RICARDO-AEA

Development of the Uncertainty Analysis of the Scottish GHG Inventory

Project Report

Report for Scottish Government

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Executive Summary

All greenhouse gas (GHG) inventories have associated uncertainty. It is one of the core tasks of the GHG inventory compilers to understand, transparently report, and reduce this uncertainty through prioritised inventory methodological improvements.

In deriving GHG emission estimates for Scotland, for many emission sources there are incomplete local data on activities and emission factors. For example, there is no established time-series of energy statistics for Scotland from 1990 and in such instances the emission estimates are based on the best-available proxy datasets, assumptions and/or expert judgement. The quality of the available activity data (AD) and emission factors (EFs) from these sources varies substantially, and it is essential to understand the uncertainty associated with the estimates of GHG emissions and removals of carbon dioxide (CO_2).

The type of model used to assess uncertainty in the GHG inventory for Scotland is a Monte Carlo model. This type of model allows correlations between sources and non-normal distributions to be included, and increases the accuracy of the estimates of uncertainties.

In order to obtain up to date information on estimated uncertainty of raw data and inventory methods, the project team has consulted with organisations that provide key datasets that underpin the Scottish inventory, as well as all inventory experts that are engaged in delivering the Scottish inventory. Improvements have been made to the whole uncertainty analysis used for the Devolved Administration (DA) GHG inventory. These improvements have included examining and improving how the model is constructed to increase transparency and accuracy, and examining and improving the treatment of correlations between sources.

Many sources of large CO_2 emissions in Scotland arise from industrial and commercial sites which are regulated under the European Union Emissions Trading System (EU ETS). The emission estimates from many EU ETS installations are based on frequent, regular sampling and analysis, and the accuracy of these measurements are dictated by the tolerances set out in the compliance framework of the EU ETS. These data are used extensively within the Scottish GHG inventory and comprise a high proportion of total Scottish emissions. The uncertainty model has been redesigned to enable the user to specifically account for the emissions within EU ETS ("traded") and excluded from EU ETS ("non-traded"), and to report separate uncertainty estimates for the traded and non-traded sectors if needed.

The effects on the uncertainties associated with each GHG in the base year and latest year, annual total GHG emissions, and on the trend in emissions have been assessed. The project team has run a series of scenarios to test the model function and to determine the sensitivity of the model to certain parameters. This analysis has considered uncertainties: in the base year, in the latest year (2013), in the base year to 2013 trend, and in the 2012-2013 trend.

The results from the updated uncertainties model suggest, for Scotland, total GHG Global Warming Potential (GWP) weighted uncertainties in 2013 are **11%,** and there is a 95% probability that GWP weighted GHG emissions were between **26% and 45%** below the levels in 1990.

The scenario analysis reveals several important features. Despite the magnitude and contribution of emissions from EU ETS sources to the GHG emissions in Scotland, the contribution to the overall uncertainty is minimal. Even if the EU ETS emissions were known exactly the overall picture of uncertainties for Scotland would look very similar. The LULUCF sector is responsible for almost the entire uncertainty in the CO_2 inventory for Scotland, whilst the agriculture sector is responsible for almost the entire uncertainty in the nitrous oxide (N_2O) inventory for Scotland, and contributes around half of the total methane uncertainty.

Further work is needed to integrate the outputs of current scientific research, which should be available in the next few months, into the uncertainty model. This research is examining the magnitude and uncertainty in emissions of nitrous oxide from agricultural soils, and is assessing the updated modelling approaches used in the LULUCF sector.

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Glossary

AD	Activity data
Base year	Base year used for reporting the UK GHG inventory, which is 1990 for CO_2, CH_4 and N_2O, and 1995 for the F-gases (HFCs, PFCs, SF_6 and NF_3)
DA	Devolved Authority, i.e. England, Scotland, Wales and Northern Ireland
DECC	Department of Energy and Climate Change
EF	Emission factor
GHG	Greenhouse gas
GVA	Gross Value Added
IPCC	Intergovernmental Panel on Climate Change
IPPU	Industrial Processes and Product Use, sector 2 in the 2006 IPCC Guidelines nomenclature
LULUCF	Land Use, Land Use Change and Forestry
Monte Carlo	A broad class of computational algorithms that rely on repeated random sampling to obtain numerical results[1]
NAEI	National Atmospheric Emissions Inventory
PDF	Probability Density Function
QA/QC	Quality Assurance/Quality Control
SNES	Sub-National Energy Statistics (published annually by DECC)

[1] http://en.wikipedia.org/wiki/Monte_Carlo_method

1 Introduction

1.1 Scottish Inventory Reporting: Tracking progress to GHG mitigation targets

The Scottish Government recognises climate change will have far-reaching effects on Scotland's economy, its people and its environment and is determined to play its part in tackling climate change. In June 2013, the Scottish Government published Low Carbon Scotland: Meeting our Emissions Reduction Targets 2013-2027. The Scottish GHG inventory is used to report on progress against legislative commitments to reduce GHG emissions and to support the monitoring of Scotland's transition to a low carbon economy. The Scottish GHG inventory is an annual statistical publication and it provides essential information for policy makers to help them both understand the effectiveness of current policies, and if necessary, introduce additional GHG mitigation measures. The level of uncertainty associated with the estimates of emissions and removals provides essential information for policy makers to make informed judgements.

For some inventory sources, the uncertainty inherent within the emission estimates due to (predominantly) scientific uncertainty regarding emission factors (i.e. the magnitude of emissions or removals associated with a specific activity) are very high and this makes the analysis of progress to targets problematic and undermines confidence in the use of inventory data. This project seeks to address this problem by analysing the uncertainties for each gas and key source category in the Scottish inventory, assessing and presenting uncertainties at a more detailed level than previously, and identifying the priorities for further work that may reduce overall inventory uncertainties in future.

1.2 Uncertainty in Emission Inventories

All GHG inventories have associated uncertainty; it is one of the core tasks of the GHG inventory compilers to understand, transparently report, and reduce this uncertainty through prioritised inventory methodological improvements. The uncertainties and associated key category analysis[2] are used to help prioritise research to improve inventory quality and reduce overall uncertainties, to ensure that reported inventory data are as accurate as can reasonably be achieved and to strengthen the evidence base for policy decision-makers. In the UK, the GHG inventory improvement programme is managed by DECC in consultation with other UK Government Departments, Scottish Government, other DA Governments, agencies and inventory experts.

The majority of emission estimation methodologies in the UK and Scottish GHGI can be represented by a calculation:

Emission = emission factor (EF) x activity data (AD)

Therefore, when considering the uncertainty of the inventory the starting point is to establish the uncertainty of the emission factors and activity data used. Many of these activities or emission factors may be used across different years or sources, and in modelling overall inventory uncertainties they cannot be treated as independent uncertainties, this is discussed in detail in Section 2.4.

GHG emission inventory estimates are based on reference data, country-specific research and expert judgements or assumptions from many data sources. In deriving GHG emission estimates for Scotland, for many emission sources there are incomplete local data on activities and emission factors For example, there is no established time-series of energy statistics for Scotland from 1990 and in such instances the emission estimates are based on the best-available proxy datasets, assumptions and/or expert judgement. The quality of the available activity data (AD) and emission factors (EFs) from these sources varies substantially, and it is essential to understand the uncertainty associated with the estimates of GHG emissions and removals of carbon dioxide (CO_2).

For example, the carbon contents of many fuels used in Scotland are accurately known, i.e. the emission factors per unit fuel use are associated with low uncertainty; therefore in order to derive accurate emission estimates from fuel combustion, the key challenge for the Scottish GHG inventory

[2] Key category analysis is an analysis that identifies sources that have particularly high contribution to the trend, uncertainty or magnitude of emissions, for the UK GHGI we use the key category analysis described in Chapter 4 of Volume 1 of the 2006 IPCC guidelines.

is to identify the best available activity data and derive uncertainty parameters for the inventory uncertainty model.

For other emission sources, estimates of emissions and removals are associated with much greater uncertainties. Uncertainties associated with emissions of nitrous oxide (N_2O) from agricultural soils (agriculture sector) and the Land Use, Land-Use Change and Forestry (LULUCF) sector in general are much higher (for all GHG inventories, by nature of the scientific uncertainties associated with the processes that release the gases). The emissions and removals of CO_2 from the LULUCF sector, and the associated uncertainties, are particularly important for Scotland as the land use and forestry sources and sinks are a more significant contributor to the GHGI in Scotland compared to other parts of the UK, and the uncertainties over carbon fluxes[3] from soils, organic matter and forestry are large.

All calculation models are simplifications of the system they are attempting to represent. GHG inventories need models that estimate GHG emissions and removals of CO_2. Models typically used to estimate emissions from stationary combustion sources only need to be simple to accurately estimate emissions as only 2 or 3 factors control emissions. Such models represent the real world situation well. The product of the fuel consumption (activity data) and the carbon factor (emission factor) will provide an accurate estimate of emissions – assuming the activity data and emission factor are known accurately, which they often are. Models needed to estimate emissions from the agriculture and LULUCF sectors need to represent the complex biological processes that cause emissions and removals, and take into account climatic conditions, soil science and a range of other factors. The models used in these situations are necessarily a considerable simplification of the "real world", and so will model that world imperfectly. The estimates of emissions they generate will have some associated uncertainty because of the limitations of the model itself.

In the inventory to minimise this type of modelling uncertainty (which we might classify as "systematic uncertainty"), we use the methods prescribed by the IPCC. These methods have been subject to rigorous peer review, and all inventories should use them to ensure accuracy and comparability. Inventories compilers should use higher Tier models for Key Categories, as we do for Scotland, and these models should provide more accurate estimates. More complex, or simpler models could be used in place of the current models; these models would give different answers, but not always necessarily more accurate answers.

1.2.1 Uncertainty Parameters for Inventory Sources

Ideally, the uncertainty estimates would be based on comprehensive measurements of activity levels and emission factors representative of the situation in Scotland, including information on the range and distribution of measurement data around the mean value. In practice, detailed analysis of the representative data is available for only a few emission sources. In some cases, (e.g. CO_2 emissions from natural gas combustion, or from high-emitting EU ETS installations), the reported emission factor is based on a large number of representative samples and it is possible to provide a realistic confidence interval.

In other cases, the central estimate and upper and lower bounds for emission factors are reported, however:

- it may not be clear whether the derived confidence interval relates to uncertainty on the mean or the sample range
- it may not be certain that the parameters available are representative of the situation in Scotland (e.g. the EFs for many sources such as agriculture and waste are influenced by factors such as climate and soil type, but it may not be clear to what degree the underlying research to derive EFs and uncertainty parameters was based on analysis of Scotland-specific conditions).

