ESTIMATING STATISTICAL UNCERTAINTIES IN THE GREENHOUSE GAS EMISSIONS MEASUREMENT AND REPORTING PROTOCOLS FOR THE UK TRADING SCHEME

Final Report

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UNCERTAINTY ESTIMATES FOR EMISSIONS IN THE UK TRADING SCHEME

In August 2001, the United Kingdom Department for Environment, Food, and Rural Affairs published a set of guidelines for measurement and reporting of greenhouse gas (GHG) emissions in the UK trading scheme.[1] These guidelines included detailed calculation formulae for ten protocols. ICF Consulting obtained data from various sources and applied Monte Carlo methods to estimate the inherent uncertainty of the emissions estimates from these protocols.

The ten protocols described in the guidelines are:

1. Protocol A1: Calculating emissions for energy related CO_2
2. Protocol A2: Import or export of heat and power
3. Protocol A3: Renewables
4. Protocol B1: Cement manufacture
5. Protocol B2: Lime production
6. Protocol B3: Limestone and dolomite use
7. Protocol B4: Soda ash
8. Protocol B5: Ammonia – use of fuels as feedstock
9. Protocol B6: Metal production
10. Protocol B7: Waste incineration – municipal solid waste (MSW) and sewage.

Uncertainty results for each subsource category are presented in this report for nine of these ten protocols. Since the assumed emission factor for renewables is zero, with no assumed uncertainty, there are no uncertainty estimates for Protocol A3. In each case, the mean, median, and 95 percent uncertainty intervals are presented for each subsource category as a percentage of the estimated CO_2 emissions for that category.

This memorandum is divided into four sections: (1) Section 1 provides a brief introduction to the sources of uncertainty in emission estimates; (2) Section 2 describes the methods used to quantify uncertainty for this study; (3) Section 3 summarises the quantitative results of the protocol and subsource-specific uncertainty analyses and; (4) Section 4 describes the methodology for discounting uncertain emissions estimates in the emissions trading scheme. The Appendix includes some comments on the methodology and tabular summaries of the assumed uncertainty distributions.

[1] *Guidelines for the Measurement and Reporting of Emissions in the UK Trading Scheme.* Department for Environment, Food, and Rural Affairs. August, 2001.

1 Sources of Uncertainty in Emission Inventories

Inventory emission estimates are subject to three key types of uncertainties: (1) scientific uncertainty, (2) random or statistical uncertainty, and (3) non-random (systematic uncertainty) or bias. Scientific uncertainty arises when the emission generation processes are imperfectly understood. The other two potential types of errors or uncertainties are inherent in almost all measurements. Random, or statistical, uncertainty, is generally related to the heterogeneity of (or the natural variations in) the underlying population or phenomenon that is being measured. Systematic uncertainty or bias tends to be related to the way the measurement is taken.

The uncertainty estimates for emissions from selected sources that were calculated for this study focus on random uncertainty. These uncertainties are calculated based on the statistical properties of the activity data and the emission factors underlying the emission estimates. Although the other two types of uncertainties are also important for assessing the reliability of inventory estimates, they are difficult to quantify, as discussed below.

1.1 Sources of Uncertainty in Emission Estimates

GHG emission estimates are affected by three key types of uncertainty: (1) scientific uncertainty, (2) random or statistical uncertainty, and (3) non-random (systematic uncertainty) or bias.

- *Scientific Uncertainty.* Scientific uncertainty arises from imperfect understanding of the emission generation process for a particular source or its subsources. If there is scientific uncertainty, the methodology used to estimate emissions may not represent the true emission generation process. Scientific uncertainty can be reduced only with the advancement in the scientific knowledge about the actual emission generation processes. This type of uncertainty is difficult to quantify. For this study, scientific uncertainty would be represented by errors in the formulations of the emissions equations used in the protocols. Due to project and resource constraints, we did not account for this type of uncertainty in our analyses, and, therefore, assumed that the equations given in the reporting guidelines perfectly represent the emissions generation processes.

- *Random or Statistical Uncertainty.* Statistical uncertainty arises from naturally occurring variations, such as the real variation in emissions from emission sources or the natural variation in human reaction times in taking measurements. Uncertainty can also originate from variability in the external conditions in which emitting units operate, such as variations in emissions seasonally or diurnally. Random uncertainty can, in theory, be detected through repeated experiments and, therefore, can be estimated using statistical analysis.

- *Non-random or Systematic Uncertainty or Bias.* Systematic uncertainty can arise from several factors, including: (a) failure to identify all of the relevant source activities or categories so that some source activities may be omitted from inventory emission calculations; (b) faulty instruments or equipment used to measure emissions, emission factors, or activity data; (c) a non-representative sample, or an incorrect procedure used to estimate emissions; or (d) applying non-representative data to a heterogeneous population to estimate emissions. This type of uncertainty is difficult to quantify, though reporting guidance, including the IPCC Good Practice Guidance used to derive the Protocols, aim to remove any intentional bias.

1.2 Calculating Random, or Statistical, Uncertainty

Random uncertainty in the GHG emission estimates for the protocols derives primarily from random errors in the underlying emission factors and activity data that are used to estimate emissions. Given known uncertainty, i.e., known or assumed probability distributions for the underlying variables in a model, the uncertainty associated with the estimates produced by the model itself can be estimated. The estimates of the emissions from a particular subsource category, such as emissions from electricity consumption (Protocol A1) are, in most cases, the product of the emission factor and activity level for the subsource. The uncertainty in the emission estimate for the subsource will be systematically related to the uncertainty in the emission estimates for the variables comprising the subsource categories.

Statistical uncertainty can be described in several different ways. One measure of the uncertainty of an estimate is the standard deviation (the average dispersion of the values from the mean), which is a measure of the *absolute* uncertainty associated with an estimate.[2] Uncertainty can also be expressed in *relative* terms, i.e., either as a fraction or as a percentage. When expressed in relative terms, uncertainty relates to the spread around the mean, given a particular level of confidence. For example, in statistical terms, the fractional uncertainty around the mean of a variable that is normally distributed can be calculated by dividing the standard deviation by the mean for the variable. This calculation provides, at approximately a 68% confidence level, a measure of the fractional uncertainty (relative to 1) around the central estimate. For two standard deviations, i.e., roughly a 95% confidence interval, the fractional uncertainty is doubled, i.e., equals twice the standard deviation divided by the mean. Percentage uncertainty is simply the fractional uncertainty multiplied by 100.

