Comparison of Tw[illegible] Power-Plant Carbo[illegible]xide Emissions Data Se[illegible]

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Estimates of fossil-fuel CO_2 emis[illegible] needed to address a variety of climate-change mit[illegible]ncerns over a broad range of spatial and temporal s[illegible] compared two data sets that report power-pla[illegible]ssions in the conterminous U.S. for 2004, the [illegible]nt year reported in both data sets. The data sets wer[illegible] from the Department of Energy's Energy Information [illegible]tion (EIA) and the Environmental Protection Agency'[illegible]tabase. Conterminous U.S. total emissions computed f[illegible]ata sets differed by 3.5% for total plant emissions (ele[illegible] useful thermal output) and 2.3% for electricity generati[illegible]hese differences are well within previous estimates of uncertainty in annual U.S. fossil-fuel emissions. However, the corresponding average absolute differences between estimates of emissions from individual power plants were much larger, 16.9% and 25.3%, respectively. By statistical analysis, we identified several potential sources of differences between EIA and eGRID estimates for individual plants. Estimates that are based partly or entirely on monitoring of stack gases (reported by eGRID only) differed significantly from estimates based on fuel consumption (as reported by EIA). Differences in accounting methods appear to explain differences in estimates for emissions from electricity generation from combined heat and power plants, and for total and electricity generation emissions from plants that burn nonconventional fuels (e.g., biomass). Our analysis suggests the need for care in utilizing emissions data from individual power plants, and the need for transparency in documenting the accounting and monitoring methods used to estimate emissions.

Introduction

In 2004, U.S. fossil-fuel CO_2 emissions (~6 $PgCO_2$/yr, or 1.6 PgC/yr) amounted to ~20% of the world's total annual emissions of fossil-fuel CO_2 (*1*). Fossil fuel consumption by U.S. power plants accounted for ~40% of total U.S. CO_2 emissions and ~8% of total global fossil-fuel CO_2 emissions. If the widely accepted relative uncertainty in annual fossil-fuel emissions, ±6 to 10% for the 90% confidence interval (*2*), is applied to recent emissions data, the absolute uncertainty of global fossil-fuel CO_2 emissions can be estimated at ±0.5 to 0.8 PgC/yr. This uncertainty exceeds the absolute uncertainty in recent multiyear average annual changes in the amount of CO_2 stored in the atmosphere (doubled standard deviation ± 0.2 PgC/yr (*3*)) and may be comparable to the absolute uncertainty estimated for multiyear average annual storage of anthropogenic CO_2 in the oceans (doubled standard deviation ± 0.8 to 1.0 PgC/yr (*3–5*)). Uncertainties in global CO_2 emissions are an important limitation in inversion calculations of annual (*6*) and seasonal to interannual (*7*) global carbon mass balance. As inversion techniques are applied to more localized carbon budgets, uncertainties in emissions from local sources such as power plants will become increasingly important.

Estimates of U.S. power-plant CO_2 emissions provide an exceptionally detailed record of monitoring under optimal circumstances at point sources. According to the Department of Energy's Energy Information Administration (EIA) (*8*), U.S. fossil-fuel CO_2 emissions are generally regarded to be accurate to within 5%, with most of the uncertainty attributed to systematic ("bias," i.e., nonrandom) error. Blasing et al. (*9*) suggested uncertainties on the order of 3−4% for estimates of monthly U.S. fossil-fuel CO_2 emissions.

In this study, we compared two different government data sets of power plant emissions in the conterminous U.S. in order to characterize the differences and to identify factors that may contribute to the differences.

Sources of Power-Plant Emissions Data. The EIA and the Environmental Protection Agency (EPA) estimate emissions of greenhouse gases at U.S. power plants in compliance with the Energy Policy Act of 1992 and Title IV of the Clean Air Act Amendments of 1990, respectively. The EIA calculates CO_2 emissions from fuel consumption data reported by electricity-generating plants. The EIA data set includes information about each plant's industrial sector classification (e.g., electric utility, commercial, or industrial), total heat input, and CO_2 emissions by fuel type (with the broad categories of coal, oil, gas, geothermal, and municipal solid waste).

