SUPPORTING INFORMATION FOR:

Whitaker, M., G. Heath, P. O'Donoughue, and M. Vorum. 2012. Life Cycle Greenhouse Gas Emissions of Coal-Fired Electricity Generation: Systematic Review and Harmonization. *Journal of Industrial Ecology.*

Summary

Please note that the article for which this document serves as supporting information has been corrected and updated by corrigenda available on the Journal's Web site. Corrigendum 2 provides changes to the results for the supercritical coal combustion technology reflecting the use of a different and corrected thermal efficiency for harmonization. The corrigendum includes a new supporting information document that contains revisions that reflect corrections from the original article regarding results for the supercritical technology. Overall conclusions have not changed.

This supporting information provides the detailed methodology for the two-stage quantitative test developed to determine the appropriate level of harmonization for a given electricity-generation technology analyzed by the Life Cycle Assessment (LCA) Harmonization Project led by the U.S. National Renewable Energy Laboratory. The full list of references reviewed for this harmonization analysis is also included.

Selection of Harmonization Level

A two-stage quantitative test was developed to determine the appropriate level of harmonization for a given electricity-generation technology analyzed by the Life Cycle Assessment (LCA) Harmonization Project led by the U.S. National Renewable Energy Laboratory. The test was intended to provide information about how to allocate limited resources to the development of more-robust estimates of central tendency and variability and to inform decision makers in the near term; the statistical approach used was not necessarily ideal.

First, the standard deviation (SD) and interquartile range magnitude (IQR = 75th – 25th percentile value) of published estimates of life cycle GHG emissions (in g CO_2e/kWh) were compared to the arithmetic mean (mean) of the pool of estimates from literature

that had passed the quality and relevance screens. Variability in published estimates was deemed "high" if the SD and IQR were greater than or equal to 50% of the mean and "low" if they were less than 50%.

The next test was only applicable to non-coal technologies, but nevertheless is described here to provide a more complete understanding of the LCA Harmonization project's methods as a whole. In this step, the range of published estimates was compared to the mean value for estimates for subcritical pulverized coal combustion (subcritical) drawn from the literature which had passed the quality and relevance screens (1,100 g CO_2e/kWh). If the range was greater than or equal to 10% of that of pulverized coal, then the published variability was considered significant. Using these tests, when variability in a given electricity-generation technology's published estimates was deemed "low" and "not significant" relative to coal, the less resource-intensive level of harmonization appeared sufficient to achieve the project goals.

For coal-fired electricity generation only the first test applied, as coal was the benchmark for the second test. For published coal estimates, the SD and IQR were approximately 20% and 25% of the mean, respectively. Both values were well below the 50% threshold for variability that would have indicated the need for the more rigorous level of harmonization.

Exclusion of Integrated Gasification Combined Cycle with Carbon Capture and Storage from Harmonization

Nine references (Corrado et al. 2006; Fiaschi and Lombardi 2002; Jaramillo et al. 2006; Koornneef et al. 2008; NETL 2010b; Odeh and Cockerill 2008; Ruether et al. 2004; SENES 2005; Wibberley 2001) with 11 estimates of life cycle greenhouse gas (GHG) emissions for integrated gasification combined cycle with carbon capture and storage systems (IGCC/CCS) passed the literature screens for the present study. As a future technology with multiple potential paths to implementation, however, the reported LCA methodologies and study assumptions in the literature varied greatly and would have required expanding the scope of the study beyond light harmonization. Therefore, only published estimates of IGCC/CCS life cycle GHG emissions are presented in this article, which ranged from 106 g to 396 g CO_2e/kWh with a mean of 230 g CO_2e/kWh, a median of 214 g CO_2e/kWh, IQR of 142-324 g CO_2e/kWh, and a standard deviation of 106 g CO_2e/kWh.

Disaggregation of Greenhouse Gas Emissions by Stage

To pass the second screen, published studies were required to be full LCAs, including assessment of GHG emissions throughout the coal-fired electricity generation life cycle. Only a subset of the studies, however, quantitatively reported GHG emissions disaggregated by life cycle stage. Based on results reported by studies that disaggregated by life cycle phase, table S1 provides GHG emissions by stage for subcritical, integrated gasification combined cycle (IGCC), fluidized bed, and supercritical pulverized (supercritical) coal combustion technologies. The table also reports results for the references that analyzed IGCC/CCS, and summarizes the results for the four non-CCS technologies collectively. Table S1 reports GHG emission estimates prior to harmonization.

Results in Table S1 are disaggregated into three general life cycle phases, with the operational phase having two sub-phases.

– **Upstream:** raw materials extraction, materials manufacturing, component manufacturing, transportation from the manufacturing facility to the construction site, and on-site construction;

– **Operational:** Ongoing combustion and fuel cycle; ongoing non-combustion or fuel cycle;

a. *Ongoing combustion and fuel cycle:* coal combustion and fuel cycle processes that are modulated by the amount of coal combusted, including mining, preparation, and transport of coal to the plant;

b. *Ongoing non-combustion and non-fuel cycle:* power plant operation and maintenance, operational non-fuel materials;

– **Downstream:** Waste disposal, power-plant decommissioning, coal mine land rehabilitation.

In general, references that provided enough information for disaggregation reported results for the upstream and operational phases. Downstream phases were addressed in fewer studies and, when studied, were found to contribute less than 1% to life cycle GHG emissions.