In many other cases, the central estimate alone is reported and no estimate of the uncertainty in the activity level or emission factor is reported. In this case, the estimation of overall uncertainty in the inventory relies on estimates of the uncertainty provided by the IPCC guidelines or by expert judgment.

[3] The LULUCF sector looks at the carbon content of soils and plant life, and the net change of carbon stored is the sink or source of emissions reported. Scotland has a large amount of forestland, which is known to have a large amount of stored carbon, but the precise amount and how that amount changes with the age of the forest is a significant source of uncertainty in reported emissions or sinks. Additionally as what is reported is the net of emissions and sinks their cancelling out of each other disguises the independent sizes of the sinks and sources and therefore hides the fact that a small change in the total sink or source would have a very large impact of the net emission or sink reported.

Scotland-specific EFs are not available for some source categories, and in these instances either UK-wide factors may be applied or EFs are estimated from other similar sources. The uncertainty in these estimates is potentially large.

This project has sought to review and assess the available information on uncertainty parameters, to ensure that as far as possible the parameters applied in the uncertainty model are appropriate for the Scottish inventory, and to identify where this has not been possible.

1.2.2 Sources of Inventory Uncertainty and Examples from the Scottish Inventory

There are many different types and sources of uncertainty that contribute to the overall uncertainty of an inventory dataset; these are common to all emission inventories. The Scottish inventory is as far as possible compiled based on methods and guidance for all national inventory submissions (i.e. methods that are consistent with 2006 IPCC GLs), but is subject to many different sources of uncertainty including: statistical, measurement, scientific.

One of the project objectives is to present insights into the different types of uncertainty, to help identify where additional research may lead to a reduction in uncertainty in future inventories; this is critical to enable the Scottish Government (overall and within policy teams) to work towards improvements that strengthen the inventory evidence base and provide greater confidence in the reported GHG reductions over time, to support reporting against mitigation targets.

The nature of the inventory source data and methods that are available to generate a Scottish inventory do not facilitate a very detailed insight into the different contributing factors to uncertainty; to try to identify the relative contributions of specific types of error within source data is impossible. However, the data sources and methods can broadly be separated out. The table below presents some examples of uncertainties in Scottish data, to illustrate the main types of uncertainty for different source estimates.

Table 1 Causes of Inventory Uncertainty and Examples from the Scottish GHG Inventory

Cause of uncertainty	Description	Scottish GHGI Context / Examples
Lack of completeness	Where data are not available, e.g. no measurements. This could lead to bias in the inventory data and trends.	A very minor source of uncertainty in the Scottish GHGI. There are few examples of potentially entirely "missing" sources, as IPCC GLs are followed. The main area of concern is any possible gaps in available energy data, due to the limited time series of energy statistics for Scotland and the possibility of missing data in UK energy stats, especially for "derived fuels" such as refinery fuel gas or process off-gases and residues. Data for recent years from industry (EUETS) reduces the risk of gaps, and this could lead to bias as there is much less detailed data for Scotland in 1990.
Use of models	Models are simplified calculation systems that aim to represent complex processes. There may be errors in the calculations or assumptions / factors embedded in model calculations that are not representative of the sources in Scotland. Models often also include interpolation and extrapolation to cover data gaps between sources or over time. The uncertainty associated with using specific models is not quantified by the IPCC, but the use of higher Tier models for Key Categories is good practice and this should improve accuracy. The GHG inventory for Scotland adopts this approach.	This is one of the main sources of overall uncertainty in Scottish GHG estimates. Key examples include: LULUCF – Carbon flux models are used to represent carbon transfers between soils-vegetation-forestry. The models aim to represent complex processes that are affected by many parameters, including soil type, species, climate etc. The source activity data are also based on periodic surveys of land use, so interpolation is required to estimate annual activities. Landfill methane (MELMOD) – The model takes a wide range of input parameters (some of which are Scotland-specific and regarded as "accurate", e.g. waste arisings sent to landfill, waste composition), and models the breakdown of organic materials into methane, the oxidation and release of methane under variable climatic conditions and based on assumptions over "typical" landfill design and methane capture and utilisation.

Cause of uncertainty	Description	Scottish GHGI Context / Examples
		Gas leakage from distribution networks – There is an industry model developed in the 1990s by British Gas which is used by all gas network operators to estimate gas leakage (a major source of methane). The model makes a series of assumptions about the leakage rates from different pipes, connections, valves etc., under different operating conditions, and the model uses input data that are annual surveys of gas network infrastructure.
Lack of data	Where either activity or emission factor data are not available. Often proxy data are used, or extrapolation and interpolation from years / sources where there are data available.	This is a moderate source of uncertainty in the Scottish GHGI, with the greatest impact on trend uncertainty due to the lack of detailed data for many sources in 1990 compared to recent years. Examples include: Energy activity data – There is a limited time series of energy data for Scotland; in recent years there are DECC sub-national energy statistics supplemented by EUETS data for high-emitting industry sectors. Analysis has identified missing data for some sectors (e.g. process off-gases, upstream oil and gas fuel use) and these "gaps" have been addressed in the dataset back to 1990 by methods such as extrapolation based on proxies such as installed plant capacity in Scotland or (UK) oil and gas annual production estimates. Fuel emission factors – There are no Scotland-specific data on e.g. carbon content of petroleum or solid fuels, other than the information from EUETS in recent years. Therefore there are a lot of examples where either UK factors or international defaults are used. Typically these will not add much uncertainty as the range of possible data is narrow; also trend uncertainty is low. F-gas estimates – There are very few bottom-up datasets for F-gas sources, and many instances where economic indicators (e.g. GVA) or population data are used as a proxy to generate "top-down" estimates from UK totals.
Lack of representativeness of data	Where the source data do not correspond to the conditions that prevail in the real world, e.g. where EFs are derived under different conditions (e.g. of climate / temperature, of technology type) to the emission sources in situ.	This is a moderate to high source of uncertainty for the Scottish inventory. Key examples are: Agricultural soils – The UK-wide EF for N_2O from agricultural soils is a highly uncertain factor for any part of the UK. It is based on research of UK conditions, aiming to represent the combination of complex processes governing nitrogen inputs to soils, conversions and releases of N_2O. The EF is applied based on activity data, but the actual emissions in Scotland will be influenced by soil type, climate, N inputs to soil, timing of fertiliser application…etc. EUETS industry emissions – At the other end of the spectrum, the very detailed, installation-specific compositional analysis of fuels used in the highest-emitting industrial sites in Scotland, that are available from EUETS (for recent years) means that data underpinning estimates of emissions from power stations, refineries, cement kilns.. are highly representative of the emission sources in Scotland, and this uncertainty type is very low for these examples.

Cause of uncertainty	Description	Scottish GHGI Context / Examples
Statistical random sampling error	Uncertainty due to the use of data that are based on a sample of the total activity. Typically the larger the sample size, the lower the uncertainty.	This source of uncertainty will affect all estimation methods to a greater or lesser degree. This type of uncertainty effects all statistical datasets that are based on surveys (for AD) and emissions research (e.g. compositional analyses) for EFs. Key examples include: Agriculture AD – Based on annual surveys (like many other statistical datasets used in the GHGI), the data uncertainty will be determined by the extent to which the surveys are representative of all farming activities. Gas compositional analysis – The carbon and methane content of natural gas is based on annual sampling and compositional analysis of the natural gas within the distribution networks in Scotland. Many thousands of gas samples are taken every year, and a weighted average is derived, and hence the statistical uncertainty in these data are regarded as low.
Measurement Error	This may be random or systematic and arises from errors in measuring and recording data, e.g. from calibration errors in measurement equipment, instrument resolution limits, assumptions in the estimation method.	This will also affect the majority of source estimates to some degree, as all estimates are based on AD and/or EFs that have had to be measured in some way. Key examples include: EUETS industry emissions – Data from operators are based on meter readings, weighbridge readings, laboratory analyses against reference materials. The EUETS system demands high standards by operators, e.g. defined uncertainty limits, specific ISO standards to use. High numbers of samples helps to limit the impacts of random uncertainties, whilst the use of ISO standards etc. helps to minimise the risk of bias from e.g. calibration errors. Therefore overall uncertainty from this source is expected to be low for EUETS sources.
Misreporting of data	Incomplete or simply incorrect reporting of data on emissions.	A minor source of uncertainty. This typically occurs when errors are made in reporting data to the inventory compilers. Basic inventory quality checking, e.g. time series consistency checks on source data often pick up such instances, but there are many potential instances where data may be mis-reported. Using national statistics and other established, quality-checked raw data helps to minimise this source of uncertainty.

The project team has used its expert knowledge of the inventory source data and methods to assess the overall quality of uncertainty parameters for each key source category (as explained in section 2.5).

Uncertainty associated with statistical random sampling and measurement errors can potentially be assessed by statistical methods. However, the other sources of uncertainty cannot generally be quantified by statistical methods and assessed predominantly by expert judgement, taking into account for example available data, practical constraints and model structures, or by the use of default uncertainty parameters recommended by IPCC. The quality rating classification (A-E) used in this report recognises that there are different causes of uncertainty. Quality ratings A or B are applied where the uncertainty is caused primarily by statistical random sampling or measurement errors while ratings D or E are applied where the uncertainty is attributable to other causes.

The use of these data quality criteria aims broadly to distinguish between data that are uncertain but are based on a representative dataset for Scotland and a reasonable evidence base, and those that are uncertain but there is no sufficient evidence base to properly determine the level of uncertainty. This enables a simplistic separation of the contribution to overall Scottish GHGI uncertainty from sources with low sampling error, and those with a higher sampling error. The results are discussed under the section summarising findings from Scenario 10.

2 Task 1: Redevelopment of the DA Inventory Uncertainty Model

2.1 The DA inventory uncertainty model

The Devolved Administration uncertainty estimation model used to generate the uncertainty estimates within the 2014 DA inventory submission was the starting point for this research. The model uses a Monte Carlo simulation to calculate 95th percentile confidence intervals for the greenhouse gas emissions for the current year and the base year and the trend in emissions. The model is a derivative of the model used for the UK GHG inventory, and includes assumptions about the correlations between certain sources.

The model is implemented in an Excel workbook using the @Risk add-on to facilitate the Monte Carlo analysis. Separate worksheets are used for the analysis for:

- Carbon dioxide current year (2013)
- Carbon dioxide base year (1990)
- Methane current year
- Methane base year
- Nitrous oxide current year
- Nitrous oxide base year
- Halocarbons current year
- Halocarbons base year

Further worksheets are used to prepare input and output data for specific sources.

The redeveloped model has been built using the same general approach (i.e. it is implemented on an Excel workbook using the @Risk add-on to facilitate the Monte Carlo analysis). The differences in approach are presented in detail later in the report.