The EPA data set, eGRID2006 version 2.1 (referred to as "eGRID" in subsequent discussion), includes CO_2 emission data from two different monitoring methods. For the year 2004, emissions from ~61% of the power plants were calculated from fuel consumption data. These plants (termed "fuel calculation plants" in this paper) accounted for only 6% (~37 TgC) of the total CO_2 emissions from power plants. Approximately 29% of the plants used continuous emissions monitoring (CEM) systems to measure gas concentrations and flow rates directly in the plant exhaust stacks. These plants (termed "stack plants" in this paper) accounted for 72% (~471 TgC) of the total CO_2 emissions from power plants. Emissions from the remaining 10% of the plants had CO_2 emissions derived from a combination of the above methods. These plants (termed "combination plants" in this paper) accounted for ~22% (~148 TgC) of the total CO_2 emissions from power plants (*10*). In addition to emissions data, the eGRID data set also includes energy data (e.g., heat input, net generation, fuel type).

Materials and Methods

We compared estimates of CO_2 emissions in the eGRID and EIA data sets at two levels: (1) individual power-plant emissions and (2) conterminous U.S. total power-plant emissions. These comparisons allowed us to analyze differences due to fuel type, monitoring method, and plant type and to identify and characterize potential sources of bias (i.e., systematic departure from expected random variation). Comparison of conterminous U.S. totals allowed us to examine the aggregated effects of individual power-plant differences and potential sources of collective bias.

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TABLE 1. The Average Signed and Average Absolute Differences Relative to the Mean for the Subsets of Individual Power Plants[a]

	average signed difference, relative to mean (%)[b]		average absolute difference, relative to mean (%)		
	electricity emissions	total emissions	electricity emissions	total emissions	number of plants
Whole data set	−3.5	1.8	25.3	16.9	2900
Nonconventional fuel plants	−47.3	−33.3	99.4	78.9	252
Coal-, oil- and gas-fired plants	0.7	5.1	18.3	11.0	2648
Monitoring method (conventional-fuel data set)					
Stack measurements	4.6	5.4	17.1	16.6	828
Stack or fuel calcs (combo)	21.0	21.7	24.8	24.4	285
Fuel calculations	−5.1	1.9	17.7	5.5	1535
CHP plants (conventional-fuel data set)					
CHP plants	−6.8	0.2	37.9	12.7	493
Non-CHP plants	5.3	5.3	9.5	9.5	1888
Fuel calculation subset (conventional-fuel data set)					
All plants in this subset	5.1	1.9	17.7	5.5	1535
CHP plants	−8.2	0.0	37.7	9.5	435
Non-CHP plants	0.6	0.6	1.8	1.9	898

[a] All values shown are for 2004. [b] Positive average signed differences indicate that, on average, the eGRID values are larger than the EIA values, and vice versa for negative average signed differences.

This paper focuses on our comparison of data from the year 2004, the most recent year for which both data sets have complete reporting. (In the Supporting Information, we show that similar trends were observed in 1998−2000 (*11*); years 2001−2003 were not available from both data sets.) We restricted our comparisons to power plants located in the conterminous United States and to those for which CO_2 emissions are nonzero in either data set. These criteria eliminated ~160 plants, leaving 2900 matched pairs of EPA and EIA estimates for individual power plants.

Comparisons of Individual Power-Plant Emissions Estimates. We conducted a statistical analysis of differences between the annual emissions estimated for individual plants in the two data sets. There were significant differences between the two data sets at the plant level, even though estimates from ~60% of the matched pairs were drawn from the same source (the fuel consumption data reported for individual plants to EIA). Because the individual plants varied over several orders of magnitude in annual emissions, we calculated relative differences (expressed as percent) by dividing the differences (eGRID − EIA) by the means of the paired eGRID and EIA estimates (percent relative difference = 100(eGRID − EIA)/ [(eGRID + EIA)/2]).

To determine possible sources of these differences, we compared subsets of the matched pairs of eGRID and EIA estimates for individual plants based on fuel type, monitoring method and plant type. In order to test the statistical significance of anomalies among these subsets, we calculated the *z* statistic, $z = (X - \mu)/\sigma_x$, where X is the observed sample (subset) mean relative difference, μ is the population (full data set) mean relative difference, and σ_x is the standard error expected among mean relative differences of random samples of the same size as the subset. We used the *z* statistic to compare the mean relative difference within each subset to the expected random variation given the mean and standard deviation of the full data set. The computed *z* value tests the null hypothesis that the observed subset mean relative difference occurred by chance. A *z* value between −1 and 1 indicates there is a relatively high probability that the observed subset mean relative difference occurred by chance. A *z* with an absolute value greater than or equal to 1.96 indicates that the probability is 5% or less that the difference is due to chance (i.e., that the observed means are due to random variation; see Supporting Information for further details).