Table S1. Greenhouse gas emissions disaggregated by life cycle stage for coal-fired electricity generation.

Technology	Parameter	Up-stream	Ongoing Combustion/Fuel Cycle	Ongoing Non-Combustion	Dow nstream

Coal—Pulverized Subcritical	Mean (g CO_2e/kWh)	<5	1140	<5	<5
	Median (g CO_2e/kWh)	<5	1150	<5	<5
	Std dev (g CO_2e/kWh)	<5	1170	<5	<5
	Mean percent of total	<1%	99%	<1%	<1%
	Count of estimates	16	19	3	9
	Count of references	11	13	3	5
Coal—IGCC	Mean (g CO_2e/kWh)	<5	850	190	<5
	Median (g CO_2e/kWh)	<5	790	190	<5
	Std dev (g CO_2e/kWh)	<5	160	N/A	<5
	Mean percent of total	<1%	82%	18%	<1%
	Count of estimates	6	6	1	2
	Count of references	5	5	1	2
Coal—Fluidized Bed	Mean (g CO_2e/kWh)	<5	1070	30	<5
	Median (g CO_2e/kWh)	5	1010	30	<5
	Std dev (g CO_2e/kWh)	<5	150	N/A	N/A
	Mean percent of total	<1%	97%	3%	<1%
	Count of estimates	3	3	1	1
	Count of references	3	3	1	1
Coal—Pulverized Supercritical	Mean (g CO_2e/kWh)	6	880	N/A	N/A
	Median (g CO_2e/kWh)	6	880	N/A	N/A
	Std dev (g CO_2e/kWh)	5	70	N/A	N/A
	Mean percent of total	<1%	99%	N/A	N/A

	Count of estimates	2	2	0	0
	Count of references	2	2	0	0
Coal— Non-CCS Subset	Mean (g CO_2e/kWh)	<5	1060	50	<5
	Median (g CO_2e/kWh)	<5	1010	10	<5
	Std dev (g CO_2e/kWh)	<5	200	80	<5
	Mean percent of total	<1%	95%	4%	<1%
	Count of estimates	27	30	5	12
	Count of references	21	23	5	8
Coal— IGCC with CCS	Mean (g CO_2e/kWh)	5	250	120	<5
	Median (g CO_2e/kWh)	<5	230	120	<5
	Std. dev. (g CO_2e/kWh)	7	130	150	N/A
	Mean percent of total	1%	66%	33%	<1%
	Count of estimates	3	3	2	1
	Count of references	3	3	2	1
The sum of percentages might not equal 100% due to independent rounding and averaging. Statistical results for mean, median, and standard deviation (std dev) are rounded to two significant digits if less than 1,000, three significant digits if equal to or greater than 1,000, and to <5 if less than 5. Percentages are rounded to the nearest whole number as an indication of uncertainty.					

As shown in table S1, for the four coal-combustion technologies without CCS, the combination of ongoing operational combustion, fuel cycle and non-combustion emissions accounted for more than 99% of life cycle GHG emissions. GHG emissions specifically related to coal combustion and the fuel cycle accounted for an average of more than 95% of life cycle GHG emissions. It

should be noted that the estimate for non-combustion, non-fuel cycle GHG emissions is based on a small dataset of only 5 estimates and the large contribution associated with IGCC plant maintenance predicted by Fiaschi and Lombardi (2002) has not been independently confirmed by other references considered in this study.

For IGCC with CCS, downstream GHG emissions were still insignificant, but the contribution from upstream processes increased to approximately 1%, as operational GHG emissions associated with coal combustion were assumed to be captured (as opposed to being emitted to the atmosphere). Of note for IGCC with CCS systems, the relative contribution to life cycle GHG emissions from operational, non-combustion, non-fuel cycle processes increases to approximately 33%. This is due to a lesser contribution to GHG emissions from the operational-combustion phase; a majority of the combustion GHG emissions are captured and stored.

Rationale for Not Harmonizing Upstream and Downstream Processes and Parameters Associated with Those Phases

Harmonization steps associated with coal mine methane, thermal efficiency, and CEFs focused on the operation phase of coal-fired electricity production, including ongoing combustion and non-combustion emissions. The complete coal-fired electricity generation life cycle also includes upstream and downstream processes (power plant construction and decommissioning), but no harmonization steps were conducted to add or subtract any impacts from upstream or downstream processes. Because more than 99% of the life cycle GHG emissions for coal-fired electricity generation are associated with the coal fuel cycle and ongoing combustion and non-combustion processes, parameters that impact the relative contributions of the upstream and downstream processes to life cycle GHG emissions were not considered important for the harmonization process. (They are reported in table 1 for informational purposes only.) These un-harmonized parameters include capacity, lifetime, and capacity factor. In addition, harmonization by system boundary –adding consistent estimates for upstream and downstream phase GHG emissions to those studies that didn't assess those phases – was judged to not significantly improve consistency in results, and was therefore not completed.

Harmonization Methods for Key Parameters

The following methods were used to harmonize results for the key parameters described here.

