Coal compared to the Base, mortality rates due to differences in $PM_{2.5}$ in counties containing nuclear plants are 1.5 times that of counties without nuclear plants, and mortality rates due to differences in ozone are 1.3 times that of counties without a nuclear plant. Inequities in exposure to pollution by race and ethnicity continue under this scenario– Black or African American people face the highest mean increase in exposure to $PM_{2.5}$ and ozone (Figure 6).

The shutdown of nuclear alongside an increase in renewable capacity to EIA projected 2030 levels leads to a decrease in mortalities due to Apr.-Sept. MDA8 ozone and an increase in mortalities due to $PM_{2.5}$ compared to the Base. There are an additional 980 (95% CI 750-1200) mortalities due to changes in $PM_{2.5}$ and a reduction of 720 (95% CI 360-1400) mortalities due to changes in ozone. The increase in $PM_{2.5}$ concentration and subsequent mortalities are concentrated in the Eastern half of the U.S., while there is a decrease in the Western half, aside from California which has a slight increase. Apr.-Sept. MDA8 ozone concentrations and related mortalities decrease in most locations aside from parts of the Southeast and Appalachia.

There are \$2.0 billion in damages due to changes in mortalities (-\$5.5 due to ozone and \$7.5 due to $PM_{2.5}$. Costs due to one year of higher CO_2 emissions are between \$2.0 and \$34.3 billion (for discount rates of 5% and 1.5%, respectively), compared to the Base. This leads to costs of between \$4.0 and \$36.3 due to one year of changes in emissions under No Nuclear + Renewables.

In No Nuclear + Renewables compared to the Base, mortality rates due to $PM_{2.5}$ in counties with nuclear plants are 1.3 times that of counties without a nuclear plant, and those due to ozone decrease by 1.3 times that of counties without a nuclear plant (Supplementary Figure 12). Inequities in exposure to pollution by race and ethnicity continue even when renewable capacity increases– Black people face the highest mean increase in exposure to $PM_{2.5}$, and the smallest decrease in exposure to ozone (Figure 7).

Detailed information about the mean exposure, mean mortality and 95% confidence intervals for each race and ethnicity are shown in Supplementary Tables 4 and 6. Supplementary Tables 7, 8, 9, and 10 show mean exposure and mean mortality rates for counties containing or not containing nuclear power plants.

Supplementary Table 1: GEOS-Chem AQS Observation Comparison for Ozone, and the Normalized Mean Bias (NMB) between interpolated GEOS-Chem data and the observational data

Region	Season	NMB (%)
Midwest	DJF	-6.6
Midwest	JJA	36.3
Northeast	DJF	-18.5
Northeast	JJA	34.4
Southeast	DJF	8.1
Southeast	JJA	60.8
Northwest	DJF	13.6
Northwest	JJA	13.7
Southwest	DJF	13.1
Southwest	JJA	12.1

Supplementary Table 2: GEOS-Chem AQS Observation Comparison: $PM_{2.5}$, and the Normalized Mean Bias (NMB) between interpolated GEOS-Chem data and the observational data

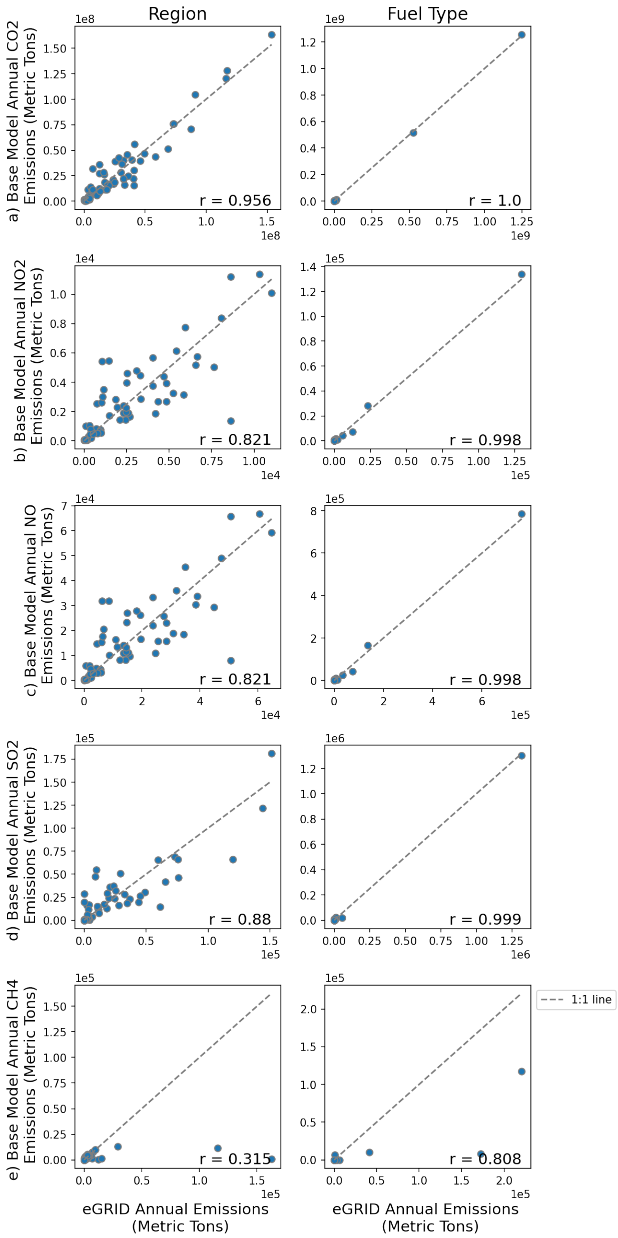
Region	Season	NMB (%)
Midwest	DJF	11.4
Midwest	JJA	-7.4
Northeast	DJF	41.3
Northeast	JJA	13.2
Southeast	DJF	28.3
Southeast	JJA	-4.2
Northwest	DJF	-42.1
Northwest	JJA	-12.0
Southwest	DJF	-37.3
Southwest	JJA	-31.3