The revisions to the model have been implemented by a small team of inventory uncertainty experts in Ricardo-AEA and the model has been verified through a detailed review and parallel checks on model calculations by a separate expert not involved in the model redesign or project implementation.

2.2 Model design: Source aggregation level

In re-developing the Scotland (and DA) GHG uncertainty model, the project team has sought to improve consistency with the UK GHGI Approach 1 (error propagation) and Approach 2 (Monte Carlo) uncertainty analyses, including consistency in uncertainty estimates for each source category.

The uncertainty model design reflects the structure used for calculations performed in the Approach 1 UK GHGI uncertainty model, i.e. uncertainty parameters for AD and EFs are applied at a level of detail that in some cases is aggregated across sources. This approach balances the model complexity against computational time for running the model, and reflects that in many instances the same uncertainty parameter (e.g. the uncertainty for a fuel-specific EF) is applicable across multiple sources.

The level of source aggregation in the DA inventory uncertainty analysis differs between greenhouse gases.

For methane, the DA uncertainty analysis is carried out at the IPCC 3rd order nomenclature for energy (sector 1) and the 2nd level otherwise (e.g. 1A1, 1B1, 2B, 4A, 5A) in most cases. The analysis distinguishes between fugitive emissions from oil, natural gas and other (1B2a, 1B2b and 1B2c) which is relevant for Scotland because of the overall significance of the oil and gas sector in Scotland. The UK Approach 1 uncertainty analysis (error propagation) is mostly carried out at the next higher level of disaggregation. For example, it distinguishes between the fugitive emissions from gasoline and DERV. The UK Approach 2 uncertainty analysis is carried out at a similar level as the Approach 1 analysis: in most cases it uses the same activity and emission uncertainty factors. In some cases, the

UK Approach 2 analysis is carried out in greater detail: however, the activity and emission factor uncertainties are still derived from the Approach 1 values.

For nitrous oxide, the DA uncertainty analysis is carried out at the IPCC 2nd order nomenclature in most cases. The UK Approach 1 Uncertainty analysis is mostly carried out at the next higher level of disaggregation. For example, it distinguishes between the nitrous oxide emissions from gasoline and DERV. The UK Approach 2 Uncertainty analysis is carried out at a similar level as the Approach 1 analysis: in most cases it uses the same activity and emission uncertainty factors. In some cases, the UK Approach 2 analysis is carried out in greater detail; however, the activity and emission factor uncertainties are still derived from the Approach 1 values.

The DA uncertainty analysis for **halocarbons** is carried out at source sector level (e.g. commercial refrigeration, stationary air conditioning) for the main halocarbon groups (HFCs, PFCs, SF_6). The UK Approach 1 and 2 uncertainty analysis use a different classification scheme, but the level of disaggregation is similar.

The DA uncertainty analysis for **carbon dioxide** distinguishes between fuel and "non-fuel" emission sources. For the non-fuel combustion sources, the analysis is carried out broadly at the IPCC 2nd order nomenclature. The analysis distinguishes between fugitive emissions from oil, natural gas and other (1B2a, 1B2b and 1B2c), as noted above. The UK Approach 1 and Approach 2 uncertainty analyses for non-fuel carbon dioxide are carried out at a similar level of disaggregation.

The DA uncertainty analysis for fuel combustion is carried out at the level of fuel type (e.g. natural gas, motor gasoline). The activity and emission factor uncertainties for each fuel type are calculated as simple emission-weighted averages from input data for detailed IPCC 4th order nomenclature for energy and 3rd level otherwise (e.g. 1A1a, 2C1) for each fuel type. The use of simple emission-weighted averages may introduce some bias in the uncertainty analysis. The UK Approach 1 uncertainty analysis is carried out at the IPCC 3rd order nomenclature for energy and the 2nd order nomenclature otherwise (e.g. 1A1, 1B2, 2B, 2C) for each fuel type. The UK Approach 2 analysis is carried out in greater detail (e.g. 1A1a), subdivided by fuel type: however, the activity and emission factor uncertainties are still derived from the Approach 1 values.

2.3 Activity Data Uncertainties: UK and DA level data

Detailed DA-specific activity data that can be used to calculate emissions are not available for all source categories. Scotland-specific activity data are available for source categories reporting under the EU Energy Trading Scheme and agricultural, land use, land use change and forestry emission sources. For many other source categories, however, the emissions for each DA are estimated "top-down", i.e. from the UK emission estimate for that source and disaggregated across the DAs on the basis of an appropriate proxy dataset (e.g. sub-national energy statistics, GVA, population).

In the DA uncertainty model used for previous analysis (e.g. the uncertainties presented in the 1990-2012 DA GHGI dataset), it was assumed that the activity uncertainties for the countries other than England could be specified independently based on expert judgement with values usually greater than the UK overall activity uncertainty. The Monte Carlo analysis was then run for Scotland, Wales, Northern Ireland and Unclassified, and also for the whole of the UK. The emission at each iteration of the Monte Carlo analysis for the remaining DA (England) was then calculated as the difference between the UK emission and the sum of the other DA emissions.

The previous method was straightforward to implement but was not a consistent method across all DAs, and assumed that England (as roughly 80% of UK emissions) could be regarded as the residual to align overall DA estimates to the UK GHGI uncertainty total. However, the calculated emissions for the DAs other than England are not constrained by the overall activity uncertainty and may be overestimated while those for England may be underestimated. In re-designing the model, the project team has retained some of the useful DA-specific uncertainty analysis but has developed the model calculations to take a consistent "bottom-up" approach which treats all constituent countries of the UK in the same way.

In re-designing the DA uncertainty model, the project team has developed a model that can be either "constrained" or "unconstrained" to the UK GHG inventory uncertainty model (i.e. constrained to deliver overall uncertainties that align with the UK model for each source category or to be unconstrained and purely based on "bottom-up" estimates of DA uncertainties). There are benefits and disadvantages to both approaches. The results from the re-developed model are presented in the Results section of this report; most of the scenarios run in this project are constrained to the UK GHGI uncertainties model outputs, except for Scenario 9 which uses Scotland-specific uncertainty parameters that are independent of the UK uncertainty model.

The approach to developing the DA uncertainty model has included an initial assessment of DA uncertainty parameters that have been calculated mathematically to align with UK uncertainty parameters. This initial draft of uncertainty parameters has then been over-laid with more focussed source category DA-specific uncertainty parameter analysis, based predominantly on expert judgement of the team of inventory compilers from Ricardo-AEA, Aether, CEH and Rothamsted Research. The detailed DA-specific analysis has focussed on the highest-emitting sources in Scotland and the sources that contribute most to the overall uncertainties in the Scottish GHGI; therefore for smaller sources and those that contribute less to the overall uncertainty, the "default" calculated uncertainty parameters have been retained, enabling resources to focus on improvements to the uncertainties for the key sources for Scotland.

The uncertainties for specific source-activities across the DAs are not independent. There is a level of uncertainty in the UK data, and extremes (e.g. all upper-end uncertainties) across all DAs would not be consistent with that UK-level constraint; there must be a relationship between the uncertainties for source-activities across the DAs. However, the uncertainty model also needs to be able to accommodate expert judgement regarding the source data and method used to derive the DA estimates. There may be valid reasons (e.g. different quality of source data) why the uncertainty in estimates for Scotland may deviate notably from other DAs for a given source or activity.

The model is structured to enable default (calculated) uncertainty parameters to be used unless over-written by specific expert judgement to reflect known issues with a specific source or activity. Implementing these DA-specific expert judgements will overall lead to a deviation from the UK model uncertainty, but the model can be run to allow this to happen so that uncertainty estimates tailored to the DA source data can be generated.

The "default" approach assumes that reasonable estimates of the relative uncertainty of the activities in each of the DAs can be made. Then the activity uncertainty for each of the DAs is given by **Equation** 1.

Equation 1 The relationship between the uncertainty of individual DAs and the UK (assuming independence between DAs)

$$\bar{U}_{Ai} = U_A w_i \frac{\sum_i |E_i|}{\sqrt{\sum_i w_i^2 E_i^2}}$$

Where U_A is the uncertainty in the UK activity;

w_i is a weighting factor for each DA representing the relative uncertainty in the activity

E_i is the emission for each of the DAs

This would mean that all the DAs are treated in a consistent manner. If it is additionally assumed that the source comprises a large number of similar sources (e.g. factories, houses, fields) distributed throughout the UK then we might use the weighting expressed in **Equation 2**.

Equation 2 Default uncertainty weighting with an inverse relationship with emissions

$$w_i = \frac{1}{\sqrt{|E_i|}}$$

Selecting an emissions sensitivity of a half yields Equation 3.

Equation 3 Resulting DA uncertainty when using equations 1 and 2 with emissions sensitivity of ½

$$\bar{U}_{Ai} = U_A \sqrt{\frac{\sum_i |E_i|}{|E_i|}}$$

The revised DA uncertainty model uses Equation 3.

This approach gives significant weighting to DAs with small emissions for a given source; the project team has also tested other approaches, e.g. to apply a weaker relationship between the uncertainty weighting and the reciprocal of the DA emissions, i.e. reducing the emissions sensitivity, which will yield a reduced spread of uncertainties compared to using a square root. Scenario 2 (discussed in the results section) explores the impact of using an emissions sensitivity of ¼.

2.4 Treatment of correlations

The estimates of the activities and emission factors are potentially correlated. The project team has considered the potential correlations and sought clarifications from experts at CEH, Rothamsted and Aether on:

- Emission factors between sources
- Emission factors between years
- Emission factors between DAs
- Activities between sources
- Activities between years
- Activities between DAs

2.4.1 Emission factors between sources

The emission factors used in the UK and DA inventories are derived primarily from measurements from nominally representative sample emission sources. In many cases, the same emission factor is used to estimate the emissions from several categories of emission. The overall uncertainty in the emission factors comprises the uncertainty in the measurement of the emission factor plus the uncertainty arising from applying the emission factor to each specific source category in the year of concern. If the uncertainty in the application of the emission factor is dominant then it is most appropriate to consider that the emission factors for the sources can be considered to be essentially independent of each other. On the other hand, if the uncertainty in the measurement dominates then the source emission factors should be considered to be correlated.

The previous DA uncertainty model considers the emission factors for each fuel used for combustion to be correlated and the Monte Carlo analysis is applied at the fuel level rather than at the source sector level. Emission factors for sources that are not based on fuel combustion are assumed to be independent of each other. The UK Approach 1 analysis, on the other hand, assumes that there are no correlations between the emission factors used for source sectors. The UK Approach 2 uncertainty model treats the emission factors as independent within the Monte Carlo analysis: however, the emission factor uncertainties associated with each source sector are increased to allow approximately for the potential correlations. The redeveloped DA uncertainty model continues to assume that the emission factors for fuel combustion are correlated within fuel types for combustion emissions, but are not correlated for other emission sources.