Global Warming Potential

References were analyzed to determine whether IPCC 2007 global warming potentials (GWPs) were used (IPCC 2007), or if emissions of GHGs could be disaggregated into, at least, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Contributions of other GHGs either were negligible within the study boundary or were not consistently reported in the literature. Life cycle GHG emissions were recalculated using IPCC 2007 GWPs for those references that reported mass emissions of carbon dioxide, methane, and nitrous oxide separately.

Transmission and Distribution Loss

References that included transmission and distribution (T&D) losses published GHG emissions per delivered kilowatt-hour (kWh) instead of GHG emissions per generated kilowatt-hour. T&D losses were removed from the system boundary by converting the denominator of the published ratio from distributed kWh to generated kWh using the T&D loss percent reported for each reference. GHG emissions associated with T&D infrastructure were also excluded by subtraction.

Coal Mine Methane

The complete description of the coal mine methane harmonization procedure was included in the Coal Mine Methane section of the article. The median of coal mine methane emissions for those references that reported the value was calculated, and this value (63 g CO_2e/kWh) was added to the reported life cycle GHG emissions for those references that did not include emissions of coal mine methane in their estimates. Plausible values for coal mine methane emissions vary greatly from mine to mine and should be carefully considered when applying the harmonized results of this study to project-specific conditions.

Thermal Efficiency

The thermal efficiency harmonization step assumes that variations in thermal efficiency affect the entire fuel cycle (including combustion) as the amount of coal required per kWh generated changes. An increase in thermal efficiency indicates a decreased coal

consumption requirement and reduced GHG emissions per generated kWh following harmonization, as shown in equation S1. For all evaluated technologies, the assumed fraction of life cycle GHG emissions related to the fuel cycle is set at 99%. The thermal efficiency used for harmonization (TE_h) varies by technology type (t), according to the following equation.

$$GHG_{h,te} = FC * \frac{TE_p}{TE_{h,t}} * GHG_p + (1 - FC) * GHG_p \qquad \text{(S1)}$$

Where:

– $GHG_{h,te}$ = Life cycle GHG emissions harmonized by thermal efficiency (g CO_{2e}/kWh); Subscript h,te denotes harmonized by thermal efficiency.

– FC = Assumed fraction of life cycle GHG emissions related to fuel cycle (99%);

– TE_p = Published thermal efficiency for each reference (%);

– $TE_{h,t}$ = Thermal efficiency used for harmonization based on technology (%); and

– GHG_p = Published life cycle GHG emissions for each reference (g CO_2e/kWh).

Combustion Carbon Dioxide Emission Factor

Analogous to the harmonization process used for thermal efficiency, life cycle GHG emissions related to the fuel cycle are also adjusted based on changes in the combustion carbon dioxide emission factor (CEF). The CEF is a function of thermal efficiency, coal carbon content, and coal heating value (as described in equation 3 of the article). To avoid double counting during cumulative harmonization steps, the CEF is utilized in lieu of thermal efficiency. The application of the CEF implicitly includes thermal efficiency but also adds the impacts of coal carbon content and coal heating value to the harmonization process. An increase in CEF indicates increased carbon dioxide emitted per kWh generated, resulting in increased life cycle GHG emissions following harmonization as shown in equation S2. As with thermal efficiency, the fraction of life cycle GHG emissions related to the fuel cycle is assumed to be 99% for all technologies, and the CEF used for harmonization varies by technology (t).

$$GHG_{h,cef} = FC * \frac{CEF_{h,t}}{CEF_p} * GHG_p + (1 - FC) * GHG_p \qquad \text{(S2)}$$

Where:

– $GHG_{h,cef}$ = Life cycle GHG emissions harmonized by CEF (g CO_{2e}/kWh). Subscript h,cef denotes harmonized by CEF;

– FC = Assumed fraction of life cycle GHG emissions modulated by the fuel cycle (99%);

– $CEF_{h,t}$ = CEF used for harmonization based on technology, *t* (g CO_2/kWh);

– CEF_p = Published CEF for each reference (g CO_2/kWh); and

– GHG_p = Published life cycle GHG emissions for each reference (g CO_2e/kWh).

Numerical Results for the Harmonization Processes

Table S2 lists the technology-specific harmonization results, after independent application of each harmonization step, for each of the life cycle GHG emission scenarios described in table 1 of the article. The published GHG emission estimates are rank ordered from least to greatest in figure 2(a) of the article, with the individual harmonization steps plotted in figures 2(b) through 2(f) to illustrate the effects of each harmonization step on the rank-ordered estimates. Figures 2(g) and 2(h) summarize the effect of system harmonization and cumulative - all parameter (system plus technical) harmonization, respectively. Table S2 provides the numerical results corresponding to the plots in figure 2.

Figure 2 in the article contains a plot for each harmonization step independently to provide insight on the impact of each harmonization step on the published GHG-emission estimates. The final plot, figure 2(h), displays the results of applying all of the harmonization steps cumulatively. Figure S1 (below) breaks-down the cumulative – all parameter harmonization step from figure 2(h) into discrete steps to show the effects of each sequential (i.e., cumulative from all previous steps) harmonization step. The sequential harmonization process included the following steps.

- Step 1. Harmonizing by IPCC 2007 GWPs.
- Step 2. Harmonizing system boundaries to exclude T&D losses.
- Step 3. Harmonizing system boundaries to add coal mine methane emissions to studies that did not explicitly report their inclusion.