Supplementary Table 3: $PM_{2.5}$ Population Weighted Exposure by Race and Ethnicity, Mean and 95% Confidence Interval

Race and Ethnicity	No Nuclear Change in Exposure Census data ($\mu g/m^3$)	No Nuclear + No Coal Change in Exposure Census data ($\mu g/m^3$)	No Nuclear + Renewables Change in Exposure Census data ($\mu g/m^3$)
Black or African American	0.20	0.27	0.06
Asian or Pacific Islander	0.12	0.14	0.03
Hispanic or Latino	0.10	0.08	0.02
White	0.17	0.18	0.04
American Indian or Alaska Native	0.11	0.13	0.02

Supplementary Table 4: $PM_{2.5}$ Mortality by Race and Ethnicity, Mean and 95% Confidence Interval

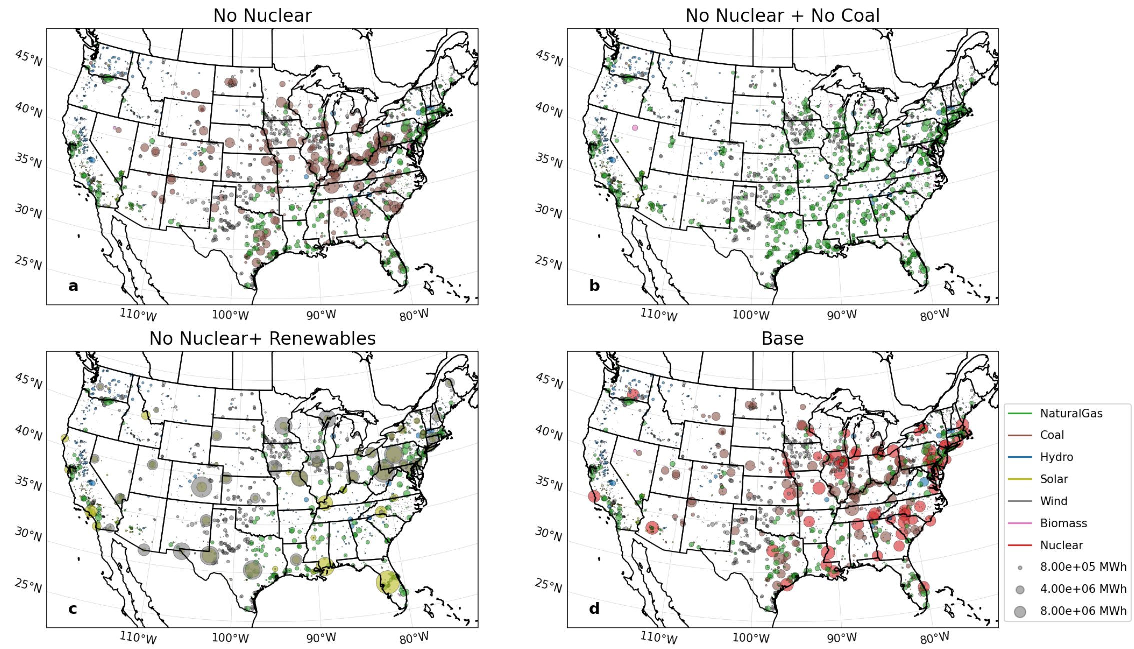
Race and Ethnicity	No Nuclear Mortality Rate per 1 million people Census Data (95% CI)	No Nuclear + No Coal Mortality Rate per 1 million people Census Data (95% CI)	No Nuclear + Renewables Mortality Rate per 1 million people Census Data (95% CI)
Black or African American	12.48 (12.15, 12.81)	16.45 (16.01, 16.88)	3.89 (3.78, 3.99)
Asian or Pacific Islander	7.18 (6.99, 7.37)	8.50 (8.28, 8.72)	1.81 (1.76, 1.86)
Hispanic or Latino	5.69 (5.54, 5.84)	5.12 (4.99, 5.26)	1.13 (1.10, 1.16)
White	11.04 (10.75, 11.34)	11.70 (11.39, 12.01)	2.94 (2.86, 3.02)
American Indian or Alaska Native	6.73 (6.55 , 6.91)	8.0 (7.79, 8.21)	1.01 (0.98, 1.03)