2.4.2 Emission factors between years

In most cases, the same or similarly derived inventory emission factors are in effect used for the base year and for the current year. The overall uncertainty in the emission factors comprises the uncertainty in the measurement of the emission factor plus the uncertainty arising from applying the emission factor in a particular year. In calculating trends in emissions, random year to year variations are of little interest and so it is appropriate to assume that the emission factors are correlated between years. The previous DA uncertainty model assumes that the emission factors in the base year and in the current year are independent of each other, except for gas leakage emissions. On the other hand, the UK Approach 1 uncertainty analysis assumes that the emission factors are correlated between years for all sources. The UK Approach 2 uncertainty model assumes that fuel combustion and Land Use Change emission factors are correlated between years but are uncorrelated for other source categories. Assuming that the emission factors are correlated has an important effect on the calculation of the uncertainty in the emission trend. The DA model has been redeveloped such that the emission factors for all sources are correlated between years, to exclude random year-to-year variations from the uncertainty in the trend. For most sources, this will be the case and it is the default approach suggested for Approach 1 uncertainties in the 2006 IPCC guidelines.

[Note that the model has been designed to include the functionality to allow the user to specify where emission factor uncertainty should be independent between years, should this be useful/necessary to implement in future work.]

2.4.3 Emission Factors between DAs

The current previous DA uncertainty model assumes that the emission factors are correlated between the DAs. As the same emission factors are generally used for all DAs, in the absence of information to the contrary the redeveloped model continues to make this assumption.

2.4.4 Activities between sources

In the past, the uncertainty in the total quantity of each fuel used in the UK was estimated from the statistical difference between the supply and demand of each fuel type presented in the UK Digest of Energy Statistics. The calculated uncertainty placed a bound on the overall uncertainty in the emissions for each fuel type. The UK Approach 2 and the DA uncertainty analysis took this constraint into account by assuming that the activity levels for source categories using the same fuel were in some way correlated. The previous DA uncertainty model treats all source categories using the same fuel in aggregate in order to avoid making assumptions about the nature of this correlation. The UK Approach 2 uncertainty model assumes that the emissions from source categories using each fuel are positively correlated. The UK Approach 1 analysis on the other hand assumes that the activities are not correlated.

Following recent discussions with the DECC team of energy statisticians that compile the Digest of UK Energy Statistics (DUKES) which underpins the UK GHGI fuel combustion estimates, it is no longer accepted that the statistical difference provides a robust estimate of the uncertainty in activity as the supply and demand estimates are not made independently. The UK inventory is for the most part compiled from the bottom up and so it is perhaps most appropriate to consider the activity estimates for each source as independent of other sources. Using this approach has allowed us to carry out the DA uncertainty analysis in more detail at the source category level, and it will also allow us to more easily report uncertainties by sector.

Theoretically there should be some relationships between sources. For example, for both fuel use activity data (across all sources for a specific fuel) and the f-gas estimates (where the UK model ensures that the total of all source estimates are reconciled to the overall UK f-gas bank size) it would be reasonable to assume a weak inverse correlation (i.e. if one source is an overestimate it is likely that a similar other source will be an underestimate). The introduction of a series of complex source-category uncertainty correlation relationships is unlikely to have a notable impact on the uncertainty model outputs, due to the nature of running Monte Carlo analysis calculations that test many thousands of different scenarios anyway. Therefore, the redeveloped DA model retains the assumption that all activities are independent.

2.4.5 Activities between years

The activity estimates for each source category are compiled separately for the base year and for the current year. They are treated as independent in all of the previous uncertainty models, and this approach is retained in the redeveloped model.

2.4.6 Activities between DAs

The estimates of DA activity are made in most instances by disaggregation from the UK totals. The estimates are therefore potentially correlated in some way. This is discussed at length in **Section** Error! Reference source not found..

2.5 Uncertainty Parameters: Data quality

The existing uncertainty estimation model uses a Monte Carlo simulation to calculate 95th percentile confidence intervals for the greenhouse gas emissions for the current year and the base year and the trend in emissions. The model is a derivative of the model used for the UK GHG inventory, and includes assumptions about the correlations between certain sources.

The current model calculates uncertainty estimates across the total of estimated activities for Scotland, typically applying EF uncertainties that are linked to those in the UK model, but the uncertainty calculation does not take account of the quality of the data used to provide the uncertainty estimates for individual source categories. For this analysis, the project team has allocated a quality rating to each of the uncertainty factors used in the analysis. The following table outlines the data quality rating scheme that has been used to provide a basis for segregating uncertainty parameters, which then enables analysis to test the relative contributions of scientific versus statistical uncertainty in the overall model outputs.

Table 2 Data quality rating for DA uncertainty parameters

Rating	Characteristics
A	Representative data set. Comprehensive reporting of sampling strategy and analysis of variance.
B	Representative data set. Standard deviation and number of samples reported
C	Mean and confidence interval reported. No information on sampling strategy or numbers of samples
D	Mean value reported only. Confidence interval from IPCC guidelines or expert judgment
E	Mean value reported for similar emission category

Inventory compilers within Ricardo-AEA, Aether, CEH and Rothamsted Research have reviewed the previous uncertainty parameters for each source-activity and updated them where necessary to reflect current data and evidence, and also have assign these quality ratings based on their judgment, i.e. to indicate their confidence in the uncertainty parameters proposed for use in the model .

The uncertainty model was then run sequentially to calculate the uncertainty attributable to quality rating A; then A and B; then A, B and C; etc. This approach provides an insight into the impacts of data quality (of the uncertainty parameters) on the calculated overall uncertainty in emissions and emission trends. The outputs indicate the areas where poor data quality has the greatest effect on the overall uncertainty of the inventory, providing a list of priorities for further work within this project and beyond.

2.6 Model Functionality: Additional Features

2.6.1 Trend in emissions over the last reported year

Previous uncertainty models have not been designed to look at the uncertainty in the reported trends in emissions for recent years, as inventories are primarily designed to inform trends over long periods; this reflects the fact that year-to-year variations and the uncertainties inherent in inventory estimates in many cases render year-to-year analysis meaningless, as uncertainties far out-weigh a discernible trend in emissions. However, as the inventories are increasingly being used to engage policy-makers across different sections of Government, and that signals of policy effectiveness are useful to explore, in this project we have tested the possibility of developing a year-to-year trend uncertainty estimate.

Therefore, the redeveloped model has been designed to enable the user to query the uncertainty in the latest year trend (i.e. currently 2012 to 2013), using the same approach used to estimate the trend uncertainty between the base year and the most recent year.

2.6.2 Separate consideration of EU ETS uncertainties

Many high-emitting sources in Scotland and across the UK are from industrial and commercial sites where fuel combustion and / or industrial process emissions are heavily regulated, well-documented and subject to third-party verification. The emission estimates from many EU ETS installations (including power stations, refineries, cement kilns etc.) are based on frequent, regular sampling and analysis to meet established uncertainty limits under the reporting requirements for EU ETS. These data are used extensively within the Scottish GHG inventory and comprise a high proportion of total Scottish emissions.

Therefore the uncertainty model has been redesigned to enable the user to specifically account for the emissions within EU ETS (“traded”) and excluded from EU ETS (“non-traded”), and to report separate uncertainty estimates for the traded and non-traded sectors if needed. The uncertainty parameters input to the model for sources that are dominated by “traded” sector emissions have also been revised and updated to reflect the level of confidence that the data reported through EU ETS brings to the Scotland source estimates.

In order to produce a traded sector uncertainty estimate the model has been redesigned to enable traded and non-traded emissions to be distinguished, and the model functionality enables the user to exclude one or the other. The 2008-2013 EU ETS data for all DAs has been analysed for recent years to assess:

- The relative contribution to the GHG inventory total (for each DA independently) at the source-activity level, e.g. power station coal and gas emissions are almost 100% covered by the EU ETS whilst road transport is not considered under the EU ETS; industrial combustion (1A2) in Scotland in 2013 is approximately 54% covered by the EU ETS. The analysis has been conducted across fuels and sectors, to align with the structure of the uncertainty model.
- The percentage share of EU ETS emissions from installation reporting at Tier 3 (i.e. conducting their own fuel compositional analysis and reporting activity data to within 2.5% uncertainty limits).

This has enabled analysis of:

- The overall estimated uncertainty of the EU ETS totals for each DA;
- The contribution to DA GHG inventory total uncertainty from the traded-share of the inventories;
- The estimate of uncertainty for specific source-activity aggregations, i.e. to improve the quality of uncertainty parameters used within the model for DA inventories as a whole.

3 Task 2: Review of Model Assumptions and Data Sources

3.1 Stakeholder Consultation

The project team has consulted with a number of key stakeholders and data providers to the Scottish GHG inventory, in order to gather evidence and expert opinion to inform the review of uncertainty model parameters and features. The following table outlines the key consultees and their feedback.

Table 3 Scotland Uncertainty Model Consultees

Contact	Feedback
Matthew Leng (DECC EU ETS statistics) **Naomi Walker** (Environment Agency lead on EU ETS)	DECC and the Environment Agency confirmed that no formal EU ETS uncertainty analysis has been performed, and that there was no need to do so as part of a Regulatory Impact Assessment. Naomi Walker clarified the information sources pertinent to operator reporting at different Tiers within EU ETS, setting out the activity data uncertainty limits for Tier3, 2 and 1, which have been used in the project calculations for uncertainty estimates of the traded share in each DA.
Don McKay and Asa Hedmark (SEPA)	SEPA were not aware of any work on UK or Scotland level EU ETS uncertainties. Asa Hedmark provided links to operator guidance on uncertainties in the EU ETS. (Consistent with the response from the EA – see above.)
John McFeat and Jim Pritchard (SEPA Waste Data Unit)	SEPA provided insights into: 1) quantities of waste disposed to landfills – now and in the past; 2) composition of waste in the landfill – how well is it characterised now, and in the past. John McFeat outlined that SEPA has a high level of confidence in the total waste arising to landfill, suggesting a confidence interval of ±1-5%, but the composition of the waste is more uncertain. Mark Broomfield (the Ricardo-AEA landfill expert who made the current estimate of uncertainty for landfill), then confirmed that "*Waste receipt quantities has only a minimal influence on the uncertainty in landfill emissions, which is driven by waste composition (as mentioned by John), gas modelling uncertainties, and uncertainties in gas collection data*" and "*John's comments give me confidence that my assessment of landfill emissions uncertainties is reasonable*".
Sabena Khan and Kerai Mita (DECC Sub-national Energy Statistics) **Alan Ferrier** (Scottish Government Energy Statistics)	DECC confirmed that there was no existing analysis of sub-national statistics uncertainties. Insights into methods and analysis of changes in DA energy data over time were proposed as the best available option to help inform Energy sector DA uncertainty parameters.