- Step 4. Harmonizing coal fuel-cycle GHG emissions by power plant thermal efficiency.
- Step 5. Harmonizing by coal CEF as a function of coal quality and thermal efficiency.

The CEF harmonization includes the impacts of thermal efficiency. Therefore, step 4 is skipped when presenting results from step 5 in figure S1.

Collective Harmonization Across Technologies

The harmonization analysis in the article uses technology-specific thermal efficiency and CEF values to harmonize each technology type independently. The results of the collective harmonization conducted by harmonizing all coal technologies to the same benchmark thermal efficiency (33%) and CEF (970 g CO_2/kWh) values are reported in Table S3 with harmonization by all parameters resulting in a median of 1,032 g CO_2/kWh (IQR = 1,000-1,090 g CO_2/kWh) compared with published median of 1,001 g CO_2/kWh (IQR = 891-1,134 g CO_2/kWh).

Table S2. Numerical results for the independent application of harmonization steps for life cycle greenhouse gas emissions of coal electricity generation.

					Harmonization Steps					
Author	Pub. Year	Tech.	Published	System - GWP	System - T&D Loss	System - Coal Mine Methane	Thermal Efficiency	Combustion CO_2 Emission Factor	System – All Parameters	Cumulative - All Parameters
Akai	1997	2	730	730	730	792	823	912	792	991
Bates	1995	1	958	958	958	958	1,001	958	958	958
Bates	1995	1	1,015	1,015	1,015	1,015	1,033	983	1,015	983
Cottrell	2003	3	959	959	959	959	902	1,099	959	1,099
Damen	2003	1	1,009	1,011	1,009	1,009	1,209	1,055	1,011	1,058
Dolan	2007	1	1,452	1,452	1,452	1,452	1,452	1,039	1,452	1,039
Dones	1999	1	762	762	762	762	762	1,066	762	1,066

Dones	1999	3	771	771	771	771	771	1,170	771	1,170
Dones	2004	1	1,048	1,048	1,048	1,048	1,048	1,062	1,048	1,062
Dones	2004	1	1,114	1,114	1,114	1,114	1,114	1,037	1,114	1,037
Dones	2004	1	1,224	1,224	1,224	1,224	1,224	1,048	1,224	1,048
Dones	2004	1	1,225	1,225	1,225	1,225	1,225	1,049	1,225	1,049
Dones	2004	1	1,250	1,250	1,250	1,250	1,250	1,048	1,250	1,048
Dones	2004	1	1,348	1,348	1,348	1,348	1,348	1,119	1,348	1,119
Dones	2004	1	1,500	1,500	1,500	1,500	1,500	1,035	1,500	1,035
Dones	2004	1	1,689	1,689	1,689	1,689	1,689	988	1,689	988
Dones	2004	2	839	839	839	839	839	949	839	949
Dones	2004	3	1,063	1,063	1,063	1,063	1,063	1,168	1,063	1168
Dones	2004	4	1,059	1,059	1,059	1,059	1,059	845	1,059	845
Dones	2007	1	980	980	980	980	1,118	1,090	980	1,090
Dones	2007	1	1,016	1,016	1,016	1,016	1,102	1,086	1,016	1,086
Dones	2007	1	986	986	986	986	1,044	1,018	986	1,018
Dones	2007	1	1,027	1,027	1,027	1,027	1,079	1,052	1,027	1,052
Dones	2007	1	1,091	1,091	1,091	1,091	1,107	1,100	1,091	1,100
Dones	2007	1	1,076	1,076	1,076	1,076	1,094	1,078	1,076	1,078
Dones	2007	1	1,099	1,099	1,099	1,099	1,102	1,086	1,099	1,086
Dones	2007	1	1,078	1,078	1,078	1,078	1,075	1,059	1,078	1,059
Dones	2007	1	1,067	1,067	1,067	1,067	1,070	1,043	1,067	1,043
Dones	2007	1	1,095	1,095	1,095	1,095	1,107	1,057	1,095	1,057
Dones	2007	1	1,144	1,144	1,144	1,144	1,074	1,058	1,144	1,058
Dones	2007	1	1,056	1,056	1,056	1,056	1,100	969	1,056	969
Dones	2007	1	1,078	1,078	1,078	1,078	1,094	956	1,078	956
Dones	2007	1	1,110	1,110	1,110	1,110	1,101	962	1,110	962
Dones	2007	1	1,168	1,168	1,168	1,168	1,096	958	1,168	958
Dones	2007	1	1,297	1,297	1,297	1,297	1,080	1,064	1,297	1,064
Dones	2007	1	1,310	1,310	1,310	1,310	1,097	1,070	1,310	1,070
Dones	2007	1	1,189	1,189	1,189	1,189	1,090	952	1,189	952