We accepted any low-probability departure from expected random variation as an indication of bias. The attribution of bias to potential sources required further knowledge and interpretation. In this paper, we describe the results of our statistical tests and use additional information where possible to attribute the biases associated with particular subsets. We also address the extent to which the observed biases affect comparisons among other subsets and analysis of the entire data set of paired estimates.

Results and Discussion

1. Differences at the Individual Plant Level. For all 2900 pairs of estimates, the average signed relative difference (eGRID minus EIA) was 1.8% for the total emissions of the plant, suggesting that, on average, individual plant emissions in the eGRID data set were slightly larger than in the EIA data set. The average absolute value of the relative differences was 16.9%, showing that the small average signed difference is a residual of larger relative differences that are both positive and negative (Table 1). Because power plant CO_2 emissions associated with electricity production (as opposed to total CO_2 emissions from the plant) are often reported and analyzed, we also compared emissions solely from the generation of electricity. As described below, plants that generate both electricity and useful thermal output (i.e., steam or heat) (termed "CHP plants") report these emissions separately. For electricity generation alone, we observed an average signed relative difference of −3.5% (individual plant electricity emissions in EIA are on average larger than those in eGRID) and an average absolute difference of 25.3%. Further analysis suggests that these average signed differences can be attributed, at least in part, to differences in both accounting and monitoring of emissions.

1.a. Differences in Accounting of Emissions from Plants That Use Nonconventional Fuels. Power plants that consume conventional fossil fuels (coal, oil, or gas) accounted for 91% of all plants and ~99% of the power-plant CO_2 emissions in the conterminous United States. A comparison of eGRID and EIA plant-level estimates of CO_2 emissions based on the fuel type used at the plant showed a systematic anomaly in

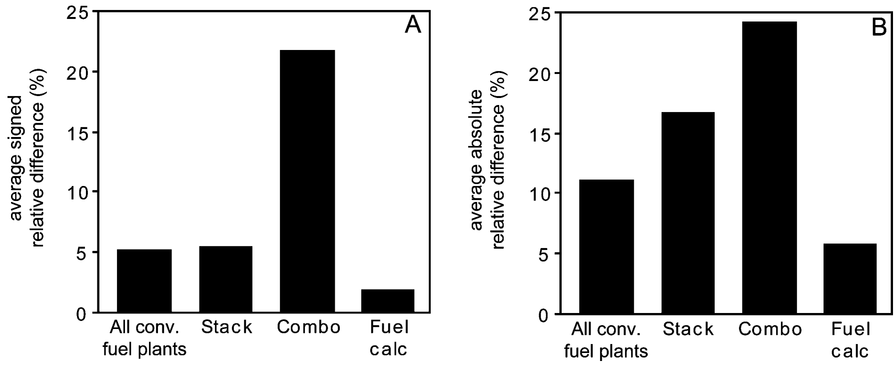

FIGURE 1. A. The average signed relative difference between eGRID and EIA CO_2 emissions reported for individual conventional-fuel power plants and subsets defined by monitoring method (stack measurement, calculation from fuel data, or a combination of the two methods) for 2004. The positive average signed relative differences indicate that, on average, eGRID estimates at the individual plant level are greater than those of EIA. B. The average absolute relative differences of the conventional-fuel data set and the monitoring method subsets, showing that the average signed differences (shown in Figure 1A) are residuals of larger differences that are both negative and positive.

the subset of plants that use nonconventional fuels (e.g., biomass, municipal solid waste, wood) (Table 1).

The average signed relative differences for plants burning nonconventional fuels were −33.3% for total emissions and −47.3% for emissions from electricity only, indicating that EIA estimates for these plants were on average much higher than eGRID estimates. The *z* values for these average signed relative differences were very negative (−5.4 and −6.3, total and electricity only, respectively), suggesting an extremely low probability that these anomalies were due to random variation. We conclude that the differences between eGRID and EIA estimates of CO_2 emissions from nonconventional fuel plants represent a significant bias.