3.2 Inventory Expert Review

The project team of UK and Scotland GHG inventory compilers have also researched available data and provided updates and expert judgements where necessary to review and update the uncertainty parameters and distributions that are deployed within the Scotland uncertainties model.

Land Use, Land Use Change and Forestry

CEH (Amanda Thomson) has provided updated uncertainty parameters, including information about the correlations between categories in the LULUCF sector, and the methodological approach used by CEH to quantify uncertainties associated with their modelling. The updates do not account for moving from the C-FLOW model to the new CARBINE model. This expected have a material impact, and is proposed as a priority for future work.

Agriculture

Rothamsted Research (Sarah Gilhespy, Alice Milne) has provided updated uncertainty parameters, including additional details (e.g. correlations, the approach by which uncertainties were produced). The data are consistent with recent work for the UK GHGI uncertainty model. There are no recent updates on uncertainty parameters or distributions through the latest research on (for example) the methane and nitrous oxide emission factor research programme. Further work is anticipated later in 2015 to provide updated uncertainty parameters associated with the ongoing field measurements and EF analysis programme that is ongoing under the Defra-funded GHG Research Platform.

Energy, IPPU, Waste

The UK level uncertainty parameters for sectors estimated by Ricardo-AEA (Energy, IPPU and Waste) were reviewed as part of an improvement to the key category analysis for the UK GHGI, and these were used as the starting point for a review of the Scotland-specific AD and EF uncertainties. The DA inventory compilation team (Glen Thistlethwaite, Neil Passant and Joanna MacCarthy of Ricardo-AEA; Justin Goodwin and Emma Salisbury of Aether) has reviewed the uncertainty parameters, taking a bottom-up approach that considered factors such as:

- Scotland-specific evidence / data to support the use of UK-level EFs and the associated uncertainty parameters in the Scotland GHGI uncertainty calculations;
- Use of EU ETS data to support derivation of Scotland-specific AD for key source categories for recent years, and the range in uncertainty of the AD over the time series for key sources (i.e. often AD uncertainty is significantly higher in the base year, as installation-level data are more scarce for 1990,1995).
- The DA driver methodology, and the expert judgement on additional uncertainty to Scotland AD for a given source, due to the use of proxy data (in many instances) to derive a Scotland estimate.

For all Key Source Categories, the Scotland AD and EF uncertainty parameters were reviewed and a data quality rating assigned based on the available data underpinning the EFs and AD.

The Ricardo-AEA team also analysed the 2008-2013 EU ETS data for Scottish installations in detail, deriving estimates by source of the percentage share of EU ETS emissions in the Scotland GHGI total, analysing the percentage of the EU ETS data that are based on Tier 3 reporting (i.e. operator analysis of fuel composition or process sources) and the numbers of sites reporting using Tier 2 or Tier 3 methodologies. These data have been used to help inform an overall uncertainty for the “traded” component of the Scotland inventory, for use within the model.

Detailed analysis of EU ETS data is documented in **Section 4**.

3.3 Impacts of Revisions to the 2015 UK GHG Inventory

The project team has also incorporated a series of improvements to the DA GHGI uncertainty model to bring the reporting into line with the 2006 IPCC Reporting Guidelines; the 2015 submission (i.e. 1990-2013 inventory data) is the first year in which the 2006 IPCC guidelines has been the official guidance to follow for the reporting of national inventories, which replaces the 1997 revised IPCC guidelines, the 2000 IPCC Good Practice Guidelines and the 2003 Good Practice Guidance for Land Use, Land-Use Change and Forestry.

The 2006 guidelines sets out new and revised methodologies for estimating emissions and includes methodologies for sources not included in previous guidance.

Additionally the nomenclature used for reporting in accordance with the 2006 IPCC guidelines has changed. Significant revisions to overall emission estimates arise from the change in the applied Global Warming Potentials (GWPs) for the non-CO_2 GHGs, which are now taken from the Fourth Assessment Report (AR4) instead of the Second Assessment Report (SAR) and 3 new gases have been included (NF_3, HFC-245fa and HFC-365mfc).

Significant changes between 2015 and 2014 UK GHGI uncertainty analysis are:

- Decreased N_2O emissions due to a reduced GWP and due to default factors for agriculture being lower in the 2006 Guidelines than previously. This has the additional impact of reducing the proportion of N_2O emissions from one of the more uncertain contributors (namely agriculture) reducing the N_2O uncertainty;

- Numerous changes to F-gases, in particular generally increasing GWPs and a more conservative estimate of uncertainty for Refrigeration and Air Conditioning (RAC) to reflect that the model hasn't been changed to account for recent RAC F-gas Regulations changes;
- Increased methane emissions due to a higher GWP and new sources that have been included in the UK and DA inventories (e.g. biological treatment of solid waste). Furthermore, in the early part of the time series the landfill waste methane emission estimates have been significantly increased due to a method revision implemented in response to UNFCCC Expert Review Team feedback.

4 Task 3: Traded Sector Uncertainty Estimates

Transparent, consistent and accurate monitoring and reporting of greenhouse gas emissions are essential for the effective operation of the EU Emissions Trading System (EU ETS), the EU's key mechanism for reducing greenhouse gas emissions cost-effectively. Installations and aircraft operators have to monitor and report their annual emissions in accordance with two Commission Regulations, the Monitoring and Reporting Regulation (MRR) and the Accreditation and Verification Regulation (AVR).

The accuracy of operator measurements and reported emissions are dictated by the tolerances set out in the compliance framework for EU ETS, and the reported data are independently verified. Therefore the EU ETS is regarded as a high quality resource of data and information about emissions, fuel consumptions, and carbon factors.

Operators report activity data, emissions factors, calorific values and emission estimates according to specified “Tiers” that define the data quality requirements for each parameter used to derive the emission estimates. The tier system defines a hierarchy of different levels for activity data, emission factors and oxidation or conversion factors; the highest-emitting installations typically are required to report their data according the highest Tier, i.e. to the most stringent reporting requirements.

Each Tier is associated with uncertainty thresholds. The higher the number of the tier chosen (maximum Tier 4), the higher the level of accuracy and the more site-specific the monitoring system becomes.

For example, considering the activity “Combustion of fuels and fuels used as process input”, and the amount of fuel [t] or [Nm^3] used, installations reporting at Tier 1 would be allowed a maximum permissible uncertainty of ± 7.5% whilst installations reporting at Tier 4 would be allowed a maximum permissible uncertainty of ± 1.5%[4].

Analysis of the EU ETS data has been conducted to establish what proportion of each of the categories’ emissions is based on EU ETS data, and to determine the uncertainty of the EU ETS emissions based on the reporting standards (Tiers) of the installations and sources included within each category.

These additional data have been used in the model in order to ensure that the standards required by EU ETS sites on emissions reporting are reflected in the uncertainty analysis, based on the assumption that a normal distribution is appropriate for the reported EU ETS emissions. Additionally the EU ETS and non-EU ETS parts can be separated to aid further understanding of the impact of EU ETS reporting standards on the overall uncertainty.

[4] http://www.emissions-EU ETS.com/attachments/348_Tier%20thresholds%20for%20calculation-based%20methodologies%20related%20to%20installations.pdf

5 Results

The following section compares the results of the redeveloped uncertainties model with the previous (2014) DA GHG inventory uncertainty model and the 2015 UK GHG uncertainties model and scenario testing to determine the models sensitivities.

5.1 Uncertainty Model Scenario Specifications

In order to test the impacts of model design and functionality, and to determine the sensitivity of the model to uncertainty estimates and correlations across different sources, the project team has run the revised DA uncertainty model for a range of scenarios to assess the overall uncertainty by gas for Scotland.

The specification and rationale for running each scenario is outlined below:

Table 4 Uncertainty Model Scenarios: Specifications and Rationale

Scenario[a]	Definition
1	***Revised Model, Default Data Entry and Assumptions*** • New uncertainties from CEH and Rothamsted Research (RR) • DA uncertainties disaggregating using emission **sensitivity 0.5** and no custom DA uncertainty splits • EU ETS and non-EU ETS emissions included, and Scotland-specific EU ETS-derived uncertainties applied to the traded emissions within the GHGI • All data qualities for uncertainties allowed
2	***Lower Emission Sensitivity*** Same as scenario 1, except: • DA uncertainties disaggregating using emission **sensitivity 0.25** and no custom DA uncertainty splits *[To explore the significance of the emission sensitivity.]*
3	***Excluding LULULCF and Agriculture*** *[Not used in final analysis – replaced by Scenarios 5 and 6.]*
4	***EU ETS Functionality Disabled*** Same as scenario 1, except: • EU ETS fraction set to 0
5	***Excluding LULUCF uncertainties*** Same as scenario 1 except: • Uncertainties for LULUCF set to 0 *[To explore the model's sensitivity to the LULUCF sector.]*
6	***Excluding Agriculture uncertainties*** Same as scenario 1 except: • Uncertainties for agriculture set to 0 *[To explore the model's sensitivity to the agriculture sector.]*

Scenario[a]	Definition
7	***Excluding Traded Sector*** Same as scenario 1 except: • Non-EU ETS emissions only *[To explore the model's sensitivity to the well-characterised emissions that are based on EU ETS data.]*
8	***Traded Sector Only*** Same as scenario 1 except: • EU ETS emissions only *[To explore the model's sensitivity to the well-characterised emissions that are based on EU ETS data.]*
9	***Expert Judgement for Energy, IPPU, Waste Sources*** Same as scenario 1 except: • Expert judgements used to over-write previous uncertainty parameters for Energy, IPPU, Waste key sources, including UK GHGI parameter revisions
10	***"Good quality" uncertainties only*** Same as scenario 1 except: • Uncertainty for data qualities D and E set to 0 *[This approach enables review of the uncertainty contribution from only those sources where confidence in the uncertainty parameters is high, i.e. to discern between scientific and statistical uncertainty.]*
11	***UK GHGI Approach 1 uncertainties*** Same as scenario 1 except: • Uncertainties from the UK Approach 1 uncertainties model used only *[To enable direct comparison between the revised DA model and the UK GHGI uncertainty model.]*
12	***UK GHGI Approach 1 uncertainties with Revised Agriculture Parameters*** Same as scenario 1 except: • Uncertainties from the UK Approach 1 uncertainties model used, but revised for agricultural sources *[To remove a "known difference" in scenario 11, and therefore to enable better comparison with the revised DA GHGI uncertainties model.]*

[a] Scenario 3 was the omission of both agriculture and LULUCF, at a later stage it was decided that it would be better to consider these separately (into scenarios 5 and 6).