Dones	2007	1	1,217	1,217	1,217	1,217	1,139	968	1,217	968
Dones	2007	1	1,251	1,251	1,251	1,251	1,143	954	1,251	954
Dones	2007	1	1,294	1,294	1,294	1,294	1,287	962	1,294	962
Dones	2007	1	1,342	1,342	1,342	1,342	1,132	962	1,342	962
Dones	2007	1	1,392	1,392	1,392	1,392	1,100	962	1,392	962
Dones	2007	1	1,407	1,407	1,407	1,407	1,120	952	1,407	952
Dones	2007	1	1,689	1689	1,689	1,689	1,108	969	1,689	969
Dones	2008	2	842	842	842	842	951	934	842	934
Dones	2008	2	920	920	920	920	1,039	848	920	848
Dones	2008	4	934	934	934	934	1,009	754	934	754
Dones	2004	1	1,048	1,048	1,048	1,048	1,048	1,062	1,048	1,062
Dyncorp	1995	1	1,201	1,201	1,201	1,201	1,188	1,033	1,201	1,033
Eur. Com.	1995	1	970	970	970	970	1,077	1,066	970	1,066
Eur. Com.	1995	1	982	982	982	982	1,090	1,072	982	1,072
Eur. Com.	1995	1	1,169	1,169	1,169	1,169	1,301	1,210	1,169	1,210
Eur. Com.	1995	1	1,150	1,150	1,150	1,150	1,176	955	1,150	955
Eur. Com.	1995	2	833	833	833	833	932	924	833	924
Eur. Com.	1995	3	972	972	972	972	1,141	1,366	972	1,366
Eur. Com.	1995	3	972	972	972	972	1,141	1,366	972	1,366
Eur. Com.	1995	3	1,014	1,014	1,014	1,014	1,136	1,353	1,014	1,353
Eur. Com.	1995	3	1,079	1,079	1,079	1,079	1,122	1,337	1,079	1,337
Eur. Com.	1999	1	936	936	936	936	1,004	981	936	981
Eur. Com.	1999	1	980	980	980	980	1,216	1,014	980	1,014
Eur. Com.	1999	1	1,085	1,085	1,085	1,085	1,164	1,123	1,085	1,123
Eur. Com.	1999	1	967	967	967	967	997	980	967	980
Eur. Com.	1999	1	1,026	1,026	1,026	1,026	960	943	1,026	943
Fiashci	2002	2	914	914	914	914	1,066	1,048	914	1,048
Friedrich	1994	1	1,290	1,191	1,290	1,290	1,370	1,336	1,191	1,233
Friedrich	1994	1	1,175	1,175	1,175	1,175	1,202	974	1,175	974
Froese	2010	3	1,030	1,030	1,030	1,030	969	1,043	1,030	1,043

Gorokhov	2000	2	796	796	796	796	822	878	796	878
Hartmann	1999	1	931	947	931	931	1,134	1,047	947	1,065
Heller	2004	1	978	978	978	978	932	978	978	978
Hondo	2005	1	975	975	975	975	1,090	1,024	975	1,024
Koornneef	2008	1	1,092	1,087	1,092	1,092	1,080	1,043	1,087	1,038
Koornneef	2008	4	837	833	837	837	963	825	833	821
Kreith	1990	3	1,041	1,041	1,041	1,104	1,041	1,068	1,104	1,132
Krewitt	1997	1	911	911	911	911	1,104	1,085	911	1,085
Krewitt	1997	1	1,061	1,061	1,061	1,061	1,201	975	1,061	975
Lee	2004	1	1,001	1,001	961	1,064	1,108	984	1,023	1,006
Lee	2004	1	1,155	1,155	1,108	1,217	1,093	954	1,171	968
Lenzen	2006	1	843	843	818	843	843	980	818	950
Lenzen	2006	1	911	911	865	911	1,003	969	865	921
Lenzen	2006	1	941	941	894	941	999	969	894	921
Lenzen	2006	1	1,011	1,011	981	1,011	918	961	981	932
Lenzen	2006	1	1,170	1,170	1,065	1,170	1,170	983	1,065	894
Lenzen	2006	1	1,175	1,175	1,116	1,175	1,044	963	1,116	915
Lenzen	2006	1	1,506	1,506	1,370	1,506	1,190	966	1,370	879
Lenzen	2006	4	716	716	680	716	811	768	680	729
Lenzen	2006	4	774	774	751	774	821	757	751	734
Lenzen	2006	4	788	788	749	788	809	768	680	730
Lenzen	2006	4	863	863	820	863	886	769	820	731
Lenzen	2006	4	1,046	1,046	952	1,046	1,040	820	952	746
Markewitz	2009	1	732	732	732	732	949	964	732	964
Markewitz	2009	1	783	783	783	783	950	965	783	965
Markewitz	2009	1	790	790	790	790	991	940	790	940
Markewitz	2009	1	861	861	861	861	948	963	861	963
Markewitz	2009	1	858	858	858	858	993	942	858	942
Markewitz	2009	1	977	977	977	977	994	943	977	943
Markewitz	2009	4	687	687	687	687	841	765	687	765