The most likely source of this bias was the differences and uncertainties in accounting for emissions from nonconventional fuel plants. In eGRID, CO_2 emissions from burning biomass were assigned values of zero in accordance with the assumption that the natural decomposition of biomass would produce CO_2 even if it were not used as fuel. For plants that burn solid waste, eGRID discounted CO_2 emissions by 70% based on the assumption that 70% comes from renewable materials (i.e., biomass) and 30% comes from nonrenewables (*10*). It does not appear that EIA discounted the CO_2 emissions for plants that used biomass or solid waste.

Because nonconventional fuel plants were a likely source of bias in comparing the full eGRID and EIA data sets, and because these plants contributed a very small (<1%) fraction of total CO_2 emissions, we excluded them from further comparison at the individual plant level. This exclusion left 2648 pairs of estimates for plants that consume coal, gas, or oil as their primary fuel (termed the "conventional-fuel data set" in this paper). For conventional fuel plants, the average signed relative difference for total emissions was 5.1%, suggesting that on average the eGRID estimates were larger than the EIA estimates. The average absolute relative difference was 11.0%, indicating that the average signed difference was a residual of larger differences that were both positive and negative.

1.b. Differences Associated with Emissions Monitoring Methods. We also observed differences between emissions estimated by eGRID and EIA for subsets based on emission monitoring methods within the conventional-fuel data set. For compliance with Title IV of the Clean Air Act Amendments of 1990, electric generating units are required to monitor CO_2 emissions. Some are required to monitor emissions via direct measurement in the stack while other units are allowed to calculate emissions from fuel consumption data. We compared subsets according to whether the eGRID emissions were monitored by CEM systems (the 828 stack measurement plants), calculated from fuel use (the 1535 fuel calculation plants) or determined using a combination of these two methods (the 285 combination plants). Combination plants have multiple generating units (e.g., boilers) of which only some units are required to use CEM systems. Currently, all coal-fired units use CEM systems; however, gas- and oil-fired units as well as small plants are permitted either to measure emissions using a CEM system or to calculate emissions from fuel consumption data (*12*).

The average signed relative differences between individual plant estimates (eGRID minus EIA) for the stack-measurement subset were 4.6% for electricity generation and 5.4% for total emissions, indicating that eGRID estimates from stack measurements tend to be higher than corresponding EIA estimates based on fuel consumption (Table 1 and Figure 1a). The average absolute relative difference in this subset was ~17% for both total plant emissions and electricity emissions, showing that the signed differences were residuals of larger differences that are both negative and positive (Figure 1b). Previous investigations similarly found that CEM estimates of emissions differ from those calculated from fuel consumption. Placet et al. (*13*) concluded that on average, CEM estimates of SO_2 emissions at the national level are ~3% higher and NO_x emissions ~20% lower than those calculated from fuel data. They also observed significant variability at the state level (32% lower to 59% higher for SO_2 and 329% lower to 80% higher for NO_x) and even greater variability at the boiler level.

In the fuel calculation subset, where both eGRID and EIA used fuel consumption data to calculate emissions, the average signed relative difference was 1.9% for total emissions, showing greater agreement between eGRID and EIA values; also, the average absolute relative difference was 5.5%, which is much lower than the average absolute difference in the other monitoring subsets. For electricity generation, the signed relative difference was −5.1%, suggesting that there was an additional influence on the relative difference (we believe it to be the influence of disparate estimates for CHP plants, which are discussed in the next section).

The average signed relative differences for the subset of combination plants were very large for electricity generation and total emissions, 21.0% and 21.7%, respectively (Table 1 and Figure 1a). It is unclear why these average signed relative differences were so large, especially because the corresponding differences were much smaller in the 1998−2000 data (see Supporting Information). The relative differences calculated for ~20% of the individual plants in this subset were ~60% or greater, meaning that the eGRID value was approximately double the EIA value or greater. We do not have enough information to determine the cause of such large differences between EIA and eGRID estimates for combination plants.