5.2 Comparisons of Results: 2013 Scotland GHG Inventory Uncertainties

Table 5 Summary of Outputs from Uncertainty Models for Scotland 2013 GHG Inventory Uncertainty[a]

Gas (kt CO_2e)	2012 Scotland GHG Uncertainties[b]		2013 Scotland GHG Uncertainties (original model)		2013 Scotland GHG Uncertainties: Revised Model										
	Central Estimate	Uncertainty	Central Estimate	Uncertainty	Scenario 1	Scenario 2	Scenario 4	Scenario 5	Scenario 6	Scenario 7[c]	Scenario 8[c]	Scenario 9	Scenario 10	Scenario 11	Scenario 12
CO_2	37,469	14.8%	36,984	16.7%	10.7%	10.7%	11.1%	2.5%	10.8%	23.5%	1.3%	11.0%	10.5%	11.0%	11.0%
CH_4	6,799	22.3%	7,872	19.3%	30.4%	26.2%	30.2%	30.1%	18.0%	30.2%	N/A	30.1%	18.0%	21.1%	21.1%
N_2O	5,052	80.8%	4,211	77.3%	69.9%	69.2%	67.0%	67.2%	7.3%	69.4%	N/A	66.7%	0.0%	195.0%	79.1%
HFC	1,134	6.2%	1,325	6.2%	29.1%	18.3%	29.1%	28.9%	29.0%	29.1%	N/A	29.0%	1.3%	29.1%	29.0%
PFC	51	56.1%	98	54.5%	52.0%	56.0%	52.0%	52.0%	52.0%	52.0%	N/A	52.0%	52.0%	52.0%	51.6%
NF_3	N/A	N/A	0.3	46.5%	55.3%	59.5%	55.2%	55.2%	55.2%	55.3%	N/A	55.2%	55.2%	55.2%	55.5%
SF_6	35	22.0%	36	19.1%	22.2%	15.8%	22.7%	22.5%	22.4%	22.6%	N/A	22.6%	1.5%	22.4%	22.2%
Total	**50,541**	**21.1%**	**50,527**	**14.1%**	**11.1%**	**10.6%**	**11.5%**	**8.2%**	**8.4%**	**18.1%**	**1.3%**	**11.2%**	**8.2%**	**22.4%**	**11.0%**

Table 6 Summary of Outputs from Uncertainty Models for UK 2013 GHG Inventory Uncertainty

Gas (kt CO_2e)	2012 UK GHG Uncertainties[b]		2013 UK GHG Uncertainties (original model)		2013 UK GHG Uncertainties: Revised Model										
	Central Estimate	Uncertainty	Central Estimate	Uncertainty	Scenario 1	Scenario 2	Scenario 4	Scenario 5	Scenario 6	Scenario 7[c]	Scenario 8[c]	Scenario 9	Scenario 10	Scenario 11	Scenario 12
CO_2	469,206	2.0%	465,934	2.2%	2.1%	2.1%	2.2%	1.0%	2.1%	4.0%	1.0%	2.3%	1.9%	2.2%	2.2%
CH_4	56,385	19.0%	55,980	18.0%	16.7%	16.5%	16.6%	16.5%	14.6%	16.5%	N/A	16.5%	14.2%	16.8%	16.7%
N_2O	27,648	58.0%	27,513	74.2%	43.9%	46.1%	44.0%	45.8%	11.9%	44.4%	N/A	43.8%	0.0%	183.2%	75.2%
HFC	16,262	9.0%	16,144	6.2%	11.4%	11.4%	11.4%	11.4%	11.4%	11.3%	N/A	11.4%	0.4%	11.4%	11.5%
PFC	253	24.0%	254	30.9%	25.0%	24.8%	24.9%	25.0%	24.9%	25.0%	N/A	25.2%	24.6%	25.0%	25.0%
NF_3	0.4	46.0%	0.4	45.8%	46.4%	46.2%	45.9%	46.4%	46.0%	46.4%	N/A	46.4%	46.2%	46.1%	46.0%
SF_6	602	10.0%	602	14.8%	4.7%	4.7%	4.7%	4.6%	4.6%	4.7%	N/A	4.6%	0.3%	4.7%	4.7%
Total	**570,356**	**4.0%**	**566,427**	**4.4%**	**3.5%**	**3.4%**	**3.4%**	**3.1%**	**2.4%**	**5.7%**	**1.0%**	**3.5%**	**2.2%**	**11.5%**	**4.8%**

Table 7 Summary of Outputs from Uncertainty Models for Scotland Base Year to 2013 GHG Inventory Trend Uncertainty[a]

Gas (kt CO_2e)	**Base Year to 2012 Scotland GHG Uncertainties**		**Base Year to 2013 Scotland GHG Uncertainties (original model)**		**Base Year to 2013 Scotland GHG Uncertainties: Revised Model**										
	Central Estimate of Trend	Trend Uncertainty	Central Estimate of Trend	Trend Uncertainty	Scenario 1	Scenario 2	Scenario 4	Scenario 5	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10	Scenario 11	Scenario 12
CO_2	-15,628	13.1%	-17,909	18.1%	4.2%	3.5%	4.6%	3.7%	4.2%	4.1%	N/A	4.6%	1.9%	4.6%	4.6%
CH_4	-6,023	15.8%	-9,785	15.7%	32.5%	27.1%	32.5%	33.1%	27.8%	33.0%	N/A	32.2%	27.9%	28.1%	27.6%
N_2O	-1,878	5.7%	-1,132	14.4%	77.5%	77.9%	78.7%	76.9%	8.2%	78.1%	N/A	77.2%	0.0%	17.6%	10.6%
HFC	1,021	85.8%	1,161	90.6%	236.5%	147.2%	239.6%	235.4%	235.7%	238.0%	N/A	234.7%	19.6%	236.8%	236.2%
PFC	-36	29.2%	-18	49.8%	65.4%	67.6%	64.5%	65.6%	64.4%	64.9%	N/A	64.7%	61.2%	65.7%	66.3%
NF_3	N/A	N/A	N/A	37.1%	66.6%	70.4%	66.5%	66.6%	66.7%	67.4%	N/A	66.5%	66.3%	66.1%	66.5%
SF_6	5	27.1%	0	28.0%	33.5%	20.8%	34.6%	33.9%	33.1%	33.9%	N/A	33.6%	2.8%	33.7%	33.4%
Total	**-22,539**	**10.0%**	**-27,682**	**13.4%**	**9.7%**	**8.4%**	**9.6%**	**9.5%**	**7.0%**	**9.6%**	**N/A**	**9.7%**	**6.5%**	**7.3%**	**7.1%**

Table 8 Summary of Outputs from Uncertainty Models for UK Base Year to 2013 GHG Inventory Trend Uncertainty

Gas (kt CO_2e)	**Base Year to 2012 UK GHG Uncertainties**		**Base Year to 2013 UK GHG Uncertainties (original model)**		**Base Year to 2013 UK GHG Uncertainties: Revised Model**										
	Central Estimate of Trend	Trend Uncertainty	Central Estimate of Trend	Trend Uncertainty	Scenario 1	Scenario 2	Scenario 4	Scenario 5	Scenario 6	Scenario 7[c]	Scenario 8[c]	Scenario 9	Scenario 10	Scenario 11	Scenario 12
CO_2	-130,134	2.5%	-130,595	2.5%	1.3%	1.3%	1.1%	1.3%	1.3%	1.3%	N/A	1.4%	0.5%	1.2%	1.2%
CH_4	-80,846	12.5%	-80,721	12.5%	18.1%	18.2%	18.4%	17.9%	17.3%	18.0%	N/A	18.1%	16.9%	17.3%	17.1%
N_2O	-29,503	36.0%	-29,571	17.3%	48.1%	47.4%	47.1%	48.2%	34.9%	47.5%	N/A	48.1%	0.0%	37.9%	36.0%
HFC	1,723	19.5%	-3,409	8.9%	12.8%	12.8%	12.7%	12.7%	12.9%	12.7%	N/A	12.7%	0.5%	12.8%	12.8%
PFC	-1,399	3.5%	-343	13.5%	19.1%	19.5%	19.0%	19.3%	19.5%	19.2%	N/A	19.1%	15.8%	19.6%	19.8%
NF_3	0.0	65.5%	-0.5	31.7%	50.2%	51.2%	50.8%	50.6%	51.0%	51.0%	N/A	50.4%	49.5%	50.6%	50.2%
SF_6	-677	7.0%	-662	10.4%	4.3%	4.3%	4.4%	4.3%	4.3%	4.3%	N/A	4.3%	0.3%	4.4%	4.3%
Total	**-240,836**	**4.5%**	**-245,301**	**3.9%**	**4.7%**	**4.7%**	**4.6%**	**4.7%**	**4.0%**	**4.6%**	**N/A**	**4.6%**	**2.9%**	**4.1%**	**4.0%**

[a] Blue numbers indicate a greater than 20% decrease in uncertainty compared with the current DA GHG uncertainties model results, red numbers indicate a greater than 20% increase in uncertainty compared with the current DA GHG uncertainties model result

[b] Model outputs for Last year's DA GHG uncertainty model are for 2012 uncertainty

[c] Scenarios 7 and 8 exclude ETS and non-ETS emissions respectively, so these uncertainties are not as a % of national emissions

5.2.1 Scenario 1: Revised Model, Default Data Entry and Assumptions

The 'Current DA GHG uncertainties model' is the result of running the original DA uncertainty model (i.e. used in the 2014 submission for 1990-2012 data) with the 2015 inventory data and revising the approach to account for sources and gases not previously estimated. Therefore the results are *comparable to the UK Approach 2 uncertainties for the 2015 GHGI at the UK level.*

The revised model Scenario 1 represents the project team's main default model set-up and assumptions, incorporating all emission sources, allowing uncertainty parameters of all qualities, including the Scotland-specific uncertainty parameters and distributions for LULUCF and Agriculture, and using the 0.5 emissions sensitivity for emission sources in Energy, IPPU and Waste. This is the scenario against which other runs of the revised model have been compared, in order to test the functionality and sensitivity of the model.

Running the revised model for the UK GHGI and comparing against the UK Approach 2 uncertainty estimates, the Scenario 1 outputs show:

- Methane uncertainty down to 17% of total in 2013 (down from 19% in the UK Approach 2); and
- Nitrous oxide uncertainty down to 44% in 2013 (down from 58% in the UK Approach 2).

These revisions are primarily due to the inclusion of the revised uncertainty values for agriculture sources from Rothamsted Research.

For Scotland the revised model Scenario 1 indicates that the Scottish data are much more uncertain than the UK Data (11% in total for Scotland; 3% in total for the UK), which reflects the much higher influence of the LULUCF uncertainty in the CO_2 inventory for Scotland in particular.