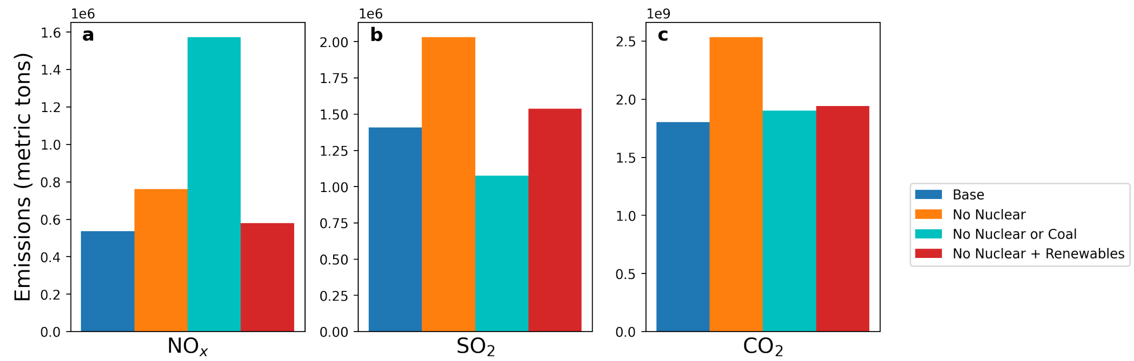
Supplementary Figure 1: **Comparison of emissions from the Base simulation and raw data from the EPA's eGRID** Scatterplots of the emissions of CO_2 (a), NO_2 (b), NO (c), SO_2 (d), and CH_4 (e) by NEEDS region and fuel type. Pearson correlations (r) are calculated and shown in the bottom right of each plot. This comparison is between the Base simulation and our raw data from EPA's eGRID.

Supplementary Table 5: Apr.-Sept. Maximum Daily 8-Hour Average (MDA8) Ozone Population Weighted Exposure by Race and Ethnicity

Race and Ethnicity	No Nuclear Change in Exposure Census data (ppb)	No Nuclear + No Coal Change in Exposure Census data (ppb)	No Nuclear + Renewables Change in Exposure Census data (ppb)
Black or African American	0.60	1.81	-0.18
Asian or Pacific Islander	0.30	0.75	-0.27
Hispanic or Latino	0.24	0.57	-0.32
White	0.48	1.09	-0.28
American Indian or Alaska Native	0.32	0.90	-0.43



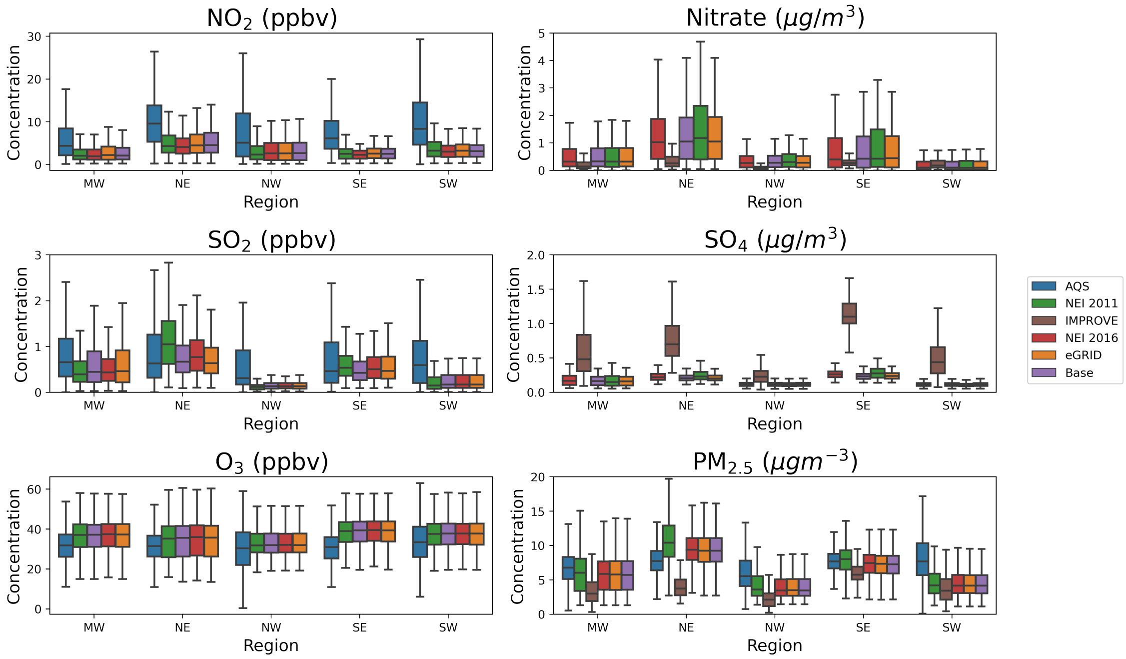
Supplementary Figure 2: **Map of electricity generating units in the No Nuclear, No Nuclear + No Coal, No Nuclear + Renewables, and Base scenarios** a) shows No Nuclear, b) No Nuclear + No Coal, c) No Nuclear + Renewables, and d) Base. Each color corresponds to a different source of electricity, and the size of the circle is scaled by annual generation of the given EGU.



Supplementary Figure 3: **Annual national sum of emissions of each of the three pollutants for the four scenarios analyzed in the main text** Each color corresponds to a different scenario– No Nuclear + No Coal, No Nuclear, No Nuclear + Renewables, and Base. Emissions are metric tons of NO_x, SO_2, and CO_2.