The z values for the average signed relative differences observed in the three monitoring subsets (stack measurement: 2.8, fuel calculation: −5.7, combination: 9.4) correspond to very low probabilities that the values could result from random variation within the conventional-fuel data set. On the basis of knowledge about the monitoring methods that define these subsets, we conclude that these differences reflect at least three sources of bias: (1) significant differences between estimates based on CEM monitoring reported by eGRID and fuel-based calculations reported by EIA for the stack-measurement plants; (2) additional differences (discussed below) between eGRID and EIA estimates of emissions from electricity generation at fuel-calculation plants; (3) unexplained differences that appear to be necessary to account for the significant bias between eGRID and EIA estimates for combination plants.

1.c. Differences in Reporting of Emissions from Combined Heat and Power (CHP) Plants. In many of our comparisons of EIA and eGRID estimates of individual plant CO_2 emissions, the average signed relative differences between emissions attributed to electricity generation were consistently lower than those observed for total emissions (Table 1). This tendency can be attributed to different methods of accounting for emissions from electricity generation at combined heat and power (CHP) facilities. These power plants produce electrical energy as well as other useful thermal output (UTO) (i.e., steam or heat), which is captured and used for industrial and commercial purposes (*10, 14*).

EIA and eGRID used different methods to classify these plants and to allocate their emissions to electricity vs UTO. If the necessary data were available, both eGRID and EIA calculated emissions associated with UTO by subtracting fuel consumed for electricity generation from the total fuel used and multiplying the resulting value by 0.8, which is the assumed "standard combustion efficiency" (*14*). However, when the data necessary for this calculation were not available, it seems that the eGRID and EIA methods diverged.

To examine these issues more closely, we conducted a comparison between CHP and non-CHP plants. For this analysis, we considered only the 493 CHP plants that were designated as CHP in both eGRID and EIA and also had UTO reported in EIA. We compared these plants to the 1888 plants that were designated as non-CHP by both eGRID and EIA. (The remaining 267 plants not included in this analysis are those labeled as "CHP" in one data set but not in the other.) We examined estimates of emissions from the generation of electricity, as well as total emissions (electricity emissions plus emissions from the generation of heat or steam).

The average signed relative differences (eGRID minus EIA) for emissions associated with electricity generation by CHP and non-CHP plants were −6.8% and 5.3%, respectively. These values indicate that the EIA estimates for individual CHP plants tend to be higher than corresponding eGRID estimates, and vice versa for non-CHP plants (Table 1). The CHP subset had a very large average absolute relative difference (37.9%) while the non-CHP subset had a much smaller average absolute relative difference (9.5%). While both of the average absolute relative differences indicate that the average signed differences are residuals of larger differences that are both positive and negative, the very large average absolute difference for CHP plants and the much smaller value for non-CHP plants reflect differences between the eGRID and EIA methods for classifying CHP plants and/or accounting for their emissions (Table 1). The z values (for which the "full data set" is defined as only the CHP and non-CHP plants of this analysis) for the average signed relative differences, −3.6 and 3.8 for CHP and non-CHP plants, respectively, correspond to very low probabilities that the observed means might have resulted from random variation.

For total emissions, the average signed relative difference for CHP plants was nearly zero (0.2%) and the average absolute relative difference decreased to 12.7%. The average signed and average absolute relative differences for non-CHP plants remained the same for total emissions because they were not affected by inconsistencies in the attribution of emissions to electricity versus UTO.

We attribute the bias in differences in emissions from electricity generation to differences between eGRID and EIA classification and/or accounting methods for emissions from CHP plants. The observed negative average signed relative difference for electricity generation from CHP plants is consistent with an accounting difference in which emissions attributed to steam/heat (nonelectricity) generation are greater in eGRID than in EIA, leaving lower reported eGRID CO_2 emissions due to electricity generation.

1.d. Differences Associated with Emissions Calculated from Fuel Consumption. Our identification of biases due to fuel type, monitoring method, and plant type led us to look further for a subset that might indicate minimal differences between eGRID and EIA emissions estimates. Because emissions from plants that do not use CEM systems—the fuel-calculation plants subset described above—were calculated in both data sets from EIA fuel consumption data, any observed differences in estimates for these plants may be due to differences in calculation parameters. Fuel calculation plants made up the majority of the conventional fuel data set, but accounted for only ~8% of the total CO_2 emissions.