Markewitz	2009	4	732	732	732	732	878	745	732	745
Martin	1997	1	1,177	1,177	1,177	1,177	1,177	1,013	1,177	1,013
May	2003	1	1,035	1,035	1,015	1,035	966	986	1,015	966
May	2003	1	1,100	1,100	1,078	1,100	1,026	1,028	1,078	1008
May	2003	1	1,215	1,215	1,190	1,215	929	960	1,190	941
May	2003	2	675	675	661	675	863	877	661	860
May	2003	2	751	751	736	751	905	916	736	897
May	2003	2	725	725	710	725	927	854	710	837
Meier	2005	1	1,006	1,006	1,006	1,006	1,006	981	1,006	981
Meier	2005	1	1,044	1,044	1,044	1,044	1,044	981	1,044	981
Meridian	1989	1	1,058	1,058	1,058	1,121	1,058	934	1,121	989
Meridian	1989	2	824	824	824	886	793	833	886	896
Meridian	1989	3	1,057	1,057	1,057	1,120	1,057	1,036	1,120	1,098
NETL	2010a	1	1,109	1,109	1,028	1,109	1,148	1,022	948	948
NETL	2010b	2	931	931	863	931	946	920	852	852
NETL	2010c	4	943	943	874	943	962	807	748	748
Odeh	2008a	1	990	990	990	990	979	1,046	990	1,046
Odeh	2008b	1	984	984	984	984	982	1,274	984	1,274
Odeh	2008b	2	861	861	861	861	806	1,043	861	1,043
Odeh	2008b	4	879	879	879	879	871	1,009	879	1,009
ORNL	1994	1	1,013	1,013	1,013	1,076	988	934	1,076	991
ORNL	1994	1	1,053	1,053	1,053	1,116	1,027	934	1,116	989
ORNL	1994	4	748	748	748	810	748	739	810	801
Pacca	2003	1	714	714	714	714	714	972	714	972
Peiu	2007	1	1,546	1,546	1,546	1,546	1,546	974	1,546	974
Ruether	2004	2	838	841	838	838	874	867	841	870
San Martin	1989	1	964	964	964	1,027	964	934	1,027	995
San Martin	1989	2	751	751	751	813	751	833	813	903
San Martin	1989	3	963	963	963	1,025	963	1,035	1,025	1,103
Schreiber	2009	4	753	753	753	753	921	838	753	838

Schreiber	2009	4	802	802	802	802	922	838	802	838
Schreiber	2009	4	872	872	872	872	937	837	872	837
SECDA	1994	1	1,266	1,266	1,266	1,266	1,172	1,043	1,266	1,043
SECDA	1994	1	1,275	1,275	1,275	1,275	1,180	1,043	1,275	1,043
SECDA	1994	1	1,288	1,288	1,288	1,288	1,192	1,052	1,288	1,052
SECDA	1994	1	1,463	1,463	1,463	1,463	1,213	1,042	1,463	1,042
SECDA	1994	2	1,130	1,130	1,130	1,130	1,082	932	1,130	932
SECDA	1994	3	1,249	1,249	1,249	1,249	1,069	1,157	1,249	1,157
SENES	2005	2	974	974	974	974	858	1,079	974	1,079
Shukla	2007	1	1,371	1,371	1,371	1,371	1,371	981	1,371	981
Spath	1999	1	760	760	760	760	900	983	760	983
Spath	1999	1	962	962	962	962	951	1,008	962	1,008
Spath	1999	1	1,045	1,045	1,045	1,045	946	1,005	1,045	1,005
Spath	2004	1	847	847	847	847	847	985	847	985
Styles	2007	1	990	990	990	990	990	959	990	959
Uchiyama	1996	1	990	990	990	990	1,138	1,023	990	1,023
Uchiyama	1996	2	858	858	858	858	1,012	910	858	910
Uchiyama	1996	4	895	895	895	895	1,005	812	895	812
White	1998	1	974	974	974	1037	882	950	1,037	1,011
Wibberley	2000	1	932	932	932	932	995	961	932	961
Wibberley	2000	2	767	767	767	767	886	861	767	861
Wibberley	2000	3	803	803	803	803	920	1,069	803	1,069
Wibberley	2000	4	842	842	842	842	882	762	842	762
Wibberley	2001	1	1,000	1,000	1,000	1,000	1,056	961	1,000	961
Wibberley	2001	1	1,025	1,025	1,025	1,025	1,091	961	1,025	961
Wibberley	2001	1	1,052	1,052	1,052	1,052	1,111	962	1,052	962
Wibberley	2001	1	1,144	1,144	1,144	1,144	1,184	953	1,144	953
Wibberley	2001	3	850	850	850	850	966	1,058	850	1,058
Wibberley	2001	4	910	910	910	910	986	770	910	770
Wibberley	2001	4	944	944	944	944	895	755	944	755

Wibberley	2001	4	982	982	982	982	984	771	982	771
Zerlia	2003	4	830	830	830	830	913	786	830	786
Zerlia	2003	4	910	910	910	910	1,001	861	910	861
Zhang	2007	1	1,180	1,180	1,180	1,180	1,180	975	1,180	975
Zhang	2007	1	1,410	1,410	1,410	1,410	1,351	1,023	1,410	1,023
Zhang	2010	1	1,001	1,001	1,001	1,001	990	994	1,001	994
Zhang	2010	1	1,194	1,194	1,194	1,194	1,114	970	1,194	970

Abbreviations: Pub. Year = year of publication of the reference; Tech. 1 = subcritical pulverized coal combustion, Tech. 2 = integrated gasification combined cycle, Tech. 3 = fluidized bed coal combustion, Tech. 4 = supercritical pulverized coal combustion. GWP = global warming potential; T&D = transmission and distribution. "System – All Parameters" applies all system harmonization steps. "Cumulative – All Parameters" applies system harmonization followed by technical harmonization. Harmonized estimates for thermal efficiency, CEF, and cumulative - all parameters are calculated using technology-specific harmonization factors. Refer to Table 1 in the article for additional scenario parameters and section 2.2 for the harmonization approach. See article for full bibliographic information for each cited reference.