Supplementary Table 6: Ozone Mortality by Race and Ethnicity, Mean and 95% Confidence Interval

Race and Ethnicity	No Nuclear Mortality Rate per 1 million people Census data (95% CI)	No Nuclear + No Coal Mortality Rate per 1 million people Census data (95% CI)	No Nuclear + Renewables Mortality Rate per 1 million people Census data (95% CI)
Black or African American	10.57 (5.31, 20.94)	31.55 (15.85, 62.49)	-2.87 (-1.44, -5.68)
Asian or Pacific Islander	5.07 (2.55, 10.05)	12.64 (6.35, 25.03)	-4.06 (-2.04, -8.05)
Hispanic or Latino	4.01 (2.02, 7.94)	9.62 (4.84, 19.06)	-4.68 (-2.35, -9.26)
White	8.69 (4.37, 17.21)	19.23 (9.66, 38.08)	-4.31 (-2.17, -8.54)
American Indian or Alaska Native	5.50 (2.76, 10.90)	15.94 (8.01, 31.58)	-6.95 (-3.49, -13.77)



Supplementary Figure 4: **Regional comparison of model and observational annual mean pollutant** We split the U.S. into five regions: the Midwest, Northeast, Northwest, Southeast, and Southwest. Each plot shows the available observational data (IMPROVE and/or AQS) alongside the model data for the eGRID, NEI 2016, Base, and NEI 2011 scenarios. Each boxplot shows the minimum, first quartile, median, third quartile, and maximum annual mean value for a pollutant. Sample sizes for each species and model are given as: n = 5275 (NO_2), 13221 (ozone), 13056 ($PM_{2.5}$), 5089 (SO_2), 1716 (NIT), 1716 (SO_4).

Supplementary Table 7: Change in $PM_{2.5}$ Population Weighted Exposure in Counties with and without nuclear plants

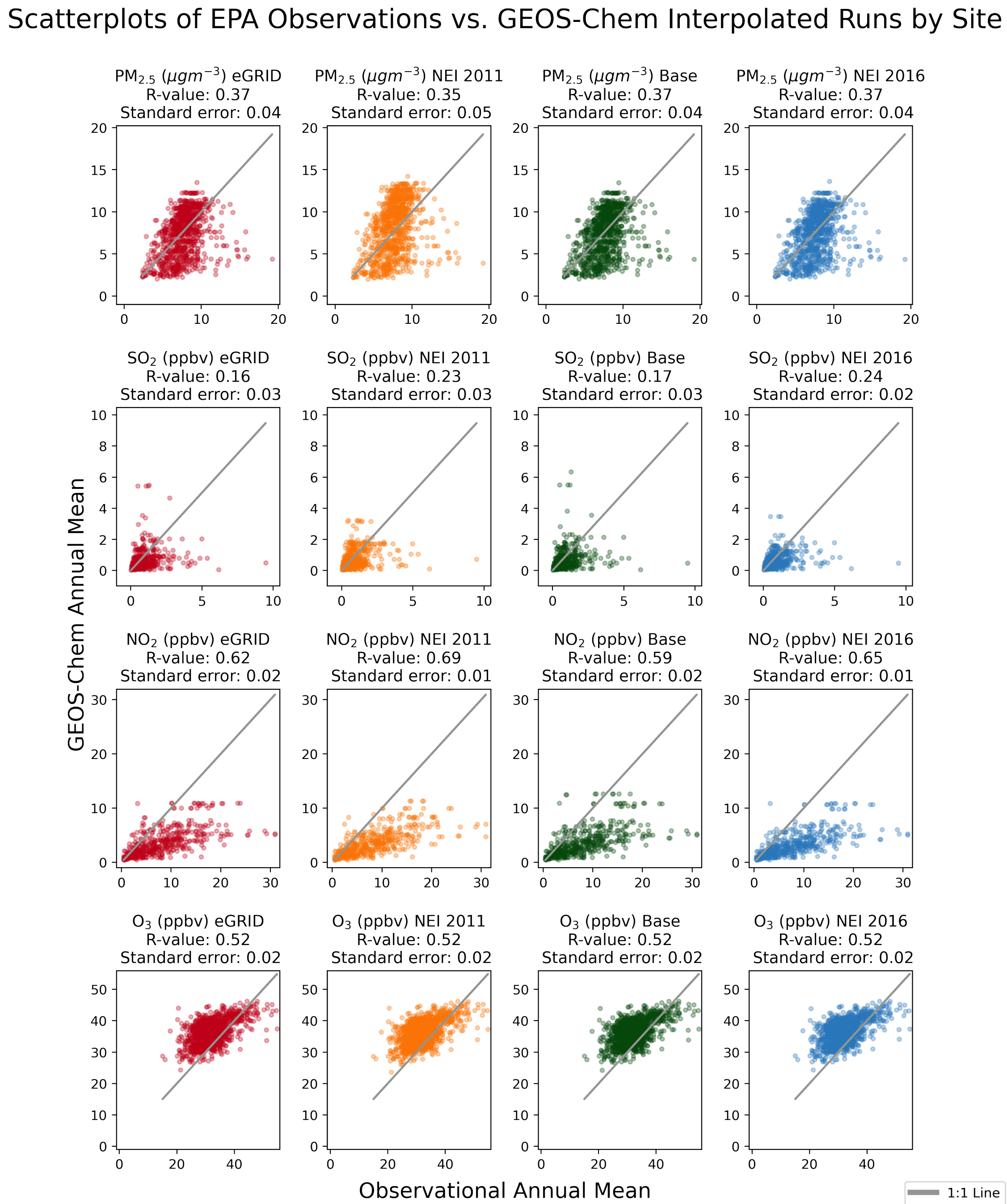
County with or without Nuclear	No Nuclear - Base $PM_{2.5}$ exposure Census Data	No Nuclear + No Coal - Base $PM_{2.5}$ exposure Census Data	No Nuclear + Renewables - Base $PM_{2.5}$ exposure Census Data
County with Nuclear	0.16	0.28	0.06
County without Nuclear	0.17	0.19	0.04