The calculation of CO_2 emissions from fuel consumption requires the "activity" (the physical amount of fuel consumed multiplied by the heat content of the fuel-also referred to as "heat input"), the "carbon coefficient" of each fuel (the amount of carbon released per unit of fuel energy consumed), and the "oxidation factor" (the fraction of carbon that is oxidized during combustion). Emissions are calculated using the following equation (*15, 16*):

$$CO_2\ \text{emiss}_{[\text{TgCO}_2]} = (\text{activity}_{[\text{MMBtu}]})(C_{\text{coeff},[\text{TgC/QBtu}]})(\text{oxid fact.})(44/12)(1 \times 10^{-9})$$

where the factors $(44/12)(1 \times 10^{-9})$ account for the conversions between TgC and $TgCO_2$ and between MMBtu (10^6 Btu) and QBtu (10^{15} Btu).

In the eGRID and EIA data sets, annual activity values are given for each plant. The oxidation factor accounts for the small amount of fuel that is not oxidized to CO_2 during combustion (oil and coal: 0.99; gas: 0.995). The carbon coefficients used by eGRID and EIA for conventional fuels are similar, as detailed in EPA (*15*) and EIA (*17*) documents. However, actual carbon coefficients, especially for coal, vary from region to region and can therefore have an impact on the accuracy of CO_2 emissions calculated from fuel consumption data (e.g. (*18*)). Carbon coefficients that incorporate more realistic information about coal variability would provide more accurate emissions estimates than those that are currently used, which only take coal rank into account (*19*). However, detailed monitoring of coal variability at the plant level would require additional data collection and reporting.

A comparison of individual plant emissions calculated from fuel consumption data showed that the average signed relative difference (eGRID minus EIA) was 1.9% for total plant emissions and −5.1% for electricity generation emissions. The CHP subset of the fuel-calculation plants had an average signed relative difference of −8.2% for electricity emissions, while the non-CHP subset had a value of 0.6% (Table 1). These means had z values (total plant: −5.0; electricity

TABLE 2. Comparison of Conterminous U.S. Total CO_2 Emissions for the Whole Data Set and Its Subsets[a]

	eGRID (TgC)		EIA (TgC)		signed difference, relative to mean (%)[b]	
	electricity emissions	total emissions	electricity emissions	total emissions	electricity emissions	total emissions
Whole data set	656.3	686.9	641.1	663.4	2.3	3.5
Nonconventional fuel plants	4.7	8.5	5.4	7.5	−14.4	11.4
Coal-, oil- and gas-fired plants	651.6	678.5	635.7	655.8	2.5	3.4
Conventional-fuel data set						
Coal-fired plants	538.5	553.7	533.3	545.9	1.0	1.4
Oil-fired plants	19.4	21.2	19.3	20.5	0.1	3.3
Gas-fired plants	93.8	103.6	83.0	89.4	12.2	14.7
Stack measurements	469.6	471.8	464.3	465.4	1.1	1.4
Stack or fuel calcs (combo)	147.9	149.3	134.9	135.2	9.2	9.9
Fuel calculations	34.1	57.4	36.5	55.2	−6.8	3.9
CHP plants	33.8	57.2	33.9	54.1	−0.3	5.6
Non-CHP plants	599.3	599.3	582.9	582.9	2.8	2.8

[a] All values shown are for 2004. [b] Positive signed differences indicate that the eGRID value is larger than the EIA value, and vice versa for negative signed differences.

generation: −5.7; CHP: −2.1; non-CHP: 6.0) that correspond to very low probabilities that the observed means might result from random variation. Thus the bias associated with electricity emissions from CHP plants, which we have attributed above to differences in the methods used by EIA and eGRID for allocating emissions to electricity and UTO, manifested itself in the fuel calculation subset.

For total plant emissions, the average relative difference in the CHP subset was 0.0%, suggesting that on average the difference between individual plants in the two data sets was very minimal. The average signed relative difference of non-CHP plants stayed the same (0.6%).

To examine differences that are not associated with identified sources of bias, we excluded stack-measurement plants, combination plants, and CHP plants, leaving 898 non-CHP plants that used the fuel calculation method. The average signed relative difference of these plants was 0.6%, for both electricity generation and total plant emissions, and the average absolute differences were 1.8% (electricity generation) and 1.9% (total emissions). These values suggest the degree of agreement between individual plant estimates that might be attainable if identified biases were removed. However, because these differences reflect only the calculation of emissions based by both eGRID and EIA on the EIA fuel consumption data, they should not be viewed as an indication of agreement between independent measurements.