Compared to the previous DA uncertainty model, the revised model Scenario 1 for Scotland indicates higher methane uncertainty and slightly lower nitrous oxide uncertainty, and broadly comparable F-gas uncertainties. The dominant change, however is for CO_2 where the improved Scotland-specific uncertainty parameters (especially for LULUCF) have reduced the uncertainty (from 17% to 11% for CO_2), This dominates the change in overall reported uncertainty to 11% on the Scotland 2013 GHGI total, compared to 14% from the previous model.

This reduction in CO_2 inventory uncertainty is also the main driver behind a reduction in the range of estimated trend uncertainties which under the original model approach was reported as a 35% reduction in GHG emissions between the Base Year and 2013, with a 95% confidence that the change was between -21% and -47% (summarised as a 13.4% uncertainty in the trends in Table 7 above). The revised model Scenario 1 now indicates a 35% reduction in GHG emissions since the Base Year, but now with a narrower range of outcomes within the 95% confidence limits (-26% to -46%), represented as a 9.7% uncertainty in the reported trend.

5.2.2 Scenario 2: Lower Emission Sensitivity

This scenario tests the impacts to model outputs from changes to the 'emissions sensitivity' mentioned in **Equation 2** of the splitting of uncertainties to the DA level. Compared to the default scenario 1 (with 0.5 emissions sensitivity), the change to a lower emissions sensitivity (0.25 emissions sensitivity) leads to a narrower range of DA emission uncertainty estimates applied to each source category (i.e. DAs with a smaller share of emissions will have lower uncertainty parameters, and DAs with a higher share of emissions will have higher uncertainty parameters, relative to Scenario 1).

At UK level this change makes no discernible impact, and the scenario results are very similar to Scenario 1; any differences are merely attributable to small variations in the respective model runs.

As Scotland contributes typically around 10% to UK GHGI emissions, then for many source categories and pollutants under this scenario a lower uncertainty will be applied; the model outputs are consistent with this general view for most pollutants.

The overall uncertainty for Scotland in 2013 is reported as 10.6%, slightly lower than in Scenario 1 (11.1%)and the trend uncertainties for Scenario 2 also shows a slightly lesser range (-27% to -44%) than from Scenario 1 (-26% to -46%).

The difference to Scenario 1 is overall quite small, mainly because the change in emissions sensitivity only affects the uncertainty parameters for Energy, IPPU and Waste; the LULUCF and agriculture uncertainty parameters are unchanged as they are DA-specific and not calculated within the model, and these two sectors have very significant impact on overall Scotland GHGI uncertainty.

5.2.3 Scenario 4: EU ETS Functionality Disabled

Within the default Scenario 1, the model calculations separate out the EU ETS component of Energy and IPPU emission estimates, and then apply specific (lower) uncertainty parameters to account for the rigorous bottom-up data management and reporting that underpins the traded share of the Scotland emissions. This ensures that the lower uncertainty of the EU ETS data is reflected in the overall uncertainty estimates for the Scotland GHGI.

In this scenario, that additional series of calculations is disabled and the model instead applies the calculated default uncertainty parameters across all Energy and IPPU sources, which are simply derived from UK parameters for each AD and EF, and additional DA uncertainty based on the 0.5 emissions sensitivity from the default approach.

The EU ETS data only affect the CO_2 estimates, and this is reflected in the model outputs which show very consistent data for all other pollutants to Scenario 1, but for CO_2 the uncertainties in this scenario are slightly higher at 11.1%, compared to 10.7% in Scenario 1.

The change in the CO_2 uncertainty and overall uncertainty is very small, indicating that the additional calculations to treat the traded emissions in a more detailed way, applying lower uncertainties to that component of the overall inventory, has very little impact on the reported uncertainties. Other scenarios confirm the dominance of LULUCF emissions on the CO_2 inventory uncertainties, and this is reflected here also in the minimal impact that taking a more rigorous approach to high-emitting CO_2 sources in Energy and IPPU has on the model outputs.

5.2.4 Scenario 5: Excluding LULUCF Uncertainties

In Scenario 5 the sensitivity of Scottish GHGI uncertainties to LULUCF is tested by setting all LULUCF uncertainties to zero. This change does not have a noticeable impact on any pollutants except CO_2, which shows in reduction in 2013 inventory uncertainty from 11% to 2.5% in Scotland compared to Scenario 1. This also reduces the overall GHGI uncertainty for Scotland in 2013 from 11.1% to 8.2%.

In addition, the reported trend uncertainty for CO_2 for Scotland from this scenario is slightly lower than for Scenario 1 (a 3.7% range compared to a 4.2% range).

In comparison, when this scenario is run across the UK as a whole, the reduction in overall CO_2 uncertainty is from 2.1% to 1.0%, and the trend uncertainty range is unchanged for CO_2 at -21% to -23%. This illustrates the relative significance to the CO_2 inventory of the LUUCF sector in Scotland.

This scenario confirms that based on the current suite of uncertainty parameter information and correlations available across all sources, that for Scotland the LULUCF sector is by far the most significant reason for the higher than average (across the UK) reported uncertainty for CO_2 emissions.

5.2.5 Scenario 6: Excluding Agriculture Uncertainties

In Scenario 6 the sensitivity of Scottish GHGI uncertainties to agriculture is tested by setting agriculture uncertainties to zero. This change has a very significant impact on the uncertainties estimated for the Scotland 2013 inventories of nitrous oxide and methane, reducing them from 70% to 7% and 30% to 18% respectively in Scotland compared to Scenario 1.

This change also has the biggest impact (of any scenario across the complete inventory of emissions), on the reported trend uncertainties since Base Year for Scotland, most notably reducing the uncertainty in the trend for nitrous oxide to only 8.2%, and an overall GHG trend uncertainty of 7.0% (i.e. a reduction of 35% since Base Year, with a 95% confidence limit range from -29% to -43%).

At UK level, this change also leads to very significant reductions in the reported uncertainty for nitrous oxide, with a 2013 uncertainty of 12% compared to a Scenario 1 figure of 44%. However for methane the impact at UK level is less marked, with only a 2% change down from 17% to 15% uncertainty in 2013 for UK total methane emissions.

The nitrous oxide inventory uncertainties across the UK are dominated by the emissions from agricultural soils, and this is the main reason that the impact of this scenario is so large at both UK and Scotland level. For methane, there are a greater number of high-emitting and uncertain sources within the inventory (e.g. agricultural sources, waste sources, fugitive emissions from fuel production), and therefore the greater impact of this scenario in Scotland indicates the greater relative significance of the agricultural sources to the Scotland inventory in 2013, compared to the UK average. (In 2013, Scotland has over a 17% share of total UK methane emissions, but only a 12% share of waste management methane emissions and less than 10% of energy sector methane emissions.)

5.2.6 Scenarios 7 and 8: Excluding Traded Sector; and Traded Sector Only

In Scenarios 7 and 8 the uncertainties of the EU ETS and non-EU ETS parts of the inventory were assessed separately, with the aim of understanding more clearly the significance of the EU ETS emissions to the carbon dioxide inventory uncertainty.

For both the UK and Scotland, EU ETS emissions comprise around half of CO_2 emissions.

For the traded share of emissions (Scenario 8), at both UK and Scotland-level the estimated uncertainty in the 2013 emissions are low at around 1%. (Scotland is slightly higher at 1.3%, compared to 1.0% across the UK.)

In the UK-wide analysis, the 2013 uncertainty of the CO_2 inventory for the non-traded share (Scenario 7) is only 4%, whereas the equivalent uncertainty for the Scotland non-traded share is much higher at 23%.

These components combine to derive a UK overall uncertainty of around 2%, compared to 11% in Scotland. This outcome reinforces the message that in Scotland the impact of highly uncertain CO_2 emission sources that are outside the EU ETS (i.e. LULUCF sources) are dominating the overall uncertainty analysis, with a relatively minor contribution to overall uncertainty from the high-emitting EU ETS sources.

5.2.7 Scenario 9: Expert Judgement for Energy, IPPU and Waste

This scenario reflects the expert judgement of the project consultees and inventory compilers in assessing the uncertainties for Scotland for Energy, IPPU and Waste sources, without the constraints to be consistent with UK-wide analysis that are inferred via the purely mathematical approach deployed in the “default” Scenario 1.

As such, this scenario represents the project team’s best estimate of the actual level of uncertainties in the Scotland inventory, through a bottom-up analysis for key source categories in Scotland.

The outcome from this scenario is very closely consistent with the Scenario 1 outcome; the 2013 Scotland CO_2 inventory uncertainty estimates are fractionally higher (at 11.0%) than Scenario 1 (10.7%); all other pollutants are closely consistent with Scenario 1, and the overall GHGI uncertainty is 11.2%, compared to 11.1% from the Scenario 1 approach.

Whilst the impacts of the expert judgement for these sources evidently has not greatly affected the outcome from the model, the transparency and quality of the input data for this scenario is regarded as a significant improvement on the purely mathematical approach deployed in Scenario 1 for these sources.

The inputs to Scenario 9 included several revisions to the previous estimates of UK-level uncertainties for AD and EFs, and these led to similarly small differences to the Scenario 1 outputs for the UK; the CO_2 inventory uncertainty at UK level when the expert judgements were included increased from 2.1% to 2.3%. These revisions are recommended to be taken forward into future iterations of the UK GHGI uncertainty model.

5.2.8 Scenario 10: “Good Quality” Uncertainties Only

Scenario 10 draws upon the data quality ratings assigned to each AD and EF uncertainty parameter through the consultation and expert review phase of the project. By testing the model outputs for only the higher-quality uncertainty data (i.e. those based on research, data analysis, and regarded as representative of Scottish emission sources) and setting the lower quality uncertainty parameters to zero uncertainty, the model presents evidence on the effects of data quality on the calculated overall uncertainty in emissions and emission trends.

For Scotland 2013 data, to remove the impact of uncertainties for low quality parameters reduces overall uncertainties (as expected), almost eliminating HFC and SF_6 uncertainties and reducing methane and carbon uncertainties significantly, and reducing the uncertainty contribution from nitrous oxide to zero.

The CO_2 inventory uncertainty is largely unchanged by excluding the lower quality data, as the Scenario 10 figure is 10.5%, compared to 10.7% in Scenario 1. The difference is due to the exclusion of uncertainty from sources rated D and E including a range of combustion sources where there are no Scotland-specific analyses of fuel composition available (especially for petroleum and solid fuels). The majority of the Scotland GHGI uncertainty is retained, as the main contributing sectors (e.g. LULUCF sources and sinks) are based on activity data and parameters / EFs that are predominantly Scotland-specific and do constitute a good evidence-base for the estimates. This reflects the uncertainty, despite good quality data inputs, of the LULUCF models.