Supplementary Table 8: Change in $PM_{2.5}$ Mortality in Counties with and without nuclear plants

County with or without Nuclear	No Nuclear - Base $PM_{2.5}$ Mean Mortality Rate per 1 million people Census Data	No Nuclear + No Coal - Base $PM_{2.5}$ Mean Mortality Rate per 1 million people Census Data	No Nuclear + Renewables - Base $PM_{2.5}$ Mean Mortality Rate per 1 million people Census Data
Nuclear containing	10.43	17.6	3.8
Non-nuclear containing	10.88	11.7	2.9

Supplementary Table 9: Change in Population Weighted Ozone Exposure in Counties with and without nuclear plants

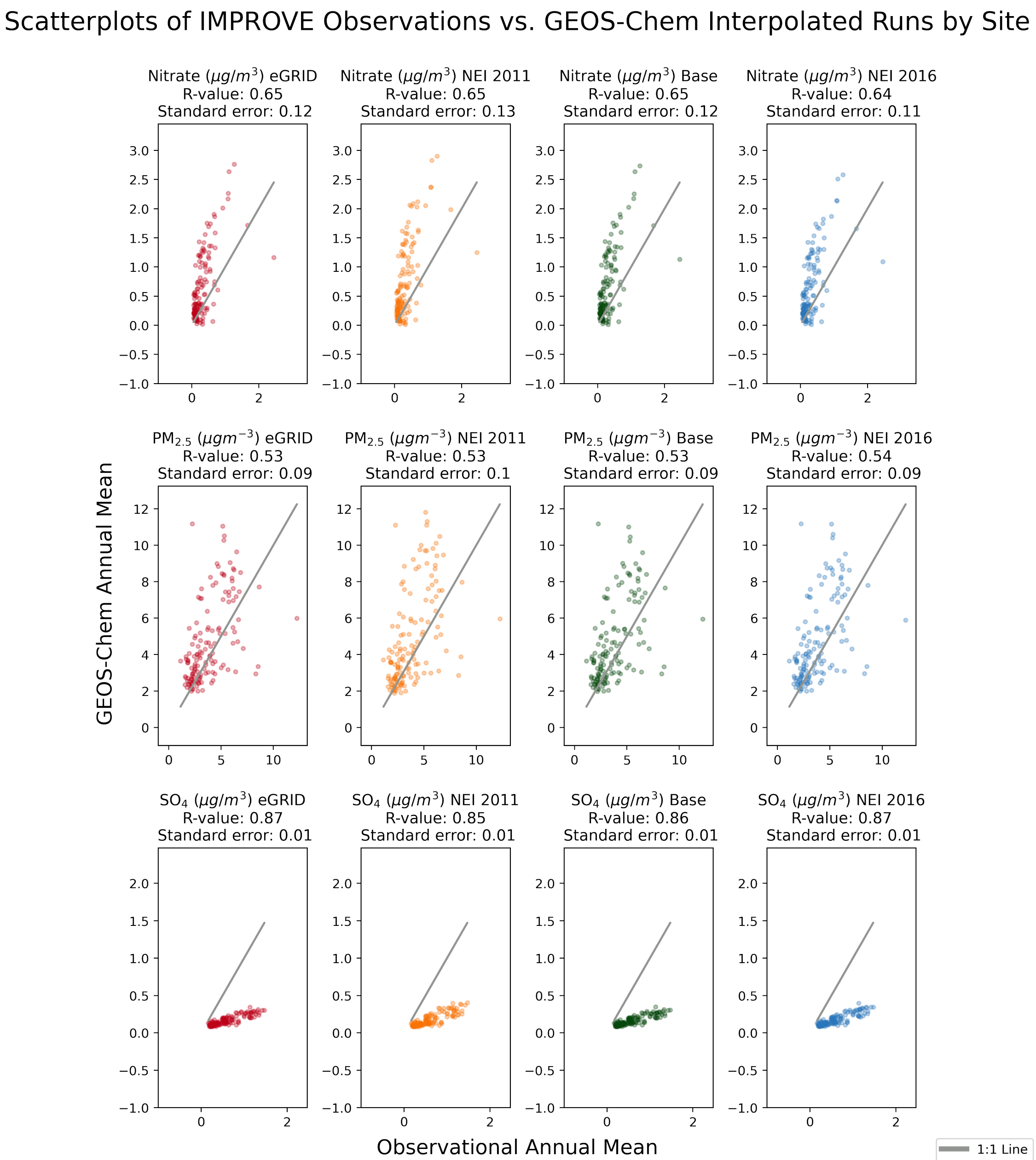
County with or without Nuclear	No Nuclear - Base ozone exposure census	No Nuclear + No Coal - Base ozone exposure census	No Nuclear + Renewables - Base ozone exposure census
Nuclear containing	0.46	1.50	-0.20
Non-nuclear containing	0.48	1.13	-0.27