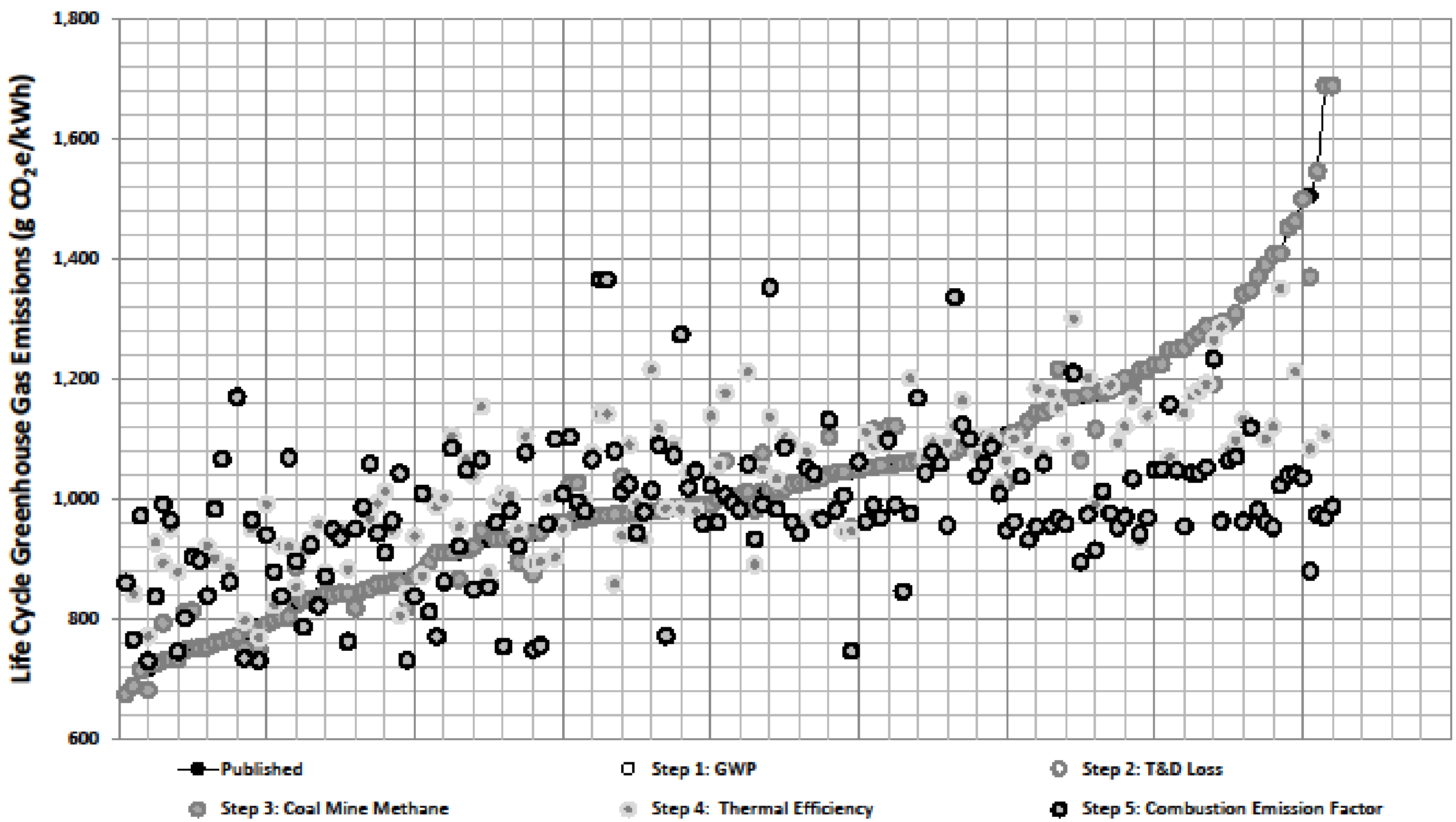

Figure S1. Results of the application of successive harmonization steps to the published dataset, rank ordered from least to greatest life cycle greenhouse gas emissions estimate. Technology-specific harmonization factors were used for thermal efficiency and combustion CO_2 emission factor harmonization. GWP = global warming potential; T&D = transmission and distribution.

Table S3. Changes to measures of central tendency and variability from application of individual harmonization steps and from the cumulative application of all harmonization parameters based on collective harmonization (i.e., using the same value for each harmonization parameter applied to all coal combustion technologies) (all values reported in grams CO_2e/kWh)

			Harmonization Steps						
Technology	Metric	Published	GWP	T&D Loss	Coal Mining Methane	Thermal Efficiency	Combustion CO_2 Emission Factor	System - All Parameters	Cumulative - All Parameters
All Technologies	Mean	1,026	1,030	1,020	1,030	1,150	1,060	1,020	1,050
	Std dev	199	200	200	200	110	80	200	80
	Minimum	675	670	660	670	940	970	660	910
	25th percentile	891	890	870	890	1,070	1,000	870	1,000
	Median	1,001	1,000	990	1,010	1,160	1,020	1,010	1,030
	75th percentile	1,134	1,130	1,110	1,130	1,220	1,090	1,120	1,090
	Maximum	1,689	1,690	1,690	1,690	1,470	1,390	1,690	1,330
	IQR Magnitude	243	240	240	240	150	90	250	90
	Range	1,014	1,010	1,030	1,010	520	420	1,030	410
	Change in mean	—	<-5%	<-5%	<5%	12%	<5%	<-5%	<5%
	Change in median	—	<5%	<-5%	<5%	16%	<5%	<5%	<5%
	Change in std dev	—	<-5%	<-5%	<-5%	-47%	-61%	<-5%	-61%
	Change in IQR	—	<5%	<-5%	<-5%	-38%	-63%	<5%	-61%
	Change in range	—	<5%	<5%	<5%	-48%	-58%	<5%	-59%
	Estimates	164	71	164	164	133	164	164	164