2. Differences in Estimates of Conterminous U.S. Total Emissions. The total emissions of all plants in the conterminous U.S. were 686.9 TgC according to eGRID and 663.4 TgC according to EIA. Pronounced differences between eGRID and EIA estimates were seen in nonconventional fuel plants at the individual plant level; however, these differences had a minimal effect on conterminous U.S. totals due to the fact that they accounted for ~1% of total emissions (eGRID: 8.5 TgC, EIA: 7.5 TgC). Here we discuss only total emissions from conventional-fuel plants. The sum of all conventional-fuel plant emissions in eGRID (678.5 TgC) is 3.5% larger than the EIA total (655.8 TgC; Table 2; Figure 2). Note that this comparison and others discussed below describe signed differences relative to the value of the smaller data set. For consistency across all of our analyses, all figures and tables show signed differences relative to the mean of the two data sets.

The differences between the eGRID and EIA conterminous U.S. totals reflect a balance among the potential sources of bias observed among subsets of individual power plants. Conterminous U.S. totals for subsets defined by all three monitoring methods were higher in eGRID (by 1.4% (stack), 10.4% (combination), and 4.0% (fuel calculation)). The aggregation of emissions to the conterminous U.S. level can mask larger differences at the individual plant level; for example, in the stack subset, the relative difference between conterminous U.S. totals was 1.4% while at the plant level the average signed relative difference was 5.4% and the average absolute relative difference was 16.6%.

Plants that use CEM methods in eGRID and fuel calculations in EIA had systematically higher emissions in eGRID, both at the individual plant level and conterminous U.S. total level. Because conterminous U.S. total power-plant emissions were dominated by large coal-fired plants that use CEM systems, resolving these differences would be an efficient way to improve accuracy and reduce uncertainties in inventories of national greenhouse gas emissions.

The total conterminous U.S. emissions from CHP plants were also higher in eGRID (57.2 TgC) than in EIA (54.1 TgC) while the emissions from electricity generation at CHP plants were similar (eGRID: 33.8 TgC, EIA: 33.9 TgC). CHP emissions, and the potential sources of bias associated with the attribution of electricity generation emissions, had a relatively

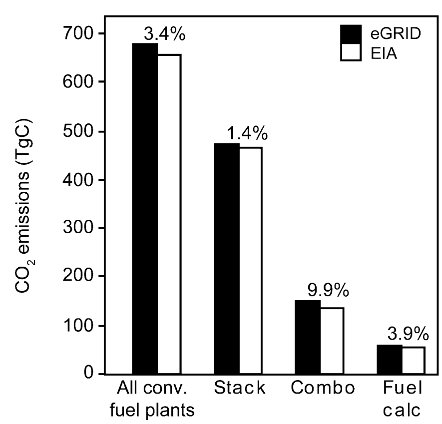

FIGURE 2. Comparison of eGRID and EIA estimates of total conterminous U.S. CO_2 emissions for conventional fuel power plants and monitoring method subsets for 2004. For each pair of columns, the eGRID value is on the left, in black. The percent difference, relative to the mean, between eGRID and EIA is shown above each pair of columns.

minor impact on the total conterminous U.S. emissions because these plants only accounted for ~5% of the overall total.

Our analysis demonstrates that plant-level and conterminous U.S. estimates of CO_2 emissions can be improved by resolution of identifiable sources of bias. However, it is important to recognize that the ongoing quantification of accuracy and uncertainties will always require the application of multiple independent estimation procedures. As strategies for mitigation of greenhouse gas emissions are debated and implemented, we suggest that attention be devoted to the importance of designed redundancy and transparency in the monitoring of power-plant emissions.

Acknowledgments

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Note Added after ASAP Publication

There were some minor errors in the version of this paper published ASAP June 25, 2008; the corrected version published ASAP July 3, 2008.

Supporting Information Available

The same comparison was completed for the years 1998−2000 (*11*), with details provided in Tables SI-1 and SI-2. This material is available free of charge via the Internet at http://pubs.acs.org.