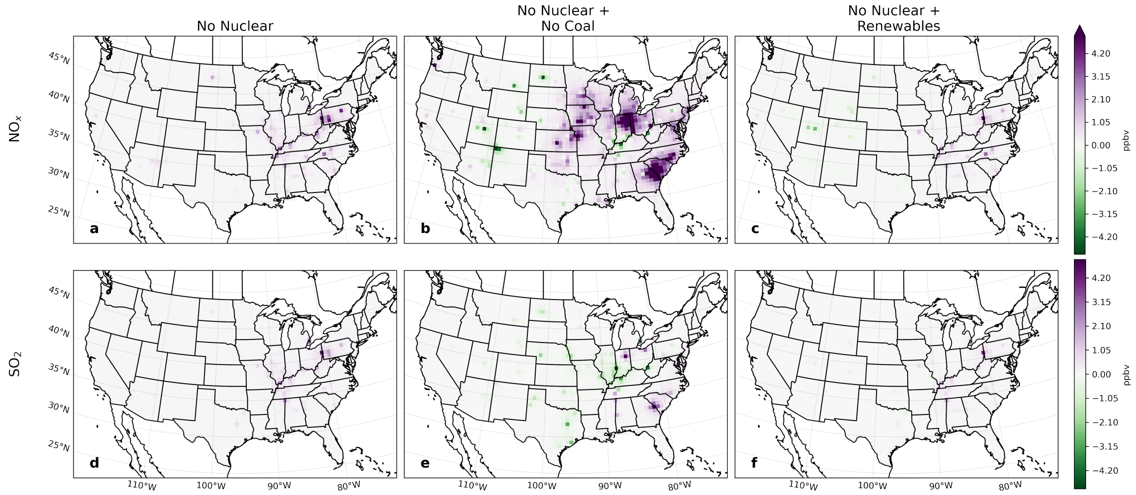
Supplementary Figure 5: **Modeled vs. Observational annual mean of each pollutant for AQS data** Scatter plots of the interpolated annual mean GEOS-Chem data as compared to the AQS observational annual mean for the eGRID, NEI 2016, Base, and NEI 2011. The 1:1 line is shown in grey. R-values and standard error are calculated as explained in Supplementary Information Section 1.

Supplementary Table 10: Change in Population Weighted Ozone Mortality in Counties with and without nuclear plants

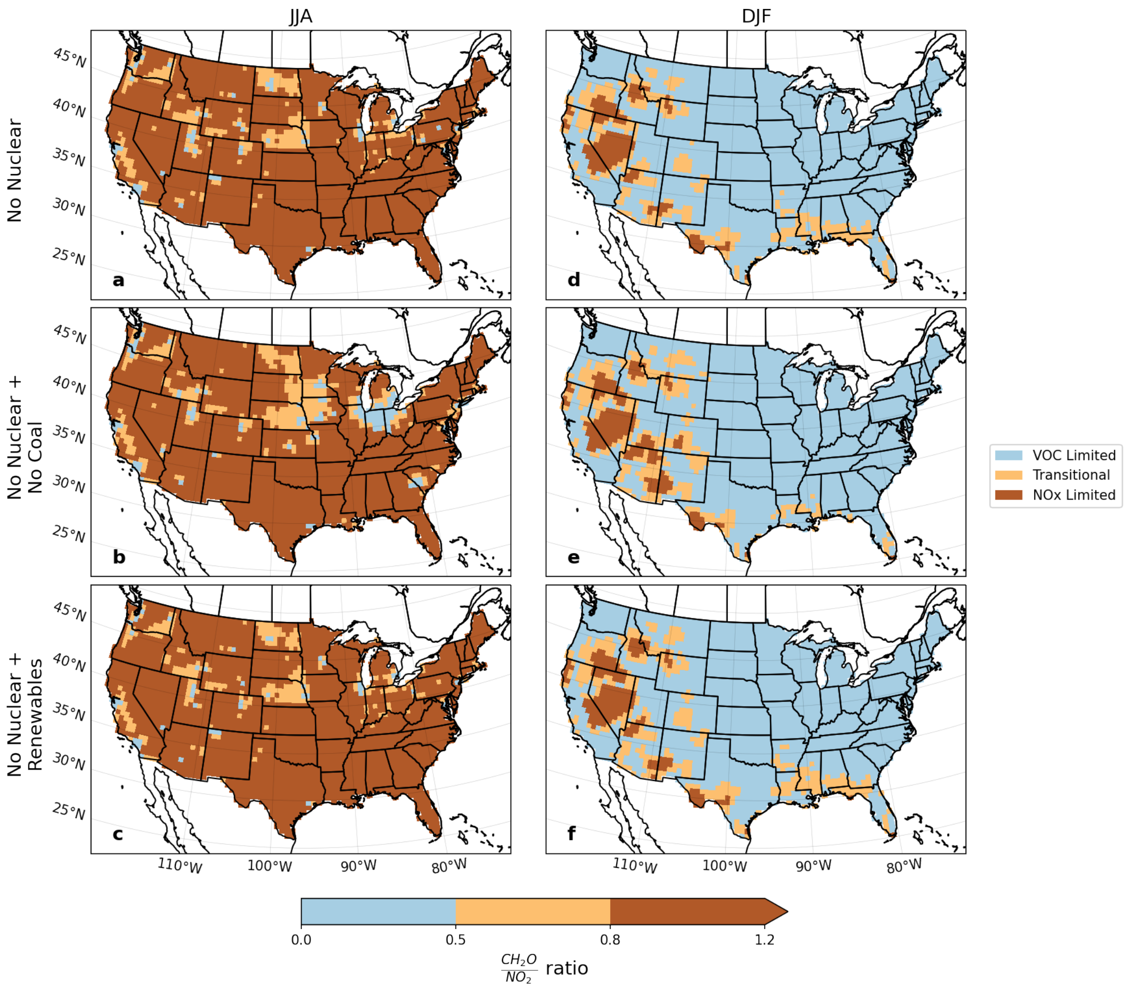
County with or without Nuclear	No Nuclear - Base ozone Mean Mortality Rate per 1 million people Census Data	No Nuclear + No Coal - Base ozone Mean Mortality Rate per 1 million people Census Data	No Nuclear + Renewables - Base ozone Mean Mortality Rate per 1 million people Census Data
Nuclear containing	8.31	26.81	-3.29
Non-nuclear containing	8.61	19.93	-4.26