References	53	19	53	53	38	53	53	53

Harmonized values are rounded to two significant digits if less than 1,000 and three significant digits if equal to or greater than 1,000. Percentages are rounded to the nearest whole number as an indication of uncertainty.

The cutoff for significance for change in measures of central tendency and variability is set at 5%.

Percent change for harmonized values compared with published estimates calculated prior to rounding and then reported to the nearest whole percent.

"Estimates" and "References" indicates the number of independent studies and published GHG emission estimates that were harmonized in each step (respectively).

The statistics reported for each step refer to the full population for that technology including both harmonized and un-harmonized estimates.

Harmonized estimates for thermal efficiency, CEF, and cumulative - all parameters are calculated using technology-specific harmonization factors.

The "All Technologies" category reports statistical results across all four evaluated technologies when technology-specific harmonization factors are used.

"System – All Parameters" applies all system harmonization steps. "Cumulative – All Parameters" applies system harmonization followed by technical harmonization.

Refer to the "Limitations of the Analysis" section of the text for a discussion of reasons for interpreting the distributional statistics reported in this article with caution based on the characteristics of the pool of available studies and estimates.

Abbreviations: Std dev = standard deviation; IQR Magnitude = interquartile range (75th – 25th percentile); GWP = global warming potential; T&D = transmission and distribution.

Relative Contributions of Carbon Dioxide, Methane, and Nitrous Oxide to Life Cycle GHG Emissions

Of the 53 references that passed the second screen, 15 references both included coal mine methane emissions in their analyses and comprehensively disaggregated and reported carbon dioxide, methane, and nitrous oxide throughout the life cycle to yield a dataset of 54 independent estimates of each GHG's contribution to total GWP. Considering all evaluated coal combustion technologies together, median contributions of each GHG to total GHG emissions on a carbon dioxide equivalent (CO_2e) basis were: CO_2 = 96% (IQR = 91-99%), CH_4 = 3% (IQR = 1-7%), and N_2O = <1% (IQR = 0-1%). The median of the published GHG emissions for these 15 references was 1,078 g CO_2e/kWh (IQR = 981-1,184 g CO_2e/kWh). The median of the combined contribution of methane and nitrous oxide for these 15 references in absolute terms was 45 g CO_2e/kWh (IQR = 14-96 g CO_2e/kWh) or about 4% of the evaluated dataset mean. Note that this subset of the evaluated literature was different than the subset analyzed to estimated coal mine methane emissions leading to different median estimates of relative methane contributions to total life cycle GHG emissions.

This dataset of disaggregated GHG emission contributions showed significant variability in the contribution of each GHG. For example, some studies of lignite coal generation with minimal coal mine methane emissions yielded estimated life cycle methane contributions of less than 1% of total GHG emissions (Dones 2007; European Commission 1995; May and Brennan 2003). Other studies of particularly gaseous hard coal mines resulted in life cycle methane emission contribution estimates of 10% to 20% of the total GHG emissions (Friedrich 1994; Hartmann 1999; Dones 2007). For nitrous oxide emissions, the European Commission (1995) estimated significantly greater contributions for nitrous oxide emissions to total GHG emissions (13% to 15%) from fluidized bed (FB) coal combustion—a contribution that is greater than the nitrous oxide emission levels reported by any other reference in the evaluated dataset for the other coal combustion technologies. The European Commission, however, acknowledged that its values for nitrous oxide should be treated with "considerable skepticism," due to lack of operational data or adequate modeling for FB technology and in the absence of other estimates for FB technologies independently confirming that level of nitrous oxide contribution (European Commission 1995).

Consequently, the European Commission estimates for nitrous oxide contributions to total GHG emissions for FB combustion were excluded from the evaluation reported in this section.

The harmonization process used for the present study added 63 g CO_2e/kWh to the total GHG emissions of those estimates that did not include coal mine methane emissions, representing about 6% of the median of the dataset harmonized by all parameters. The study made no assumptions regarding whether a particular technology type was more likely to obtain coal from mines with high or low coal mine methane emission levels, and also did not harmonize independently for nitrous oxide emissions. The addition of 63 g CO_2e/kWh to the GHG emission estimates of those studies that did not include coal mine methane, however, should approximately account for the omitted non-carbon-dioxide GHG emissions, based on the results of the GHG contribution analysis. Minor deviations in actual non-CO_2 GHG emissions for the 14 scenarios to which the coal mine methane emissions were added from the assumed value of 63 g CO_2e/kWh were not expected to significantly alter the conclusions of the harmonization process.

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For transparency, citations for all references reviewed as part of the screening process are included in this section. The references are divided into those that passed all screens, failed secondary screening, and failed primary screening.

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