Uncertainty in methane emissions is dominated by two sources: landfill (5A) and enteric fermentation (3A), of which only the landfill uncertainty is considered of data quality A-C, which is why we observe uncertainties in Scenario 10 for methane being roughly half of that in Scenario 1.

All major sources of nitrous oxide uncertainty (mostly emissions from soils, but also from livestock manure management and waste water treatment and sludge disposal) are considered to have poor quality uncertainties (i.e. D or E quality ratings). This is primarily due to the lack of a detailed Scotland-specific evidence base to accurately determine EFs from these sources, as in all cases the EFs effectively aim to represent complex processes that have many parameters affecting the emissions (e.g. for agricultural soils, the EF is based on UK-wide research, but the emissions are affected by climate, soil type, timing and scale of N inputs to soil from urea and fertilisers).

Note that the agriculture sector uncertainties have a high quality rating (A) for the activity data component, a low quality rating (D) for the emission factor component (for the reasons of the complex processes being modelled as noted above). There is ongoing research that aims to further improve the EF data quality and may lead to a higher-quality uncertainty rating for the agriculture sector, and this is therefore noted as a key sector to review in future uncertainty analysis for the UK and Scottish inventories.

Of the F-gases, HFC emissions are by far the most significant, and the uncertainty in Scottish (and UK) emissions are dominated by the main source: refrigeration and air conditioning (2F1). These emission estimates are based on a detailed model which has historically had a well-established uncertainty, but the model has not been updated to account for recent changes in legislation (this update is currently in progress). Therefore the current uncertainty quality rating is low (D) for this source, and hence the uncertainty contribution from HFCs in Scenario 10 is a small fraction of that presented in Scenario 1. Once the current research is completed, this is a key source category to review and update in future uncertainty analysis for the UK and Scottish inventories.

5.2.9 Scenario 11: UK GHGI Approach 1 Uncertainties

Scenario 11 tested the impact of using the uncertainties used to the 2015 Approach 1 uncertainty analysis, in part to help understand the difference from the UK model. The main observation is that nitrous oxide uncertainties are very significantly higher than Scenario 1, due to an update to the uncertainty used for agricultural soils being omitted from the Approach 1 uncertainties but included in the Approach 2. Most of the other gas uncertainties are very similar to Scenario 1, which is as expected, as the UK Approach 1 uncertainty parameters were those used in the revised DA uncertainties model.

Hence this scenario really only provides an explanation for why the UK Approach 1 uncertainties are much higher than the Approach 2 uncertainties.

5.2.10 Scenario 12: UK GHGI Approach 1 Uncertainties updated for Agricultural Soils

Finally, to enable a more complete cross-check to the UK Approach 1 analysis, the known difference of the agricultural soils uncertainty revision (evident in Scenario 11) was addressed in the revised DA model. This scenario generates uncertainties that are very close to the default Scenario 1, with just small differences in methane and nitrous oxide due to the impacts of revisions to Scotland-specific uncertainty parameters for sources other than agricultural soils. Overall this scenario provides a useful sense-check between the DA model and the UK Approach 1 data.

5.3 Base Year-2013 Trend Uncertainties

The revised model incorporates new data and assumptions that impact upon the reported trend uncertainties for all GHGs. The key changes and impacts are as follows:

Carbon dioxide

- The uncertainty parameters in Scenario 9 (expert judgement: Energy, IPPU and Waste) include new estimates for the difference in uncertainty for Scottish estimates in 1990 compared to 2013, which better-represents the difference in source data availability across the time series compared to previous models.
- In the previous DA model, there were very few correlations of carbon emission factors across years, which over-stated the trend uncertainties as the CEFs were determined to be independent across years. In the revised model the project team has added correlations for the CEFs, in line with the default approach recommended in the 2006 IPCC GLs.
- ➢ Overall the trend uncertainty for CO_2 is therefore considerably lower than in previous DA uncertainty models.
- Note also that the model indicates that the uncertainty for CO_2 is less in the Base Year (8%) than in the latest year (11%). This reflects the fact that the sources contributing to the Scotland emissions total through the time series are changing. The high-emitting, well-characterised and therefore lower uncertainty sources (e.g. energy industries, heavy industry) are generally declining in significance in the overall Scotland inventory, whereas the more uncertain sources and sinks of LULUCF are a much more significant component of the Scotland CO_2 inventory in 2013 than in 1990.

Methane

- The revised model includes new uncertainty parameters for landfill methane emissions, which are higher uncertainties than previously used, based on the latest analysis of source data and in spite of recent inventory improvement projects. The uncertainties are also not correlated between DAs or across years for this source.
- ➢ Overall the trend uncertainty for CH_4 is therefore higher than in previous DA uncertainty models.

Nitrous Oxide

- The revised model includes new uncertainty distributions that are customised for Scotland (and the UK) for emissions of nitrous oxide from agricultural soils, and the model does not include any consideration for correlation of the EF across years for this source.
- ➢ The results for the UK Approach 2 model and also the revised Scotland GHGI uncertainty model both now show significantly higher uncertainty in the reported trend uncertainties since Base Year.
- Note that the project team has tested the impact of adding in a high correlation across years for the agricultural soils EF for nitrous oxide, and the result is a much narrower range in trend uncertainties (~10% uncertainty compared to ~77% in the revised model without correlations). As there is further work ongoing within Rothamsted on the EFs and methods used to derive UK and Scotland GHGI estimates, at this stage the project team has opted to retain the more conservative approach to deriving trend uncertainties for this source.

5.4 2012-2013 Trend Uncertainties

The model re-design enables 2012-2013 trend uncertainties to be derived. However, the results (from all scenarios) are such that the range of possible outcomes is so great relative to the actual reported trend in emissions for the one year period, that they are not worth detailed examination.

For example, the Scenario 1 trend in 2012 to 2013 emissions is a 4% reduction in total GHGs, with a 95% confidence that the change in emissions is within the range +6% to -14%. Scenario 9 (including expert judgement for Energy, IPPU and Waste) gives an identical result, as does Scenario 5 (excluding LULUCF). The most notable feature is that for 2012-2013, the Scenario 6 (excluding agriculture) has a notably narrower range, with -4% (0% to -8% range).

6 Summary and Next Steps

6.1 Summary of Project Findings

The project has delivered a new DA GHG uncertainties model which has been designed to manage DA uncertainties in a systematic and consistent manner and accounting for the fact that the DA inventories are derived from the UK GHG inventory uncertainties model.

Additional functionality has been introduced to separate emission estimates from EU ETS sources; the model testing has indicated, however, that the traded emissions contribution to overall GHG inventory uncertainty for Scotland is very small, despite the high contribution of EU ETS to reported GHG emissions in Scotland in recent years.

There have been a number of changes to the UK GHGI over the last year, particularly due to the change in reporting guidance to use the 2006 IPCC GLs. As a consequence the relative significance of specific greenhouse gases has changed within the UK and Scottish inventories and the UK uncertainties parameters have recently been reviewed and updated; these changes to UK parameters have now been integrated into the DA updated uncertainties model.

In addition, the uncertainty distributions for Scotland (AD and EFs for all key categories) have been reviewed in detail through consultation with key data providers and inventory compilers, including a detailed analysis of Scotland-specific uncertainty parameters and distributions for agriculture and LULUCF sources, which continue to dominate total Scottish GHGI uncertainties.

The key project outputs are:

- ✓ Improved model design that allows for easier editing, manipulation and scenario generation, and has been verified by experts not directly involved in model design and project implementation.
- ✓ Improved model design to enable consideration of traded and non-traded emissions
  - ➢ Including specific uncertainty parameters that account for the requirements placed for different tiers on EU ETS installations for accuracy of reporting
  - ➢ Allows for the exclusion of traded or non-traded emissions from the analysis
- ✓ The model design allows for the allocation of 'data quality ratings' to uncertainty parameters
  - ➢ Allows the user to focus on well understood uncertainties, by setting the poorly understood uncertainties to 0, and to assess where poor quality data are impacting on the inventory uncertainty estimates
- ✓ Improved model design to enable consideration of latest annual trend uncertainties (e.g. "2012-2013 trend")
- ✓ Model will now generate "default" activity uncertainties for each DA based on the relative spread of emissions and the UK activity uncertainty
  - ➢ This treats all DAs in the same way and as a part of the UK GHGI
  - ➢ Allows experts to focus efforts on key source categories and on cases where the default may not be appropriate
- ✓ Integration of new Scotland-specific uncertainty parameters and uncertainty distributions for key source categories
- ✓ Improvement of UK uncertainty parameters for several source categories and activities
  - ➢ Includes the revision of UK uncertainty parameters to account for improvements to the 2015 UK GHGI and the change of reporting guidelines
- ✓ More accurate and lower estimates of uncertainty for Scottish GHG emissions, and a narrower range of "Base year to latest year" GHG trend outcomes.
  - ➢ Scenario 9 as presented in the Results chapter is regarded as the best estimate of the Scottish GHGI uncertainties, which indicates an 11% uncertainty on 2013

Scotland GHGI emissions, with a trend since the Base Year of -35% (-26% to -45% range).

6.2 Recommendations for Future Work

The project has enabled significant improvement to the structure and transparency of the uncertainty model for Scotland (and other DAs), but further work could be implemented to address remaining challenges:

- Further analysis is recommended to assess the impact of using loglogistic or beta distributions instead of lognormal distributions which may reduce the impact of extreme values affecting the model outputs;
- Rothamsted Research and the Centre for Ecology and Hydrology have provided Scotland-specific uncertainties and distributions based on the latest available research; both Rothamsted and CEH have ongoing inventory improvement programmes, and hence estimates of uncertainties should be revisited as new data and methods are used within the UK and DA inventories. Priorities to address are nitrous oxide emissions from agricultural soils and CO_2 emissions from LULUCF;
- The uncertainty parameters and quality ratings for HFC emissions should be revised once the ongoing study to update the Refrigeration and Air Conditioning model is finalised;
- Improvements to the uncertainty calculations for Wales, Northern Ireland and England can be integrated to the revised model. Further work is needed to identify and include the DA-specific uncertainty parameters and distributions for key source categories in these other countries;
- The UK GHGI uncertainty model should be revised in the next inventory cycle to incorporate some of the findings of this research, including the revision to uncertainty parameters for UK-level AD and EFs that have been identified through consultation and expert review;
- For the most GHG emission sources it is reasonable to assume that for high percentage uncertainties a non-normal distribution should be used, i.e. a distribution that restricts results to being strictly positive. However, as LULUCF includes both sources and sinks within the source estimation methods and models, it may be more appropriate to use a normal distribution in cases where there is a high percentage uncertainty. Alternatively it may be possible to derive source/sink-specific distributions and standard deviations rather than a percentage uncertainty figure.

7 References

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