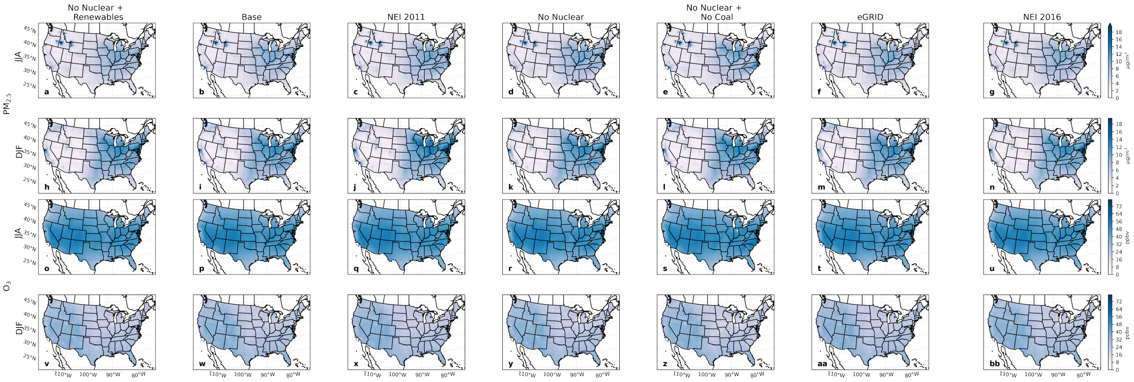
Supplementary Figure 6: **Modeled vs. Observational annual mean of each pollutant for IMPROVE data** Scatter plots of the interpolated annual mean GEOS-Chem data as compared to the IMPROVE observational annual mean for the eGRID, NEI 2016, Base, and NEI 2011 scenarios. The 1:1 line is shown in grey. R-values and standard error are calculated as explained in Supplementary Information Section 1.



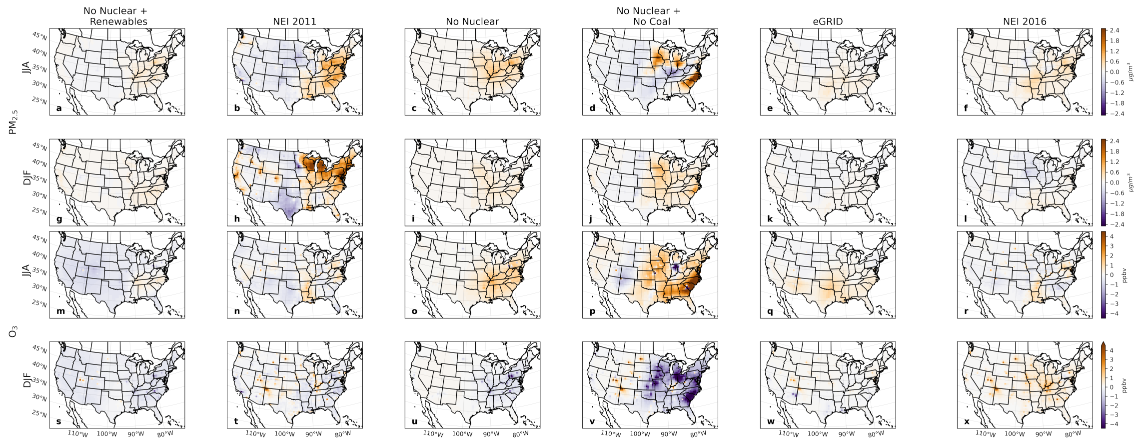
Supplementary Figure 7: **NO_x and SO_2 annual mean concentrations No Nuclear, No Nuclear + No Coal, and No Nuclear + Renewables compared to the Base**. The first column shows summer No Nuclear compared to the Base (a and d), the second column is No Nuclear + No Coal compared to the Base (b and e), and the third column is No Nuclear + Renewables compared to the Base (c and f). The top row is NO_x and the bottom row is SO_2, both in ppbv.