The IPCC Good Practice Guidance[3] presents a simpler method of analysing uncertainties, based on the error propagation equation, and a more complex one based on statistical simulation (Monte Carlo analysis). The more complex method is better able to handle the broad and sometimes asymmetric probability distributions that may be encountered in inventory work, and has been used in this study.

1.3 Company Level Uncertainty

The goal of this study is to provide uncertainty estimates that can be applied at the company level to estimate the emissions uncertainty associated with a particular emissions trade. Unlike the total UK GHG inventory, the activity level is specific to a particular company and emissions trade, rather than being the sum across all subcategories. For example, for protocol A1, the mean CO_2 emissions for a given trade will depend upon the mean activity level and the specific fuel type used. If multiple fuel types are used then the uncertainty of the total CO_2 emissions across all fuel types will depend upon the unknown distribution of activity level by fuel type and cannot be computed without this specific information. If a single fuel type is used, the mean emissions level will depend upon the mean activity level, which will vary from company to company and trade to trade. However, for a single fuel, the percentage uncertainty as a

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[2] Variance is a measure of the dispersion, or spread, of a set of values about the mean. A small (large) variance indicates that values are closer to (widely scattered around) the mean. Standard deviation is the square root of variance. Like the variance, it is a measure of the dispersion about the mean, and is useful for describing the "average" dispersion about the mean. In other words, the standard deviation indicates the average distance of a set of values from the mean.

[3] Chapter 6 in *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*, IPCC 2000.

fraction of the mean emissions level will always be the same if the percentage uncertainties of the activity level and emissions factor are known.

In view of the considerations in the last paragraph, the results of this uncertainty study will be presented as relative uncertainties for each source category. For each source, the mean activity level was assigned an arbitrary value and the associated percentage uncertainties were assigned based on our literature review of uncertainties for the UK GHG inventory supplemented by entity-level specific information obtained directly from several UK companies and industry associations. The mean or default emissions factor and its associated uncertainty were also obtained from our review of the UK inventory together with information obtained from several UK companies. Where no UK entity-level data were available, ICF Consulting used its best professional judgement informed by previous assignments to develop entity-level estimates of uncertainties for activity level and emissions data at the entity-level in Canada and the US. Since the mean activity levels were assigned to be arbitrary values for developing the Monte Carlo simulations, the mean emissions levels are also arbitrary. The final results give the mean, median, and lower and upper bounds of the emissions as a percentage of the default emissions level for each source. Results are not available for totals across multiple sources.[4]

2 Methodology for Estimating Random Uncertainty

The Monte Carlo method or technique is one means of quantifying the statistical uncertainty associated with an emission inventory estimate. Monte Carlo analysis uses statistical sampling techniques to obtain a probabilistic approximation to the solution of a mathematical equation or model. In the context of inventory uncertainty, applying the Monte Carlo method requires specifying the model used for the inventory estimate, i.e., the mathematical relationships among the emission factors, activity level, and other parameters. It also requires specifying the probability distribution of each of the uncertain variables in the model and any correlation between model parameters, as well as, possibly, point estimates for some inputs. Trials or simulations can then be created based on sampling from the given distributions to produce a distribution for the emission estimate, for which the statistical properties—including estimated mean, variance, and confidence levels—can be calculated.

The approach taken in this project was to use the Monte Carlo method to simulate the emission estimates for each subsource category, given the statistical properties and mathematical relationships underlying the component variables. For all the uncertainty analyses, ICF Consulting used an Excel-based software add-in called @Risk, which is a commercially available software. This software has several advantages in performing the simulations. In particular, it (1) incorporates a large library of possible distributions from which to choose (including typical inventory related distributions such as normal, log-normal, or uniform), (2) allows the user to specify correlations between variables, (3) can handle a large number of variables and virtually any mathematical relationship between the variables, and (4) produces user-friendly reports and data that can be transferred across platforms.

For each source category, the analysis proceeded in several steps:

[4] The @Risk software application developed for this project can be used to estimate uncertainty for the total emissions across sources given the mean activity levels for the sources.

- The **first step** was to identify the relevant subsources for each protocol, and the relevant variables for each subsource. The mathematical formula used to compute emissions for each protocol is given in the Reporting Guidelines (and also appears in the Appendix). In essence, this step created a spreadsheet model that produces an emission estimate for each subsource category.

- The **second step** was to define the probability distribution for each of the uncertain variables in the emission estimates. Probability distributions were defined for each uncertain variable based on the characteristics of the inventory data and any available uncertainty estimates. The assumed probability distributions for each uncertain variable in each protocol are tabulated in the Appendix together with the mathematical equations used to compute emissions. Both symmetric and skewed probability distributions were considered, including normal, lognormal, uniform, and triangular. The parameters of the probability distributions of the uncertain variables were determined based either on available inventory or company data, or on expert judgement. In most cases, a normal distribution was assumed for an activity level and a lognormal distribution was assumed for an emissions factor. Zero correlations were assumed between the various factors. Project resources were too limited to allow any detailed research into the appropriate forms of the uncertainty distributions or to investigate the sensitivity of the results to these distributional assumptions.

- The **third step** was to run the Monte Carlo simulations. Given the probability distributions for each variable as described above, each simulation or trial involves randomly selecting values for each variable, and calculating an emission estimate for the subsource. 10,000 trials were performed for each subsource category. Each set of 10,000 simulations generates a probability distribution for the emissions from the subsource. The statistical properties (such as mean and standard deviation) of this distribution can then be calculated, as can the uncertainty range around the default estimated emissions. Default emissions were computed assuming zero uncertainties around the default activity levels and emission factors. All results were expressed as percentages of the default emissions.

The Appendix contains tables of the input uncertainty distributions. For constant distributions, the default and mean values are equal to the constant. For triangular distributions, the default value is interpreted to be the mode, and the minimum and maximum are chosen to represent the available data. For normal distributions, the default value also equals the mean, and the standard deviation is calculated by assuming that the default value plus or minus the uncertainty percentage gives a 95 % confidence interval. In other words, for the normal case, the default value minus the uncertainty percentage equals the 2.5th percentile and the default value plus the uncertainty percentage equals the 97.5th percentile. For lognormal distributions, a negative lower uncertainty percentage and a positive upper uncertainty percentage are given (these values may have different magnitudes, such as the –3.5 to +2.5 % intervals for the activity levels in Protocol A2). As for the normal case, it is assumed that the default value plus the (negative) lower uncertainty percentage equals the 2.5th percentile and the default value plus the upper uncertainty percentage equals the 97.5th percentile. The mean and standard deviation are calculated using these two equations. In particular, because the lognormal distribution is not symmetric, the mean value does not equal the default value except for rare and asymmetric choices of the uncertainty percentages.

3 Results: Uncertainty for Each Protocol

This section describes the results of the Monte Carlo simulations of the uncertainties for each of the protocols in the August 2001 reporting guidelines. Quantitative estimates of uncertainty for each protocol are presented in Tables 1 to 9. (As mentioned above, results are not presented for Protocol A3, since for Renewables the assumed emissions are zero, with zero uncertainty.)

For each protocol, the associated table presents the mean, median, coefficient of variation (CV), lower bound, and upper bound. The mean, median, lower bound, and upper bound are expressed as a percentage of the default emissions level. Thus those columns give the distributions if the default emissions level was 100. To apply these results, each of these percentages should be multiplied by the reported emissions level (tonnes of CO_2) for the given trade or entity-level baseline emissions estimate. The lower bound is the 5^{th} percentile of the emissions. The upper bound is the 95^{th} percentile of the emissions. The interval between the lower and upper bound has a 90 % probability of including the correct emissions value. The median, by definition, is the 50^{th} percentile, so that 50 % of possible emissions values are below this value and 50 % are above this value. The CV is the standard deviation as a percentage of the mean. Although the distribution of emissions is not a normal distribution, the percentage uncertainty (at the 90 % confidence level) is approximately plus or minus 1.65 times the CV. Also in the normal case, the percentage uncertainty at the 95 % confidence level is plus or minus twice the CV.

As an example, consider CO_2 from electricity consumption, as in Protocol A1. The mean is 99.4 %, the median is 99.3 % and the 90 % interval is from 94.7 % to 104.4 %. The CV = 3.0 %. If a reported emissions value is 1000 tonnes CO_2, then, multiplying these percentages by 1000 tonnes gives a mean, median, lower bound, and upper bound of 994, 993, 947, and 1044 tonnes, respectively. The uncertainty interval about the default level is from –5.3 % to +4.4 %, which is approximately plus or minus 5 %, 1.65 times the CV.

In each case the unnormalised default emissions value is obtained by setting all the input distributions to be a constant, equal to the default values tabulated in the Appendix. The default activity level was arbitrarily chosen. Next, the Monte Carlo simulations were run using the uncertainty distributions tabulated in the Appendix to give the mean, median, CV, lower, and upper bound. Finally, the mean, median, lower, and upper bound were re-expressed as a percentage of the unnormalised default emissions value. This is mathematically the same as choosing the default activity level so that the default emissions value = 100. If all the uncertainty distributions were symmetric and the number of iterations increased indefinitely, then the mean value would also equal 100 %[5] However, since many of the input uncertainty distributions are not symmetric (e.g., lognormal emissions factor distributions), the output uncertainty distributions are also not symmetric about the default value. Therefore the mean value does not equal 100 % and would not equal 100 % even if the number of iterations increased indefinitely.

The results in Tables 1 to 9 for the various protocols can be summarised as follows:

- For Protocol A1, for most fuel types, the emissions of energy related CO_2 are fairly symmetrically distributed about the default values with a percentage uncertainty of between 4 and 7 %. Emissions from waste

[5] This comment does not apply for Protocol B1 emissions from masonry cement production because the uncertain variable b does not appear in the formula as a simple multiplicative factor.

lubricant have a much greater uncertainty of 18 %. Emissions from coal and coking coal consumption are both positively skewed with 90 percent uncertainty intervals from 96 % to 125 % of the default emissions. Emissions from renewables are zero, with no uncertainty.

- For Protocol A2, emissions from imported power are symmetric with uncertainties of about 18 % and emissions from exported power are symmetric with uncertainties of about 10 %.[6] However, these results primarily reflect the uncertainty in the emissions factor attributable to uncertainties in the fuel mix and generation efficiency. For the default emissions factor, a weighted average emissions factor was calculated based on the "most likely" fuel mix, based on information in UK energy statistics. Lacking information about the uncertainty of the relative amounts of fuels used, professional judgement was applied to develop a weighted average emissions factor of 10 % for exports and 20 % for imports. Similarly, uncertainty around the generation efficiency was assumed to be 5% for exports and 10% for imports. The difference in these uncertainty estimates reflect the fact that the fuel composition and other characteristics of exported energy could be reported with more certainty than those for imported energy. Project resources were insufficient to allow further research into the uncertainties of the fuel mix and resulting emissions factor. Thus the results for this protocol only serve to give the order of magnitude of the uncertainty.

- For Protocol B1, emissions from clinker and masonry cement production are approximately symmetrically distributed, with percentage uncertainties of about 2 and 6 %, respectively.

- For Protocol B2, emissions from lime production are symmetrically distributed, with percentage uncertainties of 2 % for high calcium and dolomitic lime, and of 13 % for hydraulic lime production.

- For Protocol B3, emissions from limestone and dolomite use are symmetrically distributed with uncertainties of 5 %.

- For Protocol B4, emissions from soda ash are symmetrically distributed with uncertainties of 5 % for production and 2 % for use.

- For Protocol B5, emissions from ammonia production are symmetrically distributed with uncertainties of between 4 and 6 %.

- For Protocol B6, emissions from metal production are symmetrically distributed with uncertainties of 4 %.

- For Protocol B7, emissions from municipal solid waste (MSW) incineration are symmetrically distributed with uncertainties of 18 %. This estimate was based on the default equation in the Reporting Guidelines with a default emissions factor of 0.275 tonnes CO_2 per tonne of MSW. Emissions from sewage sludge incineration are attributable to the fossil fuel consumption only and not to the sewage contents. The uncertainty estimates for

[6] Based on the language in this protocol and the scope of the trading scheme, shipments of energy to and from off-site within the UK were considered as exports and imports, respectively.

Protocol A1 can therefore be applied to estimate the emissions uncertainty for sewage incineration.

4 Discounting For Uncertainty In Emissions Trading

In cases where the emissions estimates are relatively uncertain, the result of an emissions trade based on the default emissions levels might lead to undesirable increases in actual emissions above the target levels. To protect against these increases and to preserve the technical integrity of the emissions trading scheme, ICF Consulting suggests that the emissions estimates used in the emissions trading scheme could be discounted based on their uncertainty. However, the discount is intended to be non-punitive, and might therefore be applied only in cases of high uncertainty or in cases where metering or other consumption records correlated to the emissions estimates do not meet normal trading standards. In cases where the discount applies, purchasers could be required to evaluate their emissions reductions at the upper bound of uncertainty (95^{th} percentile) and sellers could be required to evaluate their emissions reduction asset at the lower bound of uncertainty (5^{th} percentile). We elaborate below how such a discounting methodology might be implemented.

For purchasers of emissions reductions, suppose that the uncertainty threshold is the upper bound for imports from Protocol A2, Table 2, 118.5 %. For each of the purchaser's source emissions estimates, the upper bound emissions estimate (i.e., 95^{th} percentile) should be compared with 118.5 %. If the upper bound exceeds 118.5 %, or if metering or other consumption records correlated with the emissions estimate do not meet normal trading standards, then the estimated emissions purchase will be assumed to be the associated upper bound value for that source. Otherwise, the default emissions level will be used and no discounting of the purchaser's emissions reductions will be applied. For sellers of emissions reductions the same calculations are applied at the lower bound of uncertainty. For consistency suppose that the uncertainty threshold for sellers is the lower bound for imports from Protocol A2, Table 2, 80.2 %. For each of the seller's source emissions estimates, the lower bound emissions estimate (i.e., 5^{th} percentile) should be compared with 80.2 %. If the lower bound is below 80.2 %, or if metering or other consumption records do not meet normal trading standards, then the estimated emissions sale will be assumed to be the associated lower bound value for that source. Otherwise, the default emissions level will be used and no discounting of the seller's emissions reductions will be applied.

Table 1. Simulation Results and Uncertainty Estimates for Protocol A1

Source	CV^2	Mean	Median	$Lower^3$	$Upper^4$
	Uncertainty Distribution: Subcategory Emissions = 100 %[1]				
Energy Related CO_2 Emissions From Electricity	3.0	99.4	99.3	94.7	104.4
Energy Related CO_2 Emissions From Natural Gas	3.1	99.9	99.9	94.9	105.1
Energy Related CO_2 Emissions From Gas/Diesel Oil	2.8	99.9	99.9	95.3	104.6
Energy Related CO_2 Emissions From Petrol	2.8	99.8	99.8	95.3	104.5
Energy Related CO_2 Emissions From Heavy Fuel Oil	3.1	101.3	101.2	96.4	106.7
Energy Related CO_2 Emissions From Coal[5]	8.3	108.5	107.2	95.8	125.2
Energy Related CO_2 Emissions From Coking Coal	8.3	108.6	107.3	95.9	125.0
Energy Related CO_2 Emissions From Coke	5.7	95.6	95.9	86.3	104.0
Energy Related CO_2 Emissions From LPG	3.4	99.9	99.9	94.4	105.5
Energy Related CO_2 Emissions From Jet Kerosene	2.9	100.0	99.9	95.2	104.9
Energy Related CO_2 Emissions From Ethane	3.9	99.8	99.7	93.4	106.3
Energy Related CO_2 Emissions From Naptha	3.9	99.8	99.7	93.5	106.4
Energy Related CO_2 Emissions From Waste Lubricants	11.3	98.4	97.7	81.4	117.7
Energy Related CO_2 Emissions From Petroleum Coke	2.9	100.0	99.9	95.2	104.8
Energy Related CO_2 Emissions From Refinery Gas	3.9	99.8	99.7	93.5	106.4
Energy Related CO_2 Emissions From Other Oil Products	3.9	99.8	99.7	93.6	106.5
Energy Related CO_2 Emissions From Renewables	0.0	100.0	100.0	100.0	100.0

Notes:
[1]In all cases, the results are expressed as a percentage of the source subcategory emissions.
[2]Coefficient of Variation (CV) = Standard deviation / Mean * 100 %.
[3]Lower = 5^{th} percentile.
[4]Upper = 95^{th} percentile.
[5] The asymmetry for coal of the lower and upper bounds of the uncertainty range (5^{th} and 95^{th} percentiles) about the mean and the median reflects asymmetry in the weighted average calorific values for coal across the variety of industries assessed. Where industries have better knowledge of the calorific values of the coal they consume a more symmetrical distribution comparable with the other fuels in the Table would be expected.

Table 2. Simulation Results and Uncertainty Estimates for Protocol A2

Uncertainty Distribution: Subcategory Emissions = 100 %[1]

Source	CV[2]	Mean	Median	Lower[3]	Upper[4]
Imported Heat not from Combined Heat and Power	11.6	98.1	97.3	80.6	118.0
Imported Steam not from Combined Heat and Power	11.7	98.3	97.7	80.7	118.0
Imported Electricity not from Combined Heat and Power	11.8	98.2	97.6	80.2	118.1
Exported Heat not from Combined Heat and Power	5.9	99.1	99.0	89.8	109.0
Exported Steam not from Combined Heat and Power	5.9	99.1	98.9	89.8	109.1
Exported Electricity not from Combined Heat and Power	5.9	99.1	99.0	89.7	108.9
Imported Heat from Combined Heat and Power	11.7	98.1	97.5	80.3	118.0
Imported Steam from Combined Heat and Power	11.8	98.1	97.3	80.4	118.5
Imported Electricity from Combined Heat and Power	11.7	98.0	97.2	80.2	118.1
Exported Heat from Combined Heat and Power	5.9	99.1	98.9	89.8	109.1
Exported Steam from Combined Heat and Power	5.9	99.2	99.0	89.9	109.1
Exported Electricity from Combined Heat and Power	6.0	99.2	99.1	89.6	109.2

Notes:
[1]In all cases, the results are expressed as a percentage of the source subcategory emissions.
[2]Coefficient of Variation (CV) = Standard deviation / Mean * 100 %.
[3]Lower = 5th percentile.
[4]Upper = 95th percentile.

Table 3. Simulation Results and Uncertainty Estimates for Protocol B1

Uncertainty Distribution: Subcategory Emissions = 100 %[1]

Source	CV[2]	Mean	Median	Lower[3]	Upper[4]
Clinker Production	1.4	99.9	99.9	97.6	102.3
Masonry Cement Production Additives	3.7	99.9	99.8	94.0	106.0

Notes:
[1]In all cases, the results are expressed as a percentage of the source subcategory emissions.
[2]Coefficient of Variation (CV) = Standard deviation / Mean * 100 %.
[3]Lower = 5th percentile.
[4]Upper = 95th percentile.

Table 4. Simulation Results and Uncertainty Estimates for Protocol B2

Uncertainty Distribution: Subcategory Emissions = 100 %[1]

Source	CV[2]	Mean	Median	Lower[3]	Upper[4]
High Calcium Lime Production	1.1	100.0	99.9	98.1	101.9
Dolomitic Lime Production	1.1	100.0	100.0	98.1	101.9
Hydraulic Lime Production	7.8	99.1	98.8	86.9	112.5

Notes:
[1]In all cases, the results are expressed as a percentage of the source subcategory emissions.
[2]Coefficient of Variation (CV) = Standard deviation / Mean * 100 %.
[3]Lower = 5th percentile.
[4]Upper = 95th percentile.

Table 5. Simulation Results and Uncertainty Estimates for Protocol B3

Uncertainty Distribution: Subcategory Emissions = 100 %[1]

Source	CV[2]	Mean	Median	Lower[3]	Upper[4]
Limestone Use	3.10	99.99	100.00	94.90	105.04
Dolomite Use	3.08	100.01	100.06	94.92	105.03

Notes:
[1]In all cases, the results are expressed as a percentage of the source subcategory emissions.
[2]Coefficient of Variation (CV) = Standard deviation / Mean * 100 %.
[3]Lower = 5th percentile.
[4]Upper = 95th percentile.

Table 6. Simulation Results and Uncertainty Estimates for Protocol B4

Uncertainty Distribution: Subcategory Emissions = 100 %[1]

Source	CV[2]	Mean	Median	Lower[3]	Upper[4]
Soda ash production	3.1	100.0	100.0	94.9	105.0
Soda ash use	1.0	100.0	100.0	98.3	101.7

Notes:
[1]In all cases, the results are expressed as a percentage of the source subcategory emissions.

[2]Coefficient of Variation (CV) = Standard deviation / Mean * 100 %.
[3]Lower = 5th percentile.
[4]Upper = 95th percentile.

Table 7. Simulation Results and Uncertainty Estimates for Protocol B5

Uncertainty Distribution: Subcategory Emissions = 100 %[1]

Source	CV[2]	Mean	Median	Lower[3]	Upper[4]
Ammonia Prod. from Gas/Diesel Oil (calc. from fuel energy)	3.6	99.9	99.9	94.2	105.9
Ammonia Prod. from Heavy Fuel Oil (calc. from fuel energy)	2.8	99.9	99.9	95.4	104.5
Ammonia Prod. from Naptha (calc. from fuel energy)	3.6	99.9	99.8	94.0	106.0
Ammonia Prod. from Natural Gas (calc. from fuel energy)	2.6	100.0	100.0	95.8	104.3
Ammonia Prod. from Gas/Diesel Oil (calc. from fuel mass)	2.6	100.0	100.1	95.8	104.3
Ammonia Prod. from Heavy Fuel Oil (calc. from fuel mass)	2.6	100.0	100.0	95.6	104.3
Ammonia Prod. from Naptha (calc. from fuel mass)	2.6	100.0	100.0	95.7	104.3
Ammonia Prod. from Natural Gas (calc. from fuel mass)	2.6	100.0	100.0	95.7	104.2

Notes:
[1]In all cases, the results are expressed as a percentage of the source subcategory emissions.
[2]Coefficient of Variation (CV) = Standard deviation / Mean * 100 %.
[3]Lower = 5th percentile.
[4]Upper = 95th percentile.

Table 8. Simulation Results and Uncertainty Estimates for Protocol B6

Uncertainty Distribution: Subcategory Emissions = 100 %[1]

Source	CV[2]	Mean	Median	Lower[3]	Upper[4]
Metal Production Using Coal	2.6	99.9	99.9	95.7	104.3
Metal Production Using Coke From Coal	2.6	99.9	99.9	95.6	104.2
Metal Production Using Petrol Coke	2.6	99.9	99.9	95.7	104.2
Metal Production Using Prebaked Anodes and Coal Electrodes	2.6	100.0	99.9	95.8	104.3
Ore Used For Metal Production	2.6	99.9	99.8	95.6	104.3

Notes:

[1]In all cases, the results are expressed as a percentage of the source subcategory emissions.
[2]Coefficient of Variation (CV) = Standard deviation / Mean * 100 %.
[3]Lower = 5th percentile.
[4]Upper = 95th percentile.

Table 9. Simulation Results and Uncertainty Estimates for Protocol B7

Source	Uncertainty Distribution: Subcategory Emissions = 100 %[1]				
Source	**CV[2]**	**Mean**	**Median**	**Lower[3]**	**Upper[4]**
Municipal Solid Waste Incineration	11.0	98.6	98.0	81.8	117.4

Notes:
[1]In all cases, the results are expressed as a percentage of the source subcategory emissions.
[2]Coefficient of Variation (CV) = Standard deviation / Mean * 100 %.
[3]Lower = 5th percentile.
[4]Upper = 95th percentile.

Appendix A
Comments on Methodology and Summary of Key Assumptions

Uncertainties at entity-level versus national level

The emissions uncertainty distributions depend upon the assumed uncertainty distributions of the input variables, tabulated below. In some cases, the uncertainty at the entity level can be greater than the uncertainty at the national level. If the national estimate is obtained by adding up estimates from the individual entities, assumed to contribute independently, then the percentage uncertainty at the national level will be the percentage uncertainty at the entity level divided by the square root of the number of entities. This elementary statistical result assumes that each entity has the same percentage uncertainty and default emissions level. In practice, this simple formula will not hold because the entity-level distributions are not all the same, but the national-level uncertainty will generally be lower than the typical entity-level uncertainty in cases where the national-level emissions estimate is obtained by aggregating entity-level emissions estimates.

The uncertainty estimates at the national and entity levels may also be very different if they are based on different sources of information. At the entity level, detailed information may be available to substantially reduce the uncertainty compared to the national estimate. For example, the CaO content of Portland cement can vary from 28 % to 97 %, which leads to large uncertainties at the national level for the emissions from cement manufacture based on Protocol B1. However, an individual entity is likely to have much more detailed information on the type of cement used at that facility and so the entity-level uncertainty of the CaO content is much lower; we have assumed a 2 % entity-level uncertainty in this case.

Key Assumptions: Input Uncertainty Distributions

The following tables give the assumed distributions and parameter values for each variable in each of the Protocol equations. Units conversion factors are not given. Note that the activity level default values are arbitrarily chosen. See the main text for further discussion.

Protocol A1: Calculating Emissions for Energy Related CO2

CO_2 Emissions from each fuel (tonnes) = Energy Consumption of fuel (kWh) * Emission factor for each fuel ($kgCO_2/kWh$) * 0.001

A1: Energy Consumption						
	Unit of Measurement	Distribution	Default	Mean	S.D.	Uncertainty, %
Electricity	kWh	LogNormal	1000000	994665	15306.5	-3.5 to +2.5
Natural Gas	cubic meter	Normal	1000000	1000000	15306.1	±3
Gas/Diesel Oil	tonne	Normal	1000	1000	7.1	±1.4
Petrol	tonne	Normal	1000	1000	4.1	±0.8
Heavy Fuel Oil	tonne	Normal	1000	1000	20.4	±4
Coal	tonne	Normal	1000	1000	10.2	±2
Coking Coal	tonne	Normal	1000	1000	6.1	±1.2
Coke	tonne	Normal	1000	1000	28.6	±5.6
LPG	tonne	Normal	1000	1000	15.3	±3
Jet Kerosene	tonne	Normal	1000	1000	10.2	±2
Ethane	tonne	Normal	1000	1000	15.3	±3
Naphtha	tonne	Normal	1000	1000	15.3	±3
Waste Lubricants	tonne	Normal	1000	1000	35.7	±7
Petroleum Coke	tonne	Normal	1000	1000	10.2	±2
Refinery Gas	cubic meter	Normal	1000	1000	15.3	±3
Other Oil Products	tonne	Normal	1000	1000	15.3	±3
Renewables	tonne	Normal	1000	1000	15.3	±3

A1: Calorific Values								
	Unit of Measurement	Distribution	Default	Mean	min	max	S.D.	Uncertainty, %
Electricity		Constant	1	1.0	1	1		
Natural Gas	kWh/cubic meter	Lognormal	11	11.0			0.3	±5
Gas/Diesel Oil	kWh/tonne	Lognormal	12666	12654.3			323.1	±5
Petrol	kWh/tonne	Lognormal	12555	12543.4			320.3	±5
Heavy Fuel Oil	kWh/tonne	Triangular	11999		11644	12833		
Coal	kWh/tonne	Triangular	7583		7140	9999		
Coking Coal	kWh/tonne	Triangular	7583		7140	9999		
Coke	kWh/tonne	Triangular	8277		6888	8583		
LPG	kWh/tonne	LogNormal	13722	13709.3			350.1	±5
Jet Kerosene	kWh/tonne	LogNormal	12833	12821.1			327.4	±5
Ethane	kWh/tonne	LogNormal	14083	14070.0			359.3	±5
Naphtha	kWh/tonne	LogNormal	13249	13236.7			338.0	±5
Waste Lubricants	kWh/tonne	LogNormal	12555	12543.4			320.3	±5
Petroleum Coke	kWh/tonne	LogNormal	12555	12543.4			320.3	±5
Refinery Gas	kWh/cubic meter	LogNormal	5.6	5.6			0.1	±5
Other Oil Products	kWh/tonne	LogNormal	12555	12543.4			320.3	±5
Renewables	kWh/tonne	LogNormal	3000	2997.2			76.5	±5

A1: Emission Factor						
	Unit of Measurement	Distribution	Default	Mean	S.D.	Uncertainty, %
Electricity	kgCO2/kWh	Lognormal	0.43	0.011	0.011	±5
Natural Gas	kgCO2/kWh	Lognormal	0.19	0.001	0.001	±1
Gas/Diesel Oil	kgCO2/kWh	Lognormal	0.25	0.003	0.003	±2
Petrol	kgCO2/kWh	Lognormal	0.24	0.002	0.002	±2
Heavy Fuel Oil	kgCO2/kWh	Lognormal	0.26	0.003	0.003	±2
Coal	kgCO2/kWh	Lognormal	0.3	0.009	0.009	±6
Coking Coal	kgCO2/kWh	Lognormal	0.3	0.009	0.009	±6
Coke	kgCO2/kWh	Lognormal	0.37	0.006	0.006	±3
LPG	kgCO2/kWh	Lognormal	0.21	0.003	0.003	±3
Jet Kerosene	kgCO2/kWh	Lognormal	0.24	0.002	0.002	±2
Ethane	kgCO2/kWh	Lognormal	0.2	0.005	0.005	±5
Naphtha	kgCO2/kWh	Lognormal	0.26	0.007	0.007	±5
Waste Lubricants	kgCO2/kWh	Lognormal	0.25	0.026	0.026	±20
Petroleum Coke	kgCO2/kWh	Lognormal	0.34	0.003	0.003	±2
Refinery Gas	kgCO2/kWh	Lognormal	0.2	0.005	0.005	±5
Other Oil Products	kgCO2/kWh	Lognormal	0.24	0.006	0.006	±5
Renewables	kgCO2/kWh	Constant	0	0		

Protocol A2: Import or Export of Heat and Power

CO_2 Emissions (tonnes) = Units of Heat, Steam or Electricity (kWh) * Emission factor for Imports/Exports (CO_2/kWh) * 0.001

A2: Activity Level						
	Unit of Measurement	Distribution	Default	Mean	S.D.	Uncertainty, %
Imports of non-CHP Heat	MMBtu	Lognormal	1,000	995	15.3	-3.5 to +2.5
Imports of non-CHP Steam	MMBtu	Lognormal	1,000	995	15.3	-3.5 to +2.5
Imports of non-CHP Electricity	kWh	Lognormal	1,000,000	994,665	15,306.5	-3.5 to +2.5
Exports of non-CHP Heat	MMBtu	Lognormal	1,000	995	15.3	-3.5 to +2.5
Exports of non-CHP Steam	MMBtu	Lognormal	1,000	995	15.3	-3.5 to +2.5
Exports of non-CHP Electricity	kWh	Lognormal	1,000,000	994,665	15,306.5	-3.5 to +2.5
Imports of CHP Heat	MMBtu	Lognormal	1,000	995	15.3	-3.5 to +2.5
Imports of CHP Steam	MMBtu	Lognormal	1,000	995	15.3	-3.5 to +2.5
Imports of CHP Electricity	kWh	Lognormal	1,000,000	994,665	15,306.5	-3.5 to +2.5
Exports of CHP Heat	MMBtu	Lognormal	1,000	995	15.3	-3.5 to +2.5
Exports of CHP Steam	MMBtu	Lognormal	1,000	995	15.3	-3.5 to +2.5
Exports of CHP Electricity	kWh	Lognormal	1,000,000	994,665	15,306.5	-3.5 to +2.5

A2: Fuel share based weighted average emission factor						
	Unit of Measurement	Distribution	Default	Mean	S.D.	Uncertainty, %
Imports of non-CHP Heat	kgCO2/kWh	Lognormal	0.155	0.152	0.016	±20
Imports of non-CHP Steam	kgCO2/kWh	Lognormal	0.155	0.152	0.016	±20
Imports of non-CHP Electricity	kgCO2/kWh	Lognormal	0.225	0.222	0.023	±20
Exports of non-CHP Heat	kgCO2/kWh	Lognormal	0.155	0.154	0.008	±10
Exports of non-CHP Steam	kgCO2/kWh	Lognormal	0.155	0.154	0.008	±10
Exports of non-CHP Electricity	kgCO2/kWh	Lognormal	0.225	0.224	0.011	±10
Imports of CHP Heat	kgCO2/kWh	Lognormal	0.155	0.152	0.016	±20
Imports of CHP Steam	kgCO2/kWh	Lognormal	0.155	0.152	0.016	±20
Imports of CHP Electricity	kgCO2/kWh	Lognormal	0.151	0.149	0.015	±20
Exports of CHP Heat	kgCO2/kWh	Lognormal	0.155	0.154	0.008	±10
Exports of CHP Steam	kgCO2/kWh	Lognormal	0.155	0.154	0.008	±10
Exports of CHP Electricity	kgCO2/kWh	Lognormal	0.151	0.150	0.008	±10

A2: Generating efficiency						
	Unit of Measurement	Distribution	Default	Mean	S.D.	Uncertainty, %
Imports of non-CHP Heat	%	Normal	75	75	3.8	±10
Imports of non-CHP Steam	%	Normal	75	75	3.8	±10
Imports of non-CHP Electricity	%	Normal	33	33	1.7	±10
Exports of non-CHP Heat	%	Normal	75	75	1.9	±5
Exports of non-CHP Steam	%	Normal	75	75	1.9	±5
Exports of non-CHP Electricity	%	Normal	33	33	0.8	±5
Imports of CHP Heat	%	Normal	70	70	3.6	±10
Imports of CHP Steam	%	Normal	70	70	3.6	±10
Imports of CHP Electricity	%	Normal	35	35	1.8	±10
Exports of CHP Heat	%	Normal	70	70	1.8	±5
Exports of CHP Steam	%	Normal	70	70	1.8	±5
Exports of CHP Electricity	%	Normal	35	35	0.9	±5

Protocol B1: Cement Manufacture

For Portland cement:

CO_2 Emissions (tonnes) = [Clinker Production (tonnes) * EF Clinker] * (1+CKD)

For Masonry cement, extra CO_2 emission from additives

CO_2 Emissions (tonnes) = [Masonry Cement Production (tonnes) * (1-1/(1+b)) * c * 0.785]

EF Clinker = Fraction CaO * 0.785, where,

CKD = Cement Kiln Dust emission share, default value is 2%

b = fraction of weight added to masonry cement by non-plasticiser additives such as lime, slag, and shale (e.g., 0.03, 0.05)

c = fraction of weight of non-plasticiser additives that is lime (e.g., 0.6 - 0.8)

B1: Portland Production						
	Unit of Measurement	Distribution	Default	Mean	S.D.	Uncertainty, %
Clinker Production	tonnes	Normal	1000	1000	10.204	±2
CaO Content	%	Normal	64.6	64.6	0.659	±2
Correction factor: CKD	%	Lognormal	2	2	0.051	±5

B1: Masonry Cement						
	Unit of Measurement	Distribution	Default	Mean	S.D.	Uncertainty, %
Production	tonnes	Normal	1000	1000	10.204	±2
Correction factor: CKD	%	Lognormal	2	2	0.051	±5
Fraction of additives added (b)		Lognormal	0.04	0.04	0.001	±5
Fraction of lime in additives (c)		Lognormal	0.7	0.7	0.018	±5

Protocol B2: Lime Production

CO_2 Emissions (tonnes) = Lime Production (tonnes) * EF lime (tonne of CO_2/ tonne of lime)

where EF lime = Stoichiometric Ratio of CO_2/CaO * CaO (or CaO+MgO) Content of Lime

B2: Lime Production						
	Unit of Measurement	Distribution	Default	Mean	S.D.	Uncertainty, %
High-Calcium Lime	tonnes	Normal	1000	1000	5.102	±1
Dolomitic Lime	tonnes	Normal	1000	1000	5.102	±1
Hydraulic Lime	tonnes	Normal	1000	1000	5.102	±1

B2: CaO (or CaO+MgO) Content						
	Unit of Measurement	Distribution	Default	Mean	S.D.	Uncertainty, %
High-Calcium Lime	%	Lognormal	95	94.986	0.969	±2
Dolomitic Lime	%	Lognormal	90	89.987	0.918	±2
Hydraulic Lime	%	Lognormal	75	74.372	5.744	±15

B2: Stoichiometric Ratio of CO2/CaO				
	Unit of Measurement	Distribution	Default	Mean
High-Calcium Lime	tonne Co2/tonne of lime	Constant	0.79	0.79
Dolomitic Lime	tonne Co2/tonne of lime	Constant	0.91	0.91
Hydraulic Lime	tonne Co2/tonne of lime	Constant	0.79	0.79

Protocol B3: Limestone and dolomite use

CO2 Emissions (tonnes) = Limestone use (tonnes) * EF limestone + Dolomite use (tonnes) * EF dolomite

B3: Level of use						
	Unit of Measurement	Distribution	Default	Mean	S.D.	Uncertainty, %
Limestone	tonnes	Normal	1000	1000	30.612	±6
Dolomite	tonnes	Normal	1000	1000	30.612	±6

B3: Purity of Raw material (f)						
	Unit of Measurement	Distribution	Default	Mean	S.D.	Uncertainty, %
Limestone	%	Lognormal	100	99.996	0.510	±1
Dolomite	%	Lognormal	100	99.996	0.510	±1

Protocol B4: Soda ash production or use

Soda Ash Production: CO_2 Emissions (tonnes) = Soda ash production (tonnes) * EF Trona

	Unit of Measurement	Distribution	Default	Mean	S.D.	Uncertainty, %
Soda ash production	tonnes	Normal	1000	1000	30.612	±6
Emissions Factor	tonne CO_2/tonne Trona	constant	0.097	0.097		

Soda Ash Use: CO_2 Emissions (tonnes) = Soda ash use (tonnes) * EF Soda ash use

	Unit of Measurement	Distribution	Default	Mean	S.D.	Uncertainty, %
Soda ash use	tonnes	Normal	1000	1000	10.204	±2
Emissions Factor	tonne CO_2/tonne Na_2CO_3	constant	0.415	0.415		

Protocol B5: Ammonia - Use of Fuels as feedstock

Energy measured in terms of kWh

CO_2 Emissions from each fuel (tonnes) = Consumption of fuel (kWh) * Emission factor for each fuel (kgCO_2/kWh) * 0.001

B5: Energy Consumption measured in kWh						
	Unit of Measurement	Distribution	Default	Mean	S.D.	Uncertainty, %
Gas/Diesel Oil	kWh	Normal	1000000	1000000	25510.2	±5
Heavy Fuel Oil	kWh	Normal	1000000	1000000	25510.2	±5
Naphtha	kWh	Normal	1000000	1000000	25510.2	±5
Natural Gas	kWh	Normal	1000000	1000000	25510.2	±5

B5: Emission Factor						
	Unit of Measurement	Distribution	Default	Mean	S.D.	Uncertainty, %
Gas/Diesel Oil	kgCO2 / kWh	Lognormal	0.25	0.250	0.006	±5
Heavy Fuel Oil	kgCO2 / kWh	Lognormal	0.26	0.260	0.003	±2
Naphtha	kgCO2 / kWh	Lognormal	0.26	0.260	0.007	±5
Natural Gas	kgCO2 / kWh	Lognormal	0.19	0.190	0.001	±1

Energy measured in terms of tonne or GJ

CO_2 Emissions from each fuel (tonnes) = Consumption of fuel (tonne) * Carbon content (%) * 44/12

or CO_2 Emissions from each gaseous fuel (tonnes) = Consumption of fuel (GJ) * Emission factor for each gaseous fuel (kgCO2/GJ) * 0.001

B5: Energy Consumption measured in tonne or GJ						
	Unit of Measurement	Distribution	Default	Mean	S.D.	Uncertainty, %
Gas/Diesel Oil	Tonne	Normal	1000	1000	25.51	±5
Heavy Fuel Oil	Tonne	Normal	1000	1000	25.51	±5
Naphtha	Tonne	Normal	1000	1000	25.51	±5
Natural Gas	GJ	Normal	1000	1000	25.51	±5

B5: Carbon Content						
	Unit of Measurement	Distribution	Default	Mean	S.D.	Uncertainty, %
Gas/Diesel Oil	%	Lognormal	85	84.997	0.4337	±1
Heavy Fuel Oil	%	Lognormal	85	84.997	0.4337	±1
Naphtha	%	Lognormal	85	84.997	0.4337	±1
Natural Gas	%	Lognormal	75	74.997	0.3827	±1

B5: Natural Gas Emission Factor						
	Unit of measurement	Distribution	Default	Mean	S.D.	Uncertainty, %
Natural Gas	kgCO2/GJ	Lognormal	53	52.998	0.27	±1

Protocol B6: Metal Production

CO_2 Emissions (tonnes) = Reduction agent (tonne) * Emission factor for each agent (tonne CO_2/ tonne agent) + (tonne carbon in ore - tonne carbon in metal)* 44/12

B6: Reduction Agent Consumption						
	Unit of measurement	Distribution	Default	Mean	S.D.	Uncertainty, %
Coal	Tonne	Normal	1000	1000	5.102	±1
Coke from coal	Tonne	Normal	1000	1000	5.102	±1
Petrol Coke	Tonne	Normal	1000	1000	5.102	±1
Prebaked anodes and coal electrodes	Tonne	Normal	1000	1000	5.102	±1

B6: Emission Factor						
	Unit of measurement	Distribution	Default	Mean	S.D.	Uncertainty, %
Coal	tonne CO2 / tonne agent	Lognormal	2.6	2.598	0.066	±5
Coke from coal	tonne CO2 / tonne agent	Lognormal	3.0	2.997	0.077	±5
Petrol Coke	tonne CO2 / tonne agent	Lognormal	3.6	3.597	0.092	±5
Prebaked anodes and coal electrodes	tonne CO2 / tonne agent	Lognormal	3.6	3.597	0.092	±5

B6: Tonne carbon in ore						
	Unit of Measurement	Distribution	Default	Mean	S.D.	Uncertainty, %
Consumption level of ore	tonne	Normal	1000	1000	5.1020	±1
Carbon content for ore	%	Lognormal	0.1	0.0999	0.0026	±5

B6: Tonne carbon in metal						
	Unit of Measurement	Distribution	Default	Mean	S.D.	Uncertainty, %
Production level of metal	tonne	Normal	1000	1000	5.102	±1
Carbon content of metal	%	Lognormal	2	1.998	0.051	±5

Protocol B7: Waste Incineration - Municipal Solid Waste (MSW) and Sewage

CO2 Emissions (tonnes) = 0.275 * MSW combusted (tonnes)

B7: MSW Combusted						
	Unit of Measurement	Distribution	Default	Mean	S.D.	Uncertainty, %
Level of MSW combusted	tonnes	Normal	1000	1000	35.7	±7

B7: MSW Emission factor						
	Unit of Measurement	Distribution	Default	Mean	S.D.	Uncertainty, %
Emission factor	tonne CO2 / tonne MSW	Lognormal	0.275	0.271	0.028	±20