Literature Cited

(1) Marland, G.; Boden, T. A.; Andres, R. J. Global, regional, and national CO_2 emissions. In *Trends: A Compendium of Data on Global Change*; Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy: Oak Ridge, TN, 2005.

(2) Marland, G.; Rotty, R. M. Carbon dioxide emissions from fossil-fuels: A procedure for estimation and results for 1950−1982. *Tellus, Ser. B:* **1984**, *36*, 232–261.

(3) Denman, K. L.; Brasseur, G.; Chidthaisond, A.; Ciais, P.; Cox, P. M.; Dickinson, R. E.; Hauglustaine, D.; Heinze, C.; Holland, E.; Jacob, D.; Lohmann, U.; Ramachandran, S.; da Silva Dias, P. L.; Wofsy, S. C.; Zhang, X. Couplings between changes in the climate system and biogeochemistry. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: New York, 2007.

(4) Le Quere, C.; Aumont, O.; Bopp, L.; Bousquet, P.; Ciais, P.; Francey, R.; Heimann, M.; Keeling, C. D.; Keeling, R. F.; Kheshgi, H.; Peylin, P.; Piper, S. C.; Prentice, I. C.; Rayner, P. J. Two decades of ocean CO_2 sink and variability. *Tellus, Ser. B:* **2003**, *55*, 649–656.

(5) Takahashi, T.; Sutherland, S. C.; Sweeney, C.; Poisson, A.; Metzl, N.; Tilbrook, B.; Bates, N.; Wanninkhof, R.; Feely, R. A.; Sabine, C.; Olafsson, J.; Nojiri, Y. Global sea-air CO_2 flux based on climatological surface ocean pCO_2, and seasonal biological and temperature effects. *Deep-Sea Res. Part II* **2002**, *49*, 1601–1622.

(6) Manning, A. C.; Keeling, R. F. Global oceanic and land biotic carbon sinks from the Scripps Atmospheric Oxygen Flask Sampling Network. *Tellus, Ser. B:* **2006**, *58*, 95–116.

(7) Gurney, K. R.; Chen, Y. H.; Maki, T.; Kawa, S. R.; Andrews, A.; Zhu, Z. X. Sensitivity of atmospheric CO_2 inversions to seasonal and interannual variations in fossil fuel emissions *J. Geophys. Res. [Atmos.]*, **2005,** *110*, art. no. D10308.

(8) U.S. Energy Information Administration. *Documentation for Emissions of Greenhouse Gases in the United States 2003*; EIA: Washington, D.C., 2005.

(9) Blasing, T. J.; Broniak, C. T.; Marland, G. The annual cycle of fossil-fuel carbon dioxide emissions in the United States. *Tellus, Ser. B:* **2005**, *57*, 107–115.

(10) eGRID. Technical Support Document (Emissions & Generation Resource Integrated Database), Washington, D.C., 2006.

(11) Ackerman, K. V.; Sundquist, E. T., Comparison of two U.S. power-plant carbon dioxide emissions datasets Eos Trans. AGU, 2006, *87*, (52),Fall Meet. Suppl., Abstract A41C-0042.

(12) U.S. Environmental Protection Agency. *Plain English Guide to the Part 75 Rule*; EPA: Washington, D.C., 2005.

(13) Placet, M.; Mann, C. O.; Gilbert, R. O.; Niefer, M. J. Emissions of ozone precursors from stationary sources: a critical review. *Atmos. Environ.* **2000**, *34*, 2183–2204.

(14) U.S. Energy Information Administration. *Electric Power Annual 2004*; EIA: Washington, D.C., 2005.

(15) U.S. Environmental Protection Agency. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990−2004*; EPA: Washington, D.C., 2006.

(16) U.S. Energy Information Administration. *Documentation for Emissions of Greenhouse Gases in the United States 2002*; EIA: Washington, D.C., 2004.

(17) U.S. Energy Information Administration. *Electric Power Annual 2005*; EIA: Washington, D.C., 2006.

(18) Quick, J. C.; Brill, T. Provincial variation of carbon emissions from bituminous coal: influence of inertinite and other factors. *Int. J. Coal Geol.* **2002**, *49*, 263–275.

(19) Hong, B. D.; Slatick, E. R. Carbon Dioxide Emission Factors for Coal. In *Quarterly Coal Report*. In U.S. Energy Information Administration: Washington, D.C., 1994.

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