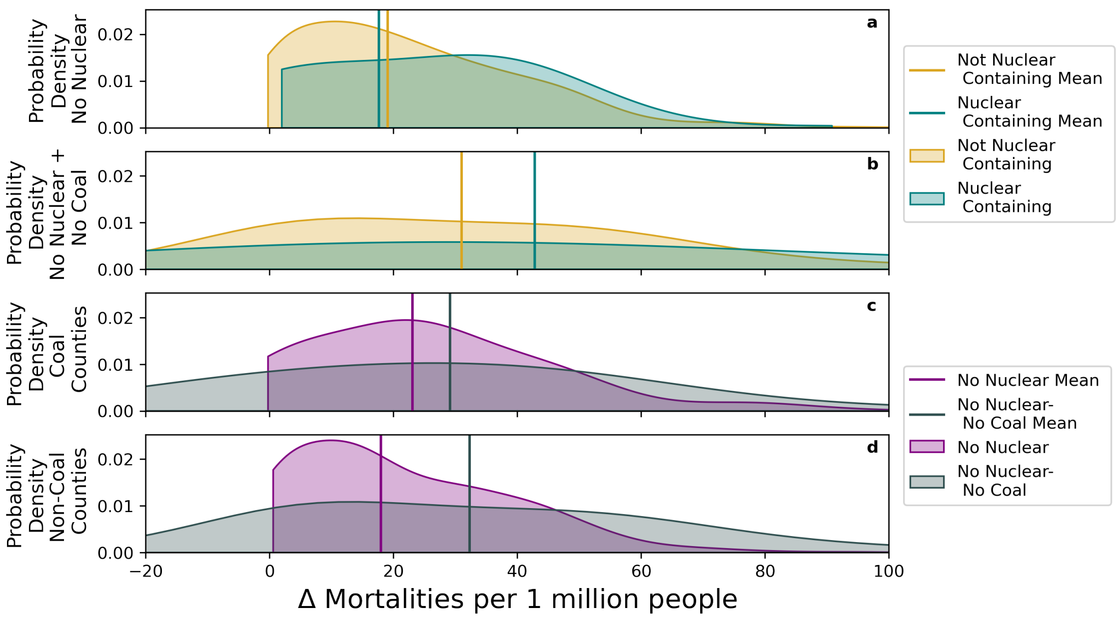
Supplementary Figure 8: **Maps of summer and winter ozone regimes** Summer (JJA) and winter (DJF) ozone regimes for No Nuclear (a, d), No Nuclear + No Coal (b, e), and No Nuclear + Renewables (c, f). The CH_2O:NO_2 ratio determines the ozone regime, as explained in Supplementary Information Section 1.



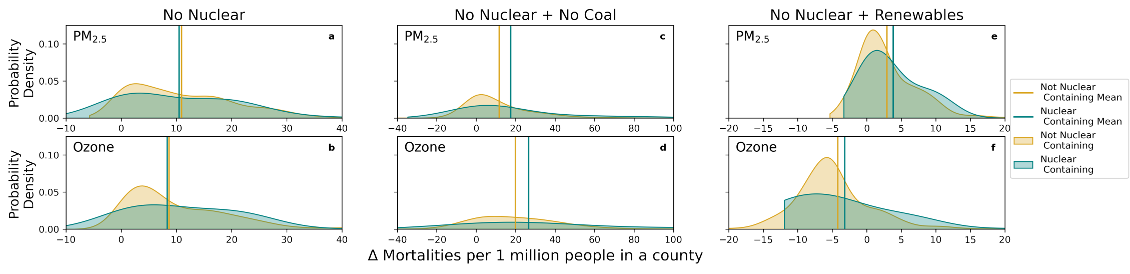
Supplementary Figure 9: **Maps of mean summer and winter ozone and $PM_{2.5}$ concentration** Summer (JJA) and winter (DJF) concentrations of $PM_{2.5}$ (top two rows) for No Nuclear + Renewables, Base, NEI 2011, No Nuclear, No Nuclear + No Coal, eGRID, and NEI 2016. Summer (JJA) and winter (DJF) concentrations of ozone (bottom two rows) for No Nuclear + Renewables, Base, NEI 2011, No Nuclear, No Nuclear + No Coal, eGRID, and NEI 2016.



Supplementary Figure 10: **Maps of the difference in ozone and $PM_{2.5}$ concentrations between No Nuclear and the Base** Differences in summer (JJA) and winter (DJF) concentrations of $PM_{2.5}$ (top two rows) for No Nuclear + Renewables, NEI 2011, No Nuclear, No Nuclear + No Coal, eGRID, and NEI 2016 compared to the Base. Differences in summer (JJA) and winter (DJF) concentrations of ozone (bottom two rows) for No Nuclear + Renewables, NEI 2011, No Nuclear, No Nuclear + No Coal, eGRID, and NEI 2016 compared to the Base.



Supplementary Figure 11: **Probability density estimation for changes in mortalities per 1 million people in counties with and without coal plants, and with and without nuclear plants** Changes in mortalities per one million people between No Nuclear + No Coal and the Base by counties with and without nuclear plants (a and b), and with and without coal plants (c and d) for $PM_{2.5}$ and ozone combined. Curves are the probability density estimation, weighted by population. Mean changes in mortalities per 1 million people are shown as vertical lines, and the spread across all counties are shaded.



Supplementary Figure 12: **Probability density estimation for changes in mortalities per 1 million people in counties with and without nuclear plants** Changes in mortalities per one million people between No Nuclear (a and b), No Nuclear + No Coal (c and d), and No Nuclear + Renewables (e and f) and the Base by county for $PM_{2.5}$ (top row) and Ozone (bottom row). Curves are the probability density estimation, weighted by population. Mean changes in mortalities per 1 million people are shown as vertical lines, and the spread across all counties are shaded.

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