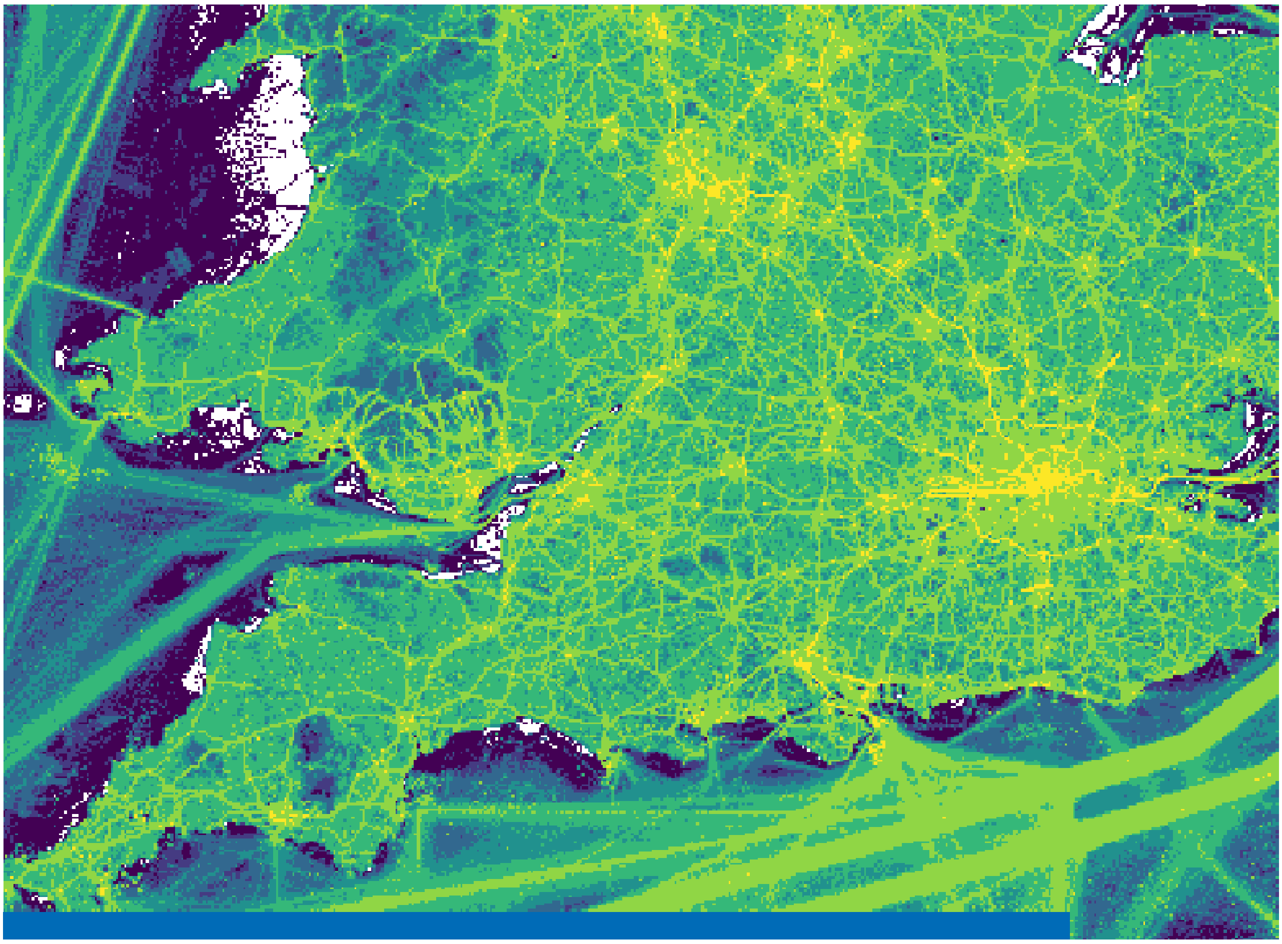

National Atmospheric Emissions Inventory

UK Spatial Emissions Methodology

A report of the National Atmospheric Emission Inventory 2019

Prepared by Ricardo Energy & Environment for Department for Business, Energy and Industrial Strategy; Department for Environment, Food and Rural Affairs; The Scottish Government; Welsh Government; Department of Agriculture, Environment and Rural Affairs for Northern Ireland

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List of Abbreviations

AADF	Annual Average Daily Flow
ANPR	Automatic Number Plate Recognition
BEIS	Department for Business, Energy and Industrial Strategy
BRES	Business Register and Employment Survey
BSOG	Bus Service Operators Grant system
CEH	Centre for Ecology & Hydrology (now called UK CEH)
CLRTAP	Convention on Long-range Transboundary Air Pollution
DAERA	Department of Agriculture, Environment and Rural Affairs
DUKES	Digest of UK Energy Statistics
Defra	Department for Environment, Food and Rural Affairs
DfI	Department for Infrastructure
DfT	Department for Transport
DVLA	Driver and Vehicle Licensing Agency
E-PRTR	European Pollutant Release and Transfer Register
EA	Environment Agency
ECUK	Energy consumption in the UK
EEMS	Environmental and Emissions Monitoring System
EMEP	European Monitoring and Evaluation Programme
ETS	Emissions Trading System[1]
GHGs	Greenhouse Gases
GIS	Geographic Information Systems
GNFR	Gridded Nomenclature for Reporting
HGVs	Heavy goods vehicles
IDBR	Inter-Departmental Business Register
IGER	Institute of Grassland and Environmental Research
IPC	Integrated Pollution Control
IPPC	Integrated Pollution Prevention and Control
LA	Local Authority
LAPC/APC	Local Authority Pollution Control/Air Pollution Control
LGVs	Light goods vehicles
LPG	Liquid Petroleum Gas
LSOA	Lower Layer Super Output Area
MAAQ	Defra's Modelling of Ambient Air Quality
MCGA	Maritime and Coastguard Agency

[1] The UK participated in the EU ETS until 31 December 2020. This was then replaced with the UK Emissions Trading Scheme From 1 January 2021.

MMR	Monitoring Mechanism Regulation
MSOA	Middle Layer Super Output Area
MSW	Municipal Solid Waste
NAEI	National Atmospheric Emissions Inventory
NECR	National Emissions Celling Regulations
NFR	Nomenclature for Reporting
NIPI	Northern Ireland Pollution Inventory
NISRA	Northern Ireland Statistics and Research Agency
NMVOC	Non-Methane Volatile Organic Compounds
NO_x	Nitrogen Oxides
NRS	National Records of Scotland
NRW	Natural Resources Wales
ONS	Office for National Statistics
OS	Ordnance Survey
OSNI	Ordnance Survey of Northern Ireland
PCM	Pollution Climate Mapping
PM	Particulate Matter
SECA	Sulphur Emission Control Area
SEPA	Scottish Environment Protection Agency
SIC	Standard Industrial Classification
SMMT	Society of Motor Manufacturers & Traders
SNAP	Selected Nomenclature for reporting of Air Pollutants
SPRI	Scottish Pollutant Release Inventory
TfL	Transport for London
TRL	Transport Research Laboratory
UKPIA	UK Petroleum Industries Association
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
VKM	Vehicle kilometres
WEI	Welsh Emission Inventory

Executive summary

This report describes the methods used to map emissions in the National Atmospheric Emissions Inventory (NAEI). The maps provide spatially resolved modelled estimates of emissions compiled at 1x1km resolution for each SNAP[2] sector. One set of maps is produced for the most recent inventory year, as the inventory is reported two years in arrears, so maps for 2019 have been produced this year. The mapped emissions data are made freely available on the NAEI website at: https://naei.beis.gov.uk/data/mapping.

The geographical distribution of emissions across the UK is built up from several data sources and methods that are individually tailored to each sector. For large industrial and commercial sources, emissions are compiled based on data from a variety of official UK regulatory sources. For diffuse emission sources, distribution maps are generated using appropriate surrogate statistics that indirectly indicate the spatial distribution of emissions for each sector. The method used for each source sector varies according to the data available.

Emissions maps are a crucial evidence base supporting a variety of Government policy support work at the national level. In particular, the maps are used as input into a programme of air pollution modelling studies. They also provide a spatial overview of emissions and are used to compile, and report gridded emissions to the United Nations Economic Commission for Europe (UNECE) Convention on Long-Range Transboundary Air Pollution (CLRTAP). Local area statistics are compiled from the maps and related data as well. For example, carbon dioxide emissions from fuel use at the Local Authority level have been produced for Defra and BEIS since 2005 using data from the NAEI's mapping work. As of March 2008, these datasets were designated as National Statistics. In addition, the emission maps provide an illustrative and intuitive way for engaging with non-technical audiences who may wish to find out about emissions in their area.

Uncertainty analyses have been undertaken to consider the accuracy of the emission maps for some of the major air quality pollutants and greenhouse gases. Quality ratings have been used for this purpose. The pollutants with the highest quality ratings have a large proportion of their emissions from point sources, whereas pollutants with a greater proportion of their emissions from area sources have lower quality ratings.

The distribution of emissions presented in the NAEI maps has been verified for key pollutants which are used in UK scale air quality modelling.

[2] Selected Nomenclature for reporting of Air Pollutants

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1 Introduction

The UK National Atmospheric Emission Inventory (NAEI) and Greenhouse Gas Inventory (GHGI) are compiled by Ricardo Energy & Environment on behalf of the Department for Business, Energy and Industrial Strategy (BEIS), the Department for Environment Food and Rural Affairs (Defra), the Scottish Government, the Welsh Government, and the Department of Agriculture, Environment and Rural Affairs (DAERA) for Northern Ireland. This report describes the methodology used to compile spatially disaggregated emissions maps at a 1x1km grid resolution under the NAEI system.

The NAEI is the reference for air emissions in the UK and provides annual estimates for a wide range of important pollutants including air quality pollutants, greenhouse gases, pollutants contributing to acid deposition and photochemical pollution, persistent organic pollutants and other toxic pollutants such as heavy metals. A spatially disaggregated inventory is produced each year using the latest version of the national inventory.

A series of reports describing the methods used for calculating national total emission estimates under the NAEI and other outputs of the inventory system are published annually on the NAEI website at naei.beis.gov.uk/reports. These includes the Informative Inventory Report (IIR) and Greenhouse Gas National Inventory Report (NIR), which present detailed information on the methodologies, emission estimates and trends for air quality pollutants and greenhouse gas emissions, respectively.

1.1 Emission mapping scope and purpose

Emission maps are routinely produced within the NAEI for the 33 pollutants[3], listed below

Table 1-1 Pollutants mapped in the NAEI

1,3-butadiene	Nitrous oxide
Benzene	Methane
Carbon monoxide	Arsenic
Carbon dioxide (CO_2)	Cadmium
Particulate Matter (PM_{10} $PM_{2.5}$ PM_1 & $PM_{0.1}$)	Chromium
Nitrogen Oxides (NO_x)	Copper
Non-Methane Volatile Organic Compounds	Lead
Sulphur dioxide (SO_2)	Mercury
Ammonia	Nickel
Benzo[a]pyrene	Selenium
Benzo[b]fluoranthene	Vanadium
Benzo[k]fluoranthene	Zinc
Indeno[123-cd]pyrene	Black Carbon
Dioxins	Polychlorinated biphenyls
Hydrogen chloride	Hexachlorobenzene

The maps provide modelled estimates of the distribution of emission at a 1x1km resolution and are aggregated to UNECE sectors using the Selected Nomenclature for reporting of Air Pollutants (SNAP). The SNAP reporting sectors used are shown in Table 1-2 below. Data for large point sources are reported separately.

[3] 29 pollutants plus 4 particulate matter size fractions.

Table 1-2 UNECE Emissions Sectors Classification

UNECE Sector Code	Description
1	Combustion in energy production and transfer
2	Combustion in commercial, institutions, residential and agricultural sectors
3	Combustion in industry
4	Production process
5	Extraction / distribution of fossil fuels
6	Solvent use
7	Road transport
8	Other transport and machinery
9	Waste treatment and disposal
10	Agricultural, forests and land use change
11	Other sources and sinks

Mapped emissions are made freely available in ASCII file format on the NAEI website at naei.beis.gov.uk/data/map-uk-das. The maps are also available through an online interactive GIS tool at naei.beis.gov.uk/emissionsapp. Both formats provide a valuable resource for user groups interested in local air quality and greenhouse gas emissions:

- The maps are frequently used as a starting point in the compilation of local emission inventories, which may then be used to assess the status of current and future air quality;
- Emission estimates for point sources and emissions arising from the surrounding area are used in modelling studies as part of Environmental Impact Assessments.

The emission maps provide an important evidence base that is used to support a variety of policies at UK and Devolved Administration (DA) Government scales. In particular, spatially disaggregated emission estimates (1x1km) and road link-specific emissions information from the NAEI are used annually to underpin Defra's modelled air quality data[4]. These models are incorporated into the UK's national air quality compliance assessments that are published by Defra.

They are also used to compile and report on emissions as part of the UK's commitment to the UNECE Convention on Long-range Transboundary Air Pollution (CLRTAP). Under this reporting convention UK emissions are aggregated to the prescribed nomenclature for reporting sectors (NFR and GNFR sectors) and mapped to a 0.1º x 0.1º Long/Lat EMEP Grid spatial resolution in a geographic coordinate system (WGS84). The last submission was in May 2021 and these datasets are available through the WebDab emission database[5].

Local area statistics are also compiled from the maps and related data e.g. the Local Authority data on carbon dioxide emissions[6] and fuel use[7] which have been produced for Defra, BEIS and DA's since the 2005 release. These datasets were classified as National Statistics subject to implementing a small number of requirements across the range of BEIS statistics[8].

[4] http://uk-air.defra.gov.uk/data/modelling-data
[5] http://www.ceip.at/webdab-emission-database/
[6] https://www.gov.uk/government/collections/uk-local-authority-and-regional-carbon-dioxide-emissions-national-statistics
[7] https://www.gov.uk/government/collections/sub-national-consumption-of-other-fuels
[8] https://uksa.statisticsauthority.gov.uk/wp-content/uploads/2015/12/images-report3prioritiesfordesignationasnationalstatistics6january2009_tcm97-25304.pdf

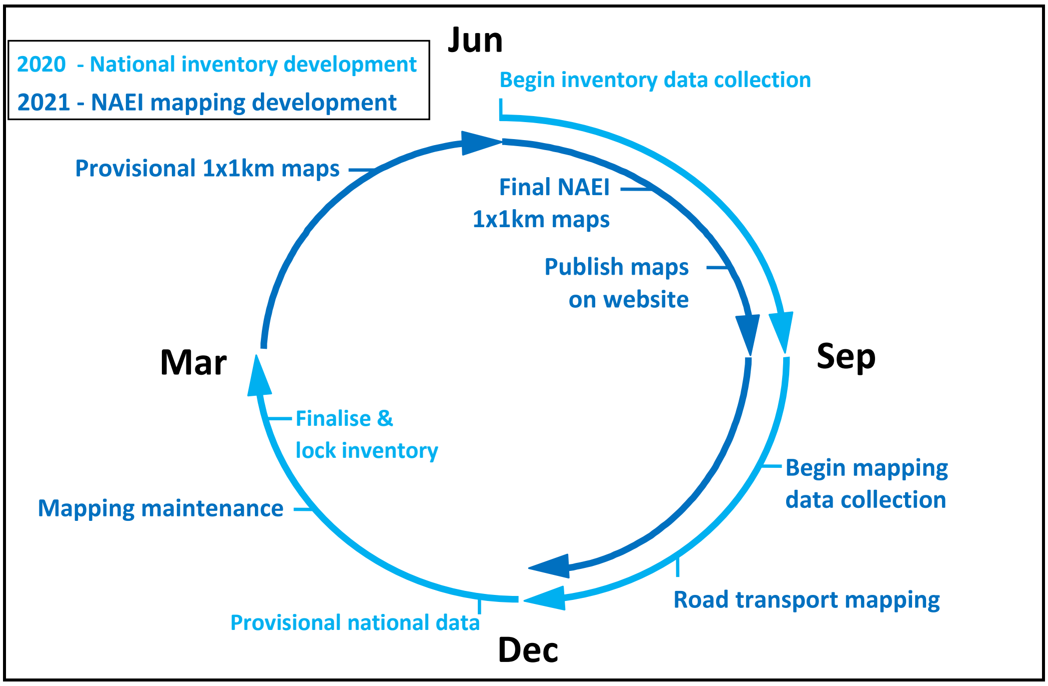
1.2 Annual cycle of map compilation

The NAEI is compiled two years in arrears on an annual basis. Each year the full inventory time-series (1990 – latest inventory year) is recalculated to take account of improved data inputs and any advances in compilation methods. Updating the full time-series is an important process as it ensures that the entire dataset is calculated using the latest methodology. National totals and temporal trends are reported under the UK National Emissions Ceiling Regulation 2018 (NECR)[9], EU Monitoring Mechanism Regulation (MMR), UNECE, UNFCCC and other international commitments.

Emissions maps are routinely compiled for only the latest year in the NAEI time-series. Hence, in general, there is no consistent time-series in spatially disaggregated emissions maps[10]. However, since 2006, a time-series relative to a 2005 base year has been calculated for CO_2 end-user emission maps and sub-national energy consumption estimates. These maps and datasets were developed to support national policy on energy consumption and carbon emissions on behalf of BEIS. There is a commitment in future years to back-calculate the emissions maps for end-user CO_2 and fuel use to take into account improvements in mapping methodology and to ensure that a comparable time-series starting in 2005 is always maintained.

The maps are compiled after the inventory is finalised in March each year. This annual cycle of activity is represented schematically in Figure 1-1.

Figure 1-1 The 2019 NAEI mapping cycle



[9] The NECD has been transposed into UK law via the 232/2018 -European Union (National Emission Ceilings) Regulations 2018, see The National Emission Ceilings Regulations 2018 (legislation.gov.uk)
[10] Archived emissions data are available here: https://naei.beis.gov.uk/data/mapping-archive

2 National Inventory Compilation

The NAEI compiles emissions for several individual sectors producing a detailed and accurate estimate of emissions across the UK. For each sector a national total estimate is produced from a combination of emissions defined by reported activity data and emission estimates based on modelling. For example, minor road traffic emissions are modelled from regional flow and fleet mix data, while emissions from commercial & public sectors described by an employment-based energy consumption model adjusted by recorded levels of gas consumption.

The NAEI obtains most of its data on fuel consumption from the Digest of UK Energy Statistics (DUKES). National totals based on these data are further refined for the industrial and energy generation sectors taking into account other more detailed data from the regulators of industrial processes: the Environment Agency (EA), the Scottish Environment Protection Agency (SEPA), Natural Resources Wales (NRW) and the Department of Agriculture, Environment and Rural Affairs Northern Ireland (DAERA). Data from the returns under the greenhouse gas Emissions Trading System (ETS) are also used.

Emission estimates are calculated by applying an emission factor to an appropriate activity statistic:

$$\textit{Emission} = \textit{Emission Factor} \times \textit{Activity Data}$$

An emission factor is defined as the average emission rate of a given pollutant for a given source, relative to units of activity. These are generally derived from: measurements made on various sources representative of an emission sector; the concentrations of elements in fuels burnt – represented in an emission factor; or, stoichiometric or empirical relationships between emissions and specific activities. Examples of emission factors include the amount of NO_x emitted from a car per kilometre it travels and the amount of SO_2 emitted from a power station per tonne of coal burned.

Activity statistics are obtained from Government statistical sources, such as DUKES[11] and Transport Statistics Great Britain[12] alongside those from organisations such as trade associations and research institutes. For example, the UK Petroleum Industries Association (UKPIA) provides data on the sulphur content of fuels, and the Institute of Grassland and Environmental Research (IGER) provides data on livestock numbers and fertiliser usage.

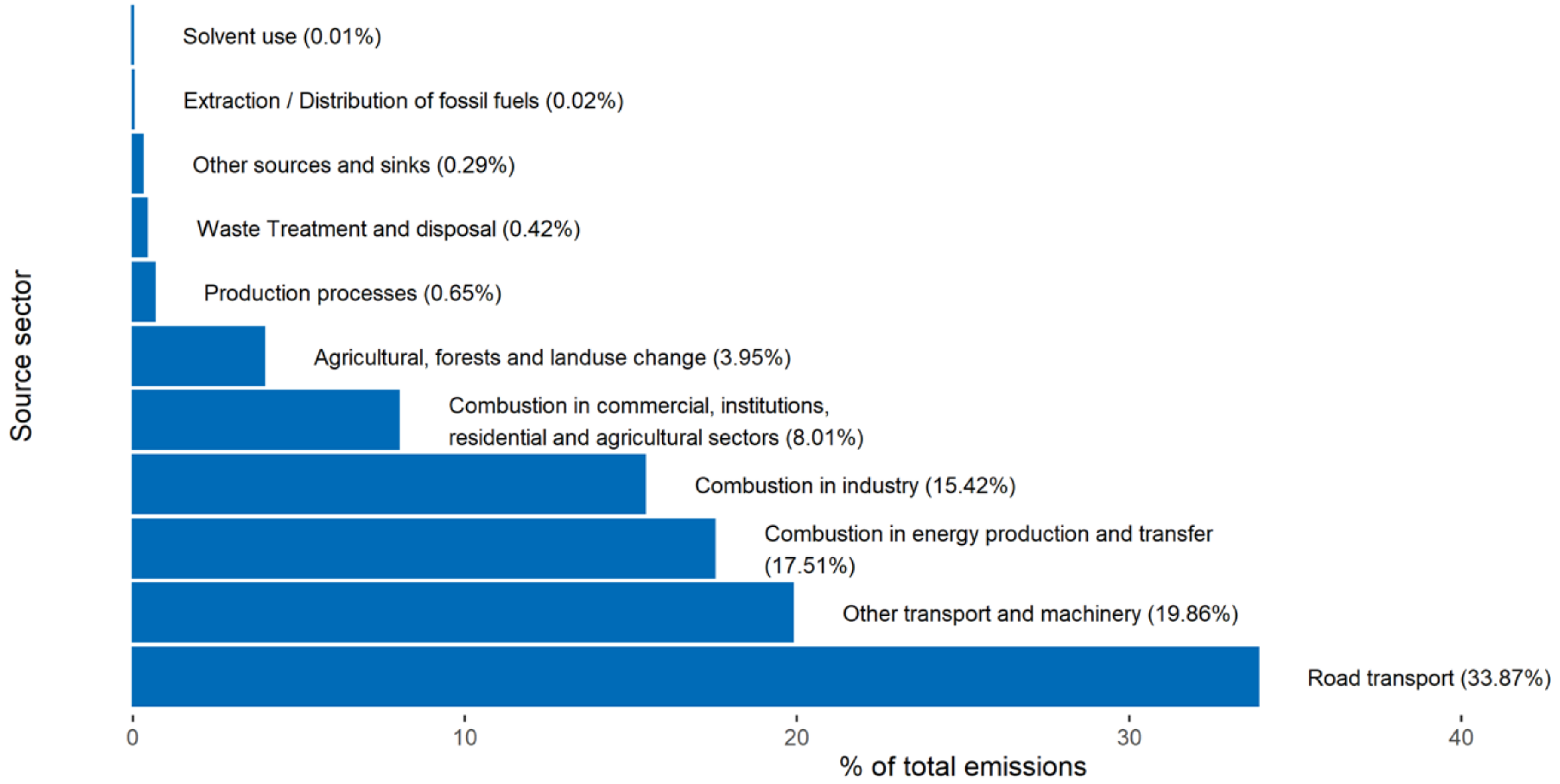
Emissions of NOx in 2019 for the NAEI source sectors is presented in Figure 2-1, and a map of the total NO_X emissions is shown in Figure 2-4. Emission estimates of NO_X are in fact compiled in considerably more detail than this. The NO_X inventory will be used throughout this report as an aide to illustrate the mapping methods used.

Figure 2-2 and Figure 2-3 illustrate how the relative contribution of emissions from different sectors varies by pollutant. The UK Informative Inventory Report (Richmond, et al., 2021) and Greenhouse Gas Inventory Report (Brown, et al., 2021), provide details of emissions by sector at a national level.

Figure 2-4 shows the spatial distribution of UK total NO_X emissions in 2019. As well as emissions from sources on mainland UK, emissions from shipping routes are also visible.

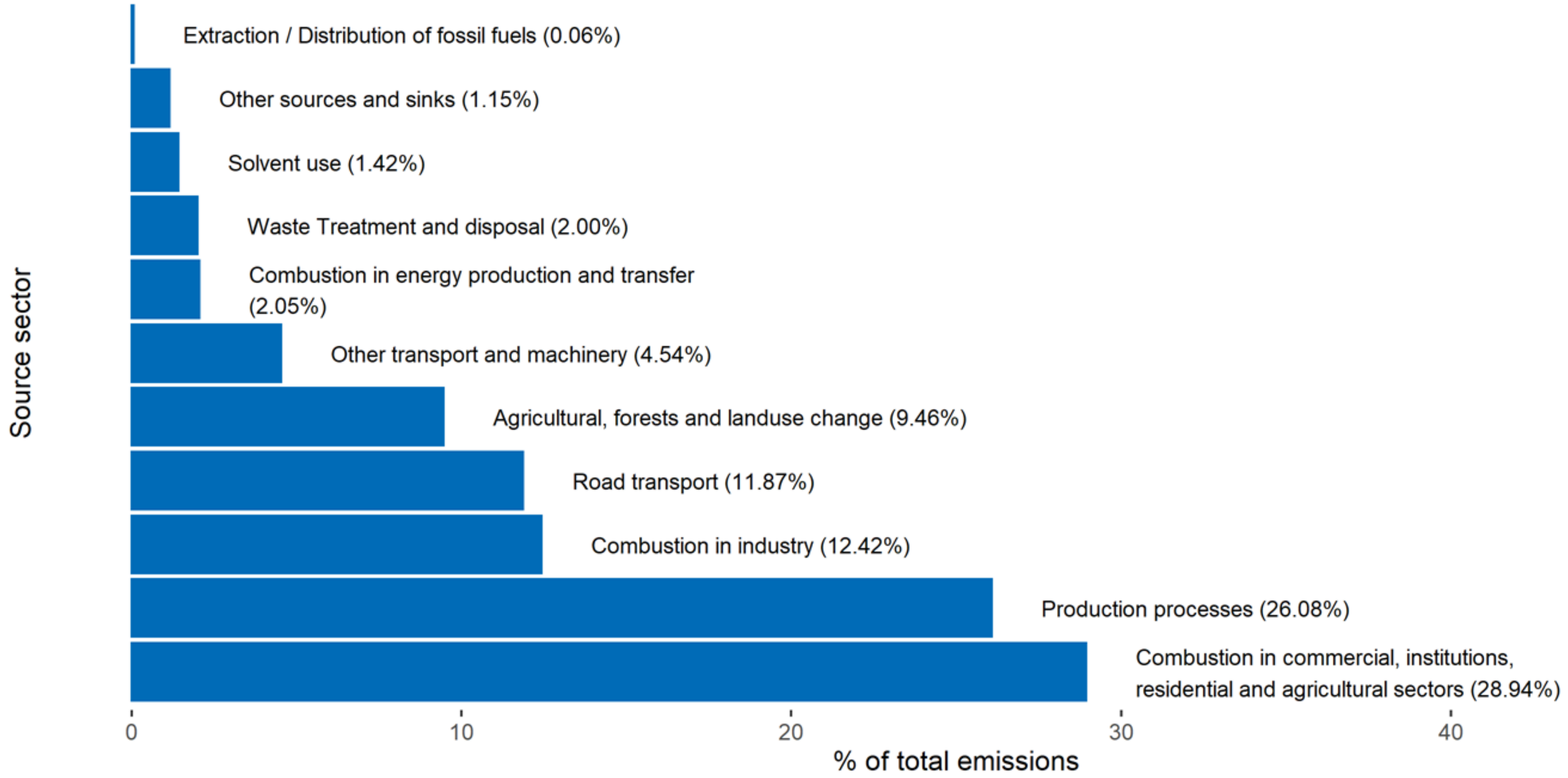
[11] https://www.gov.uk/government/collections/digest-of-uk-energy-statistics-dukes
[12] https://www.gov.uk/government/statistics/transport-statistics-great-britain-2019

Figure 2-1 NO_X Emissions in 2019 by UNECE Source Sector as shown on the NAEI 1x1km maps [13]



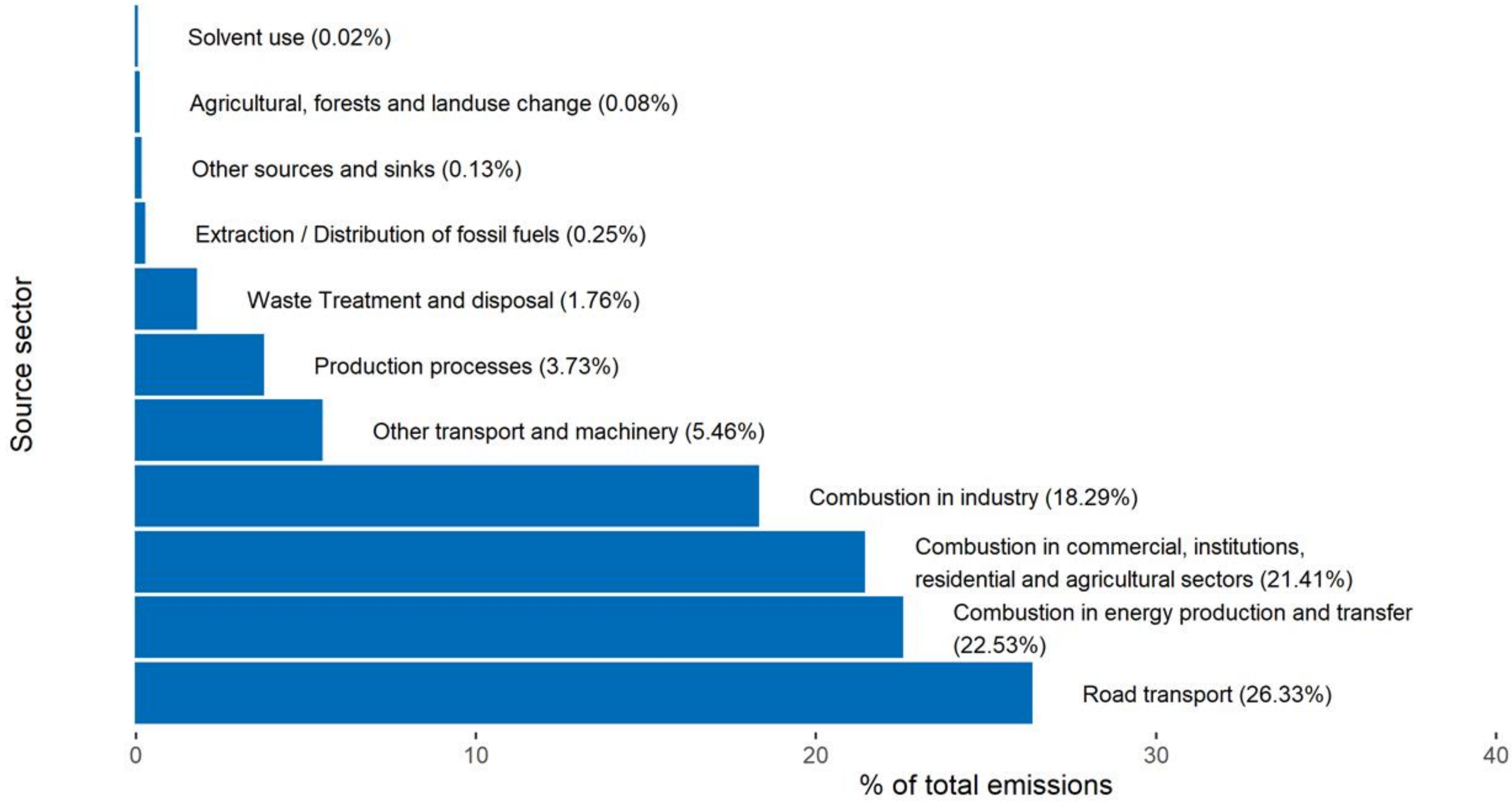
[13] Includes emissions from shipping activity outside the UK territory, but within the extent of the emission maps as published. These emissions are not included in the national totals.

Figure 2-2 PM$_{10}$ Emissions in 2019 by UNECE Source Sector as shown on the NAEI 1x1km maps [14]



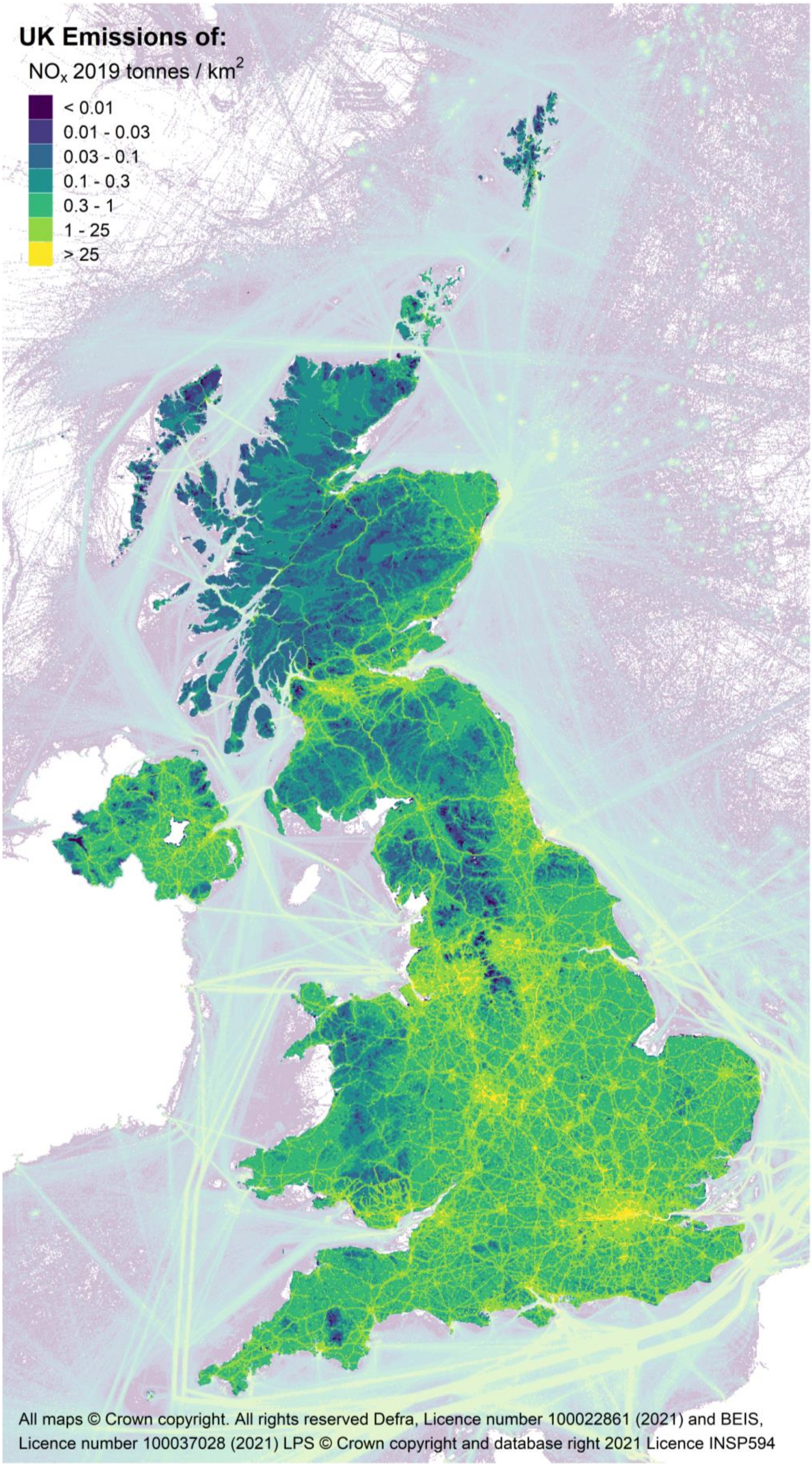
[14] Includes emissions from shipping activity outside the UK territory, but within the extent of the emission maps as published. These emissions are not included in the national totals.

Figure 2-3 CO_2 Emissions in 2019 by UNECE Source Sector as shown on the NAEI 1x1km maps [15]



[15] Includes emissions from shipping activity outside the UK territory, but within the extent of the emission maps as published. These emissions are not included in the national totals.

Figure 2-4 UK total NO_X emissions in 2019



3 Methods for calculating emission distributions

A spatial characterisation of emission distributions across the UK is built up from several component distributions for each NAEI emission sector. These individual sectoral distributions are developed using statistics appropriate to each sector. For large industrial 'point' sources, emissions are compiled from detailed official sources prepared by the EA, SEPA, NRW, DAERA and Local Authorities. These enable both the geographic location and the magnitude of the emissions to be characterised. For other smaller and more widely distributed sources, known as 'area' sources, less detailed information on the location and magnitude of emissions is available. For these sources, a map of the distribution of emissions is generated using appropriate surrogate statistics at a sector level. The method used for each source sector varies according to the data available. Table 3-1 presents the types of mapping distributions used for each of the UNECE sectors (described in Table 1-2) within the NAEI. The mapping methods used to develop these distributions are explained in the following sections.

Table 3-1 Methods used to map emissions in each of the 11 UNECE emission sectors

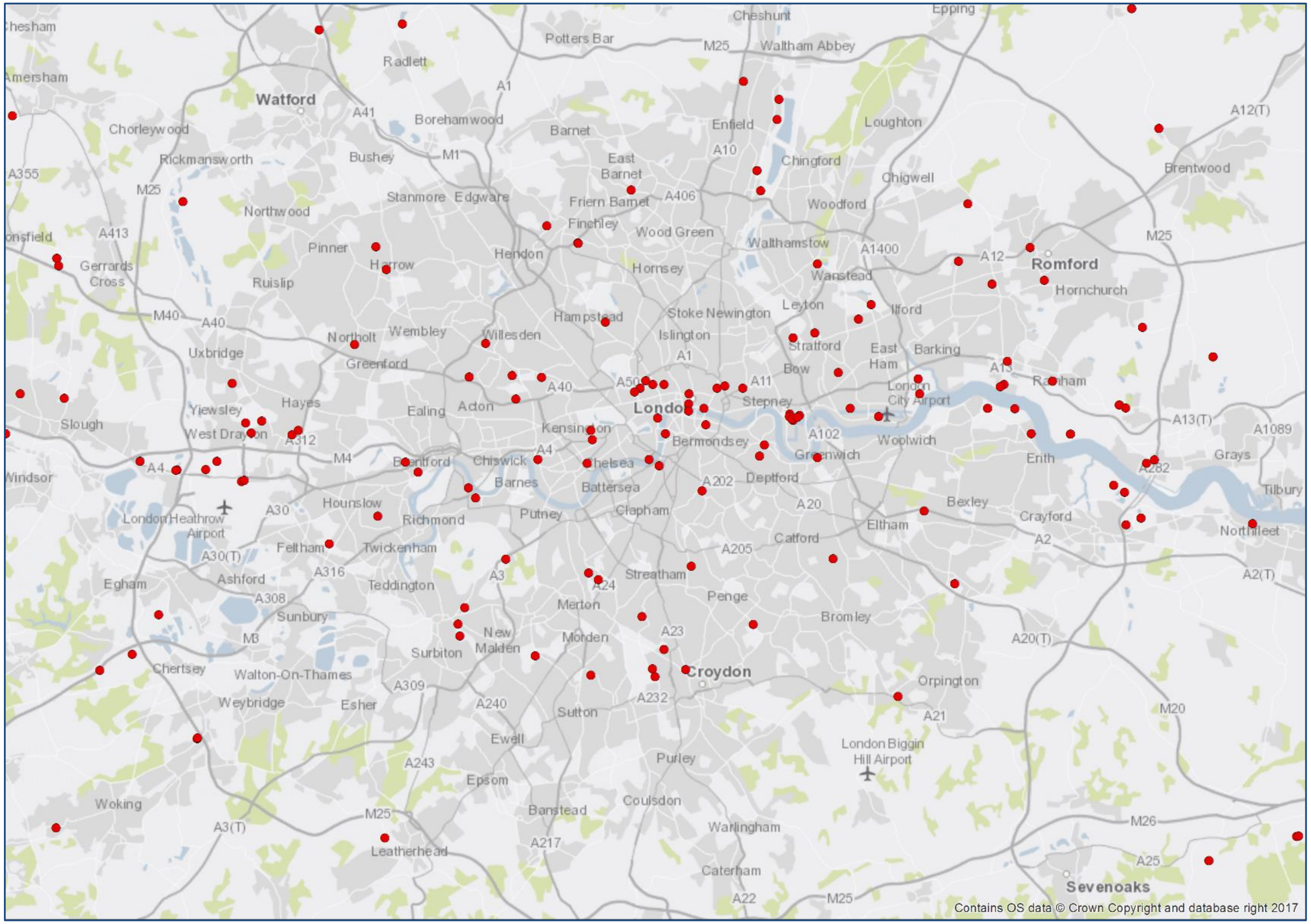
Source sector and method	Report Section	UNECE Emission Sectors[16]										
		1	2	3	4	5	6	7	8	9	10	11
Accidental fires	Section 3.11 (35)									✓		✓
Agriculture	Section 3.5 (p.28)								✓		✓	
Airports	Section 3.9 (p.34)								✓			
Domestic	Section 3.4 (p.24)		✓			✓						
IDBR[17] agriculture	Section 3.2 (p.14)		✓									
IDBR[16] commercial & public	Section 3.2 (p.14)		✓									
IDBR[16] employment	Section 3.2 (p.14)	✓	✓	✓	✓		✓		✓	✓		
IDBR[16] industry	Section 3.2 (p.14)			✓								
Landfill	Section 3.12 (p.35)									✓		
Offshore	Section 3.13 (p.36)	✓				✓				✓		
Other	Section 3.14 (p.37)				✓	✓			✓			✓
Point Sources	Section 3.1 (p.9)	✓	✓	✓	✓	✓	✓			✓		
Population	Multiple Sections				✓	✓	✓		✓			✓
Rail	Section 3.6 (p.28)								✓			
Road transport	Section 3.3 (p.16)				✓			✓				
Shipping	Section 3.7 (p.29)				✓				✓			

3.1 Industrial and commercial sources

The NAEI receives detailed data on individual point sources in the industrial and commercial sector. A point source is an emission source at a known location, which has grid references and therefore it can be mapped directly; see illustrative example for London area Figure 3-1. Point sources across the UK may be either collectively responsible for the total emission for that sector (such as coal-fired power stations, where the sector is made up solely of large operational facilities, for which emission reporting is mandatory), or in part (such as combustion in industry, for which only the larger combustion plants within the sector are required to report emissions). In the latter case, the residual emission (i.e. the portion of the national total emission not released by installations represented by point sources) is mapped as an area source.

[16] SNAP https://www.ceip.at/fileadmin/inhalte/ceip/00_pdf_other/nfr09_snap_gnfr.pdf
[17] IDBR Inter-Departmental Business Register

Figure 3-1 Illustration of industrial and commercial NAEI point sources in the London area



Point source emissions are compiled using a variety of different data sources and techniques. For convenience, the point source data can be divided into four groups:

1. Point sources regulated by the Environment Agency, Scottish Environment Protection Agency, Natural Resources Wales and the Northern Ireland Environment Agency, which are processes regulated under the Industrial Emissions Directive (IED). Data for these point sources are made available to the NAEI in the form of the Environment Agency's Pollution Inventory (PI), the Scottish Environment Protection Agency's Scottish Pollutant Release Inventory (SPRI), Natural Resources Wales' Welsh Emissions Inventory (WEI) and the Northern Ireland Pollution Inventory (NIPI). Some additional information for some of these regulated processes is made available directly from process operators or trade associations;
2. Point sources registered with and trading emission credits under the EU-Emissions Trading System (EU ETS);
3. Point sources regulated under Local Authority Pollution Control/Air Pollution Control (LAPC/APC) in England and Wales, and in Scotland respectively, for which emissions data are estimated by Ricardo Energy & Environment based on site-specific data collected from regulators. Some sites that were once regulated under LAPC/APC are now covered by IED and for these, some emissions data are available via the European Pollutant Release and Transfer Register (E-PRTR);
4. Point sources where emissions are modelled by distributing national emission estimates over the known sources based on capacity or some other 'surrogate' statistic.

For emissions included in group 1 above, the most important sources of information are the various regulators' inventories. The largest of these data sets is the PI, which includes emissions data for most pollutants covered by the NAEI. The PI covers processes regulated by the Environment Agency in England including those regulated under the IED. It does not include any data on processes regulated by local authorities. Reporting of emissions started in 1991 and is conducted annually. The completeness of reporting for the largest point sources is very high from the late 1990s onwards. From 1998 onwards, emission reporting is only required where emissions exceed a 'reporting threshold', e.g. for carbon monoxide the reporting threshold in 2003 was 100 tonnes and this means that some point sources do not have to report emissions. The reporting thresholds mean that data can be much more limited for sectors that consist mainly of medium rather than large industrial operations (for example industrial combustion) where it is far more likely that emissions will be below the reporting threshold.

The SPRI was first compiled for 2002 and from 2004 onwards it was compiled annually. As with the PI, process operators do not need to report emissions which are below reporting thresholds.

The WEI covers sites regulated under IED in Wales. These sites were once included in the PI, but responsibility for compiling the Welsh data now rests with Natural Resources Wales. Data for Welsh sites extends back to 1991 (in the WEI and in historical versions of the PI) and the same reporting thresholds apply as in the PI.

The NIPI contains annual data from 1999 onwards and the same reporting thresholds apply as in the PI.

The E-PRTR contains much data which replicates what is in the regulators' inventories and so E-PRTR is not used as a source of additional information on processes regulated by the national regulators. It is, however, used as a source of information for a small number of processes regulated by local authorities (see below for further information).

The regulators' inventories do not contain emissions data for every potential release from permitted processes. Operators do not need to report emissions if these do not exceed reporting thresholds. There are also instances where operators provide no information at all on pollutants that might be expected to be emitted i.e. they neither report an emission nor do they report that releases are below the threshold. The inventory agency therefore reviews the available data and identifies potential gaps, before generating emission estimates to fill these gaps (by extrapolation from data for other years and/or other processes). This gap-filling is done for the UK inventory, but the gap-filled point source data are then also used in the UK maps. These gap-filled point source data are likely to be considerably more uncertain than point source data based on emissions data in the regulators' inventories, but they also tend to make only a relatively small contribution to UK emissions of each pollutant.

The regulators' inventories provide much of the point source data used in the NAEI maps for NO_X, SO_2, CO, HCl, benzene, 1,3-butadiene, NMVOC, PM_{10}, metals, and persistent organic pollutants. Sectors covered include power stations, refineries, chemicals manufacture, cement kilns, lime kilns, non-ferrous metals production, and large industrial combustion plants.

Of the process operators and trade associations providing emissions data directly to Ricardo Energy & Environment, notable examples are:

- Tata Steel Ltd & British Steel Ltd who have provided emissions data for integrated steelworks broken down into emissions from coke ovens, sinter plant, blast furnaces, basic oxygen furnaces, electric arc furnaces, flaring/losses, stockpiles and combustion plant. PI & WEI emissions data for the steelworks do not give this breakdown. Tata Steel have also previously supplied data for their electric arc steelmaking facility, however this is now operated by Liberty and so data have not been collected after 2016. The Tata Steel / British Steel data cover most of the pollutants mapped in the NAEI for steelworks;
- United Kingdom Petroleum Industry Association (UKPIA) supply NO_X, SO_2, CO, PM_{10} & NMVOC emissions data for fuel combustion and for non-combustion processes at crude oil refineries;
- Oil & Gas UK provide emissions data for offshore oil and gas exploration and production installations as well as various onshore installations linked to the production of oil and gas. These data are taken from the Environmental Emissions Monitoring System (EEMS) database which is compiled for Oil & Gas UK and BEIS. The data cover NO_X, SO_2, CO & NMVOCs.

The use of carbon dioxide emissions data from the EU ETS requires careful cross-checking with the carbon dioxide emissions reported in the PI/SPRI/WEI/NIPI, and with data from trade associations and process operators. This need arises because there is considerable duplication of emissions in these various sources and it is vital that where emissions data are included from the EU ETS dataset, that data for the same installations are not also included from other sources.

The cross-checking requires a thorough understanding of how the various processes permitted under IED and reported in the PI/SPRI/WEI/NIPI relate to processes that are permitted under EU ETS. Identifying the same installation in each of the data sets is not always straightforward since operator names, site names and even site addresses and postcodes can differ for the same site in both sets of data. In the past, this led to some revision of data from one version of the maps to the next, but the NAEI team's understanding of these relationships has improved to the point that further revisions are relatively unlikely.

Additionally, even where a given installation is present in both the EU ETS and other data sets, the exact scope of the emissions data may not be the same. For example, emissions data in the PI and other regulators' inventories will include carbon dioxide from biofuels, whereas the EU ETS data will not. The PI will also include emissions from driers, furnaces and other plants where fuels are burnt to provide heat which is used within the combustion device. In many cases, the EU ETS data set will exclude the emissions from these types of plant prior to 2012 (EUETS phase III). As a result, there is a need to understand how the scope of each IED permit compares with the scope of each EU ETS permit. This is a major task which would require significant resources to do fully. As a proportionate interim measure, resources have been focussed on understanding the relative scope of permits for those installations which report very different carbon emissions in different data sets. Good progress has been made in understanding key differences; even so, fully understanding these is a work in progress.

One sector that is particularly complex is that of the terminals receiving crude oil and gas from the North Sea production installations. For these facilities, we have emissions data from the EU ETS, the PI & SPRI, and also from the EEMS database, compiled for UK Oil & Gas and BEIS. These datasets often contain very different emissions data for the same installation, and it is not always possible to identify a clear reason for this. Carbon dioxide point source emissions data for complex sources such as these are therefore subject to a high degree of uncertainty and are liable to be revised if new information becomes available.

The EU ETS data gives detailed information on the types of fuels burnt at each site. This is used to split emissions data for pollutants other than carbon dioxide that are available from the PI, SPRI, WEI and NIPI. The procedure involves generating a fuel consumption profile for each facility and year. Subsequently, a series of default emission factors, taken from the NAEI, is used to calculate a theoretical emission of each pollutant and fuel type. These theoretical emissions are then used to calculate an emissions profile for each facility, indicating the likely distribution of emissions between the different fuels burnt at that site. Finally, the emissions profile is combined with the emission data reported in the PI/SPRI/WEI/NIPI to give fuel-specific emission estimates.

Point source data for some processes regulated under LAPC/APC are based on information obtained from regulators. This was an important information stream for processes using solvents during the late 1990s and early 2000s, but this type of information has not been collected since, due to the resource-intensive nature of the data collection, both for the inventory agency and, potentially, for the regulators asked to provide such information. Data for a small number of solvent-using processes continues to be available via the E-PRTR, but for most sites, the points data are now based on historic reported data and therefore subject to considerable uncertainty.

Even given the comprehensive information compiled in the above registers and datasets, point source data are not available for all installations. For those sites with emissions below the reporting thresholds described above, or for most sites regulated by local authorities, the NAEI will not be able to collect any emissions data from the regulator. Furthermore, some industrial emission sources are not regulated. For most pollutants, the available data are likely to cover those sites and sectors that emit significant quantities: that is why the sites are regulated and emissions reported in the various data sets. In the case of NMVOC and, to a lesser extent, particulate matter, there are significant emissions from the LAPC/APC sites where emissions data are not generally available. For NMVOCs, there are also significant emissions from industrial processes which are not regulated under air pollution legislation (for example, emissions of ethanol and other NMVOCs from bakeries, breweries and the manufacture of malt whisky and other spirits). In these cases, 'modelled' point source data are generated using national emission factors and a 'surrogate' activity statistic. Examples of this approach are given below:

- Estimates of plant capacity, including estimates made by Ricardo Energy & Environment can be used to allocate the national emission estimate. This approach is, for example, used for bread bakeries where Ricardo Energy & Environment has estimated the capacity for each of about 70 large mechanised bakeries;
- Emission estimates for one pollutant can be used to disaggregate the national emission estimate of another pollutant. For example, emissions of PM_{10} from certain coating processes have been estimated by allocating the national total to sites based on their share of the national NMVOC emission;
- Assuming that plants which do not report emissions have similar rates of emission as plants within the same sector which do report emissions. In these cases, emissions are calculated by assuming that these sites will emit at the same rate as other sites where data exists, which are comparable in size and with similar abatement measures in place, where recorded;
- Emissions can be distributed using surrogate data other than capacity. For example, in the case of malt whisky distilleries, emissions of NMVOCs from distillation are distributed using capacity, except in cases where this is not known, where the number of stills is used as a measure of the scale of operations and therefore emissions;
- Assuming that all plants in a given sector have equal emissions. In a few cases where there are relatively low emissions per plant in a sector, and no activity data can be derived at site-level, emissions are assumed to be equal at all of the sites. This approach is used for only a small number of sources, for example animal rendering plants and animal feed manufacturers.

With the possible exception of using plant capacity as a surrogate, many of the approaches listed above will yield emission estimates which are subject to much higher uncertainties than the emissions reported by site operators in the PI/SPRI/NIPI or EU ETS etc. However, most of the emission estimates generated using these methods are, individually, relatively small and the generation of point source data by these means is judged better than mapping the emissions as area sources. This would mean mapping emissions across the whole of the UK using much less targeted surrogate data, such as employment data or population, which are likely to be poorly correlated to emissions.

3.2 Other industrial, commercial and public sector consumers

As indicated above, the emissions at large point sources represent a substantial proportion of the total industrial and commercial fuel consumption. Subtracting these site-specific emissions from each NAEI sector total calculates a residual emission[18], which is mapped as an 'area source'. This residual emission is allocated to the UK grid using distribution maps for each sector derived from employment statistics. Each distribution map provides the percentage of the UK's residual sector fuel consumption estimate to be allocated to each 1x1km.

The method used is described in a separate document - Employment based energy consumption mapping in the UK[19]. The following data sets were used:

- Office of National Statistics Inter-Departmental Business Register (IDBR), which provides data on employment at business unit level by Standard Industrial Classification (SIC) code[20];
- Energy Consumption in the UK (ECUK) data on industrial and service sector fuel usage[21];
- Site-specific fuel consumption as described in **Section 3.1**. These are compiled from data for regulated processes reported in the EA Pollution Inventory, Scottish SPRI, DoE NI Inventory of Statutory Releases, by the EU-ETS and from other data obtained by the inventory
- Xoserve's Off-Gas Postcode dataset[22];
- Business Register and Employment Survey (BRES) annual employment estimates for the UK split by Region and Broad Industry Group (SIC2007)[23].

The first step was to allocate NAEI point sources to SIC sector and to identify the relevant individual businesses at these locations in the IDBR employment database. This was to calculate the energy use for each sector which is already accounted for by point sources and therefore allow the subsequent estimation of the residual energy that needs to be distributed using the employment data.

The employment data by SIC codes in the IDBR database were matched with the BEIS energy consumption datasets to calculate total employment for each sector for which energy consumption data were available. Fuel intensity per employee was calculated for each sector. For commercial and public service sectors the employment data needed to be aggregated to match the level of aggregation of the energy data. In the case of industrial sectors, a comparable approach was used and the energy intensity calculation was done at the level of 2-digit SIC codes. Energy consumption data were available for coal, gas oil, fuel oil and natural gas. These were combined to calculate industry specific fuel intensities for coal, oil and gas.

The IDBR employment data at local unit level were aggregated to 2-digit SIC codes at Local Authority resolution using postcodes and grid references provided as part of the database. The employment totals for each sector were then multiplied by the appropriate fuel intensity per employee values to make fuel use distributions across the UK. It has been assumed that fuel intensity for each sector is even across the sector. This is a simplification of reality but necessary because of a lack of more detailed estimates of fuel use.

The resulting fuel distributions have been refined using a subsequent set of modelling steps:

- Sites of employment corresponding to the locations of the highest emissions (as defined by the NAEI point source database) have been removed from the distributions. This is to prevent double counting of emissions at these locations (emissions are mapped as point sources).
- High-resolution gas consumption data at Middle Layer Super Output Area (MSOA) has been used to adjust the distribution of gas predicted by the employment and energy intensity data. An adjustment has also been applied in Northern Ireland based on local authority level gas consumption data.
- Evidence of areas with natural gas availability, Xoserve's Off-Gas Postcode dataset has been used to identify sites that are in or out of the natural gas grid.

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[18] Residual emission = national total – point source emission total

[19] Employment Based Energy Consumption Mapping in the UK: A report of the National Atmospheric Emissions Inventory 2019 (publishing.service.gov.uk)

[20] https://www.ons.gov.uk/aboutus/whatwedo/paidservices/interdepartmentalbusinessregisteridbr

[21] https://www.gov.uk/government/statistics/energy-consumption-in-the-uk (Industrial and Services tables)

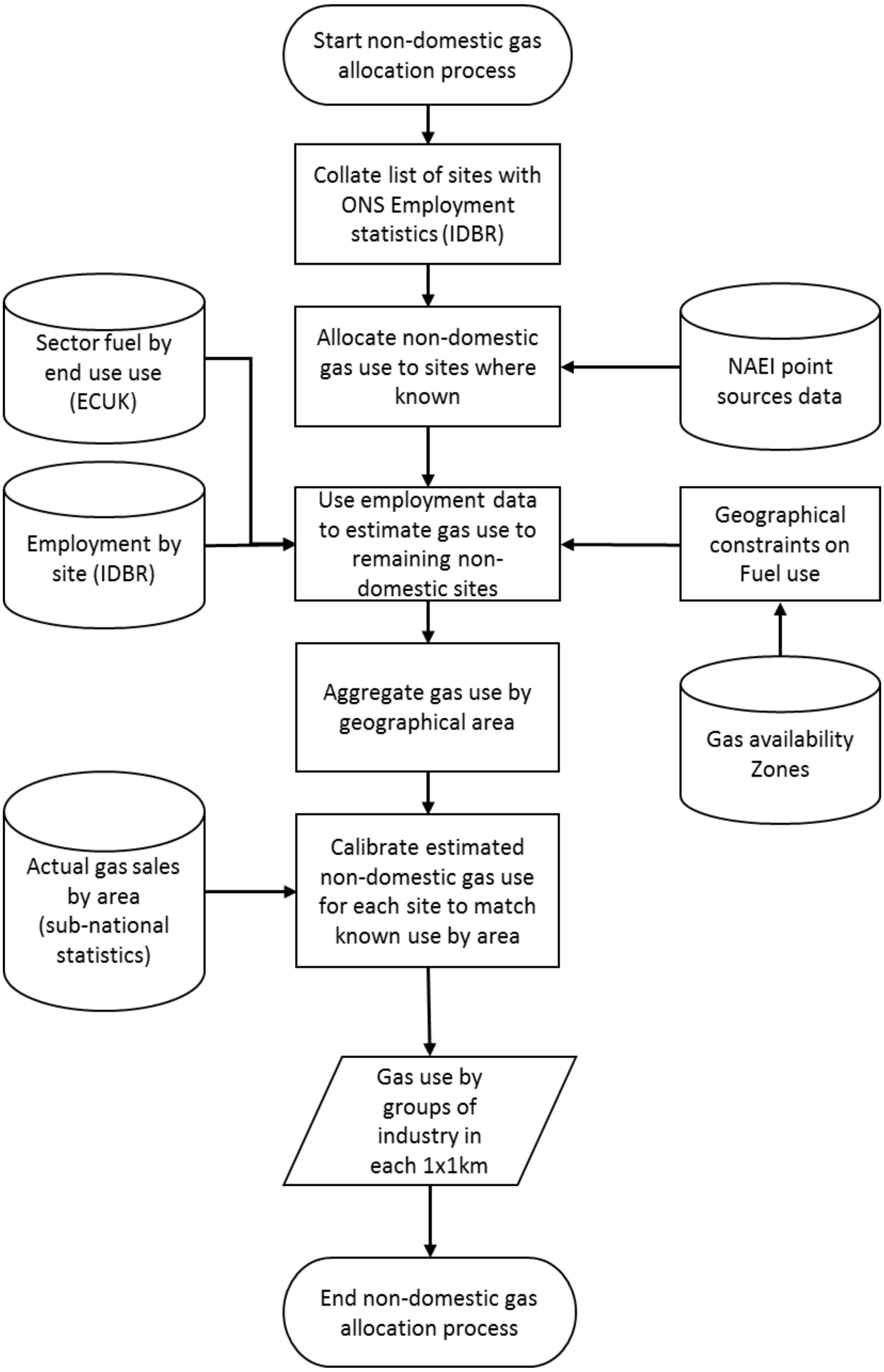
[22] https://www.xoserve.com/media/2687/off-gas-postcodes-v2.xlsx

[23] http://www.ons.gov.uk/ons/rel/bus-register/business-register-employment-survey/index.html

- Based on expert knowledge of fuel use by industry and businesses the distributions of fuel oil and gas oil have been modified so that consumption is lower per employee in grid squares with Natural Gas availability using a weighting factor.
- The distribution of coal has been further limited to outside the locations of large urban areas.

Figure 3-2 shows the process to convert industrial & commercial fuel usage from individual employment sites into emissions.

Figure 3-2 Non-domestic gas use allocation process



3.3 Road transport

Exhaust emissions from road vehicles and the related fuel consumption estimates are calculated within the NAEI using emission factors and activity data for each vehicle type. The emission factors are calculated based on the composition of the vehicle fleet (age profile and fuel mix), and together with fuel consumption are applied to detailed spatially resolved traffic movements. The vehicle fleet age profiles, Euro standard and fuel mix estimated within each of the Devolved Administrations are derived using Regional Vehicle Licensing Statistics (from the DVLA) and the DfT's Automatic Number Plate Recognition (ANPR) database. Therefore, as the fleet mix varies by location, different emission factors are applied to different road types in the Devolved Administrations.

3.3.1 Emission factors and fuel consumption factors

Fuel consumption factors and emission factors combined with traffic data for 6 major classes of vehicles are used to estimate national fuel consumption and emissions estimates from passenger cars (conventional and hybrid), light goods vehicles (LGVs), rigid and articulated heavy goods vehicles (HGVs), buses/coaches and mopeds/motorcycles. The vehicle classifications are further sub-divided by fuel type (petrol or diesel) and the regulatory emission standard the vehicle or engine had to comply with when manufactured or first registered. The vehicle Euro emission standards apply to the pollutants NO_x, PM, CO and hydrocarbons but not to CO_2 or fuel consumption. Nevertheless, the Euro standards are a convenient way to represent the stages of improvement in vehicle or engine design that have led to improvements in fuel economy and are related to the age and composition profile of the fleet. For example, the proportion of pre-Euro 1 and Euro 1-4 vehicles in the national car fleet can be associated with the age of the car fleet (year of first registration).

Fuel consumption and emission factors are expressed in grams of fuel or emissions per kilometre driven respectively for each detailed vehicle class. The methodology combines traffic activity data (from DfT's national traffic census) with fleet composition data and fuel consumption/emission factors. The vehicle fleet composition data are based on licensing statistics and evidence from Automatic Number Plate Recognition (ANPR) data from DfT; these provide an indication of the vehicle mix by engine size, vehicle size, age, engine and exhaust treatment technology, Euro emission standards, and fuel type as observed on different road types. Fuel consumption factors are based on a combination of published compilations of factors derived from vehicle emission test data from European sources and factors from industry on the fuel efficiency of cars sold in the UK. In the former case, representative samples of vehicles are tested over a range of drive cycles associated with different average speeds on different road conditions. There are many parameters that affect the amount of fuel a vehicle uses and average vehicle. Speed is one of them, so the NAEI uses functions that relate fuel consumption to average speed.

The emission and fuel consumption factors are taken from the EMEP/EEA Emissions Inventory Guidebook 2019[24] where they are expressed as functions related to average speed and are consistent with the factors in COPERT 5.3. COPERT 5 "*Computer Programme to Calculate Emissions from Road Transport*" is a model and database of vehicle emission factors developed on behalf of the European Environment Agency and is used widely by other Member States to calculate emissions from road transport. For fuel consumption, the approach includes a method for estimating emissions from passenger cars which applies a year-dependent 'real-world' correction to the average type-approval CO_2 factor weighted by new car sales in the UK from 2005-2019. The new car average type-approval CO_2 factors for cars in different engine size bands were provided by the Society of Motor Manufacturers and Traders[25]. The real-world uplift uses empirically-derived equations in the Guidebook that take account of average engine capacity and vehicle mass. The uplift is applied to the speed-related functions given in the Guidebook. For other vehicle types, the fuel consumption-speed curves provided in the Guidebook are used without a further uplift

The emission maps are calculated from the speed-related emission factors multiplied by vehicle flows. The method for calculating these maps is described in the next section.

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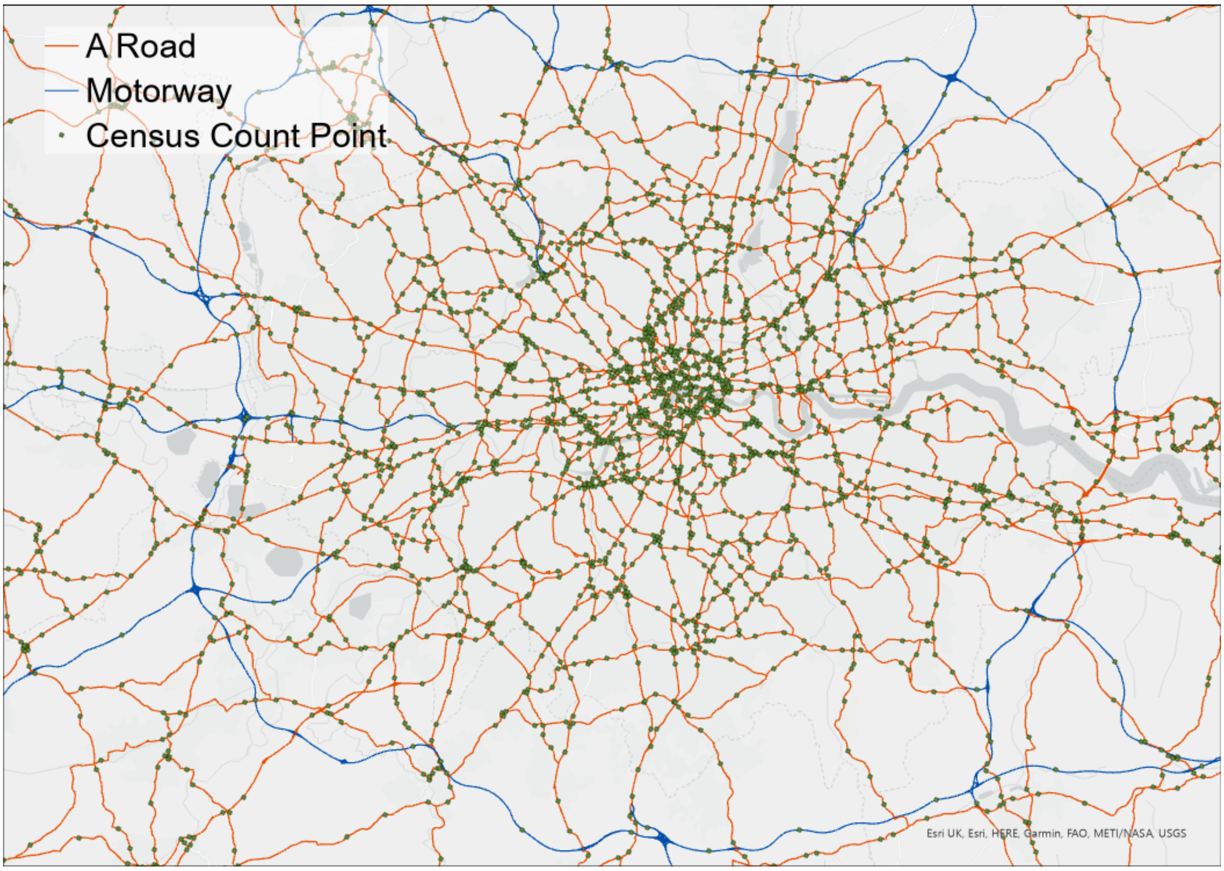
[24] EMEP/EEA air pollutant emission inventory guidebook 2019 — European Environment Agency (europa.eu)
[25] SMMT | Supporting & promoting the UK automotive industry

3.3.2 Road transport mapping methodology

The base map of the UK road network used for calculating hot exhaust road traffic emissions has been developed from a range of mapping datasets. The Ordnance Survey Open Roads (OSOR) dataset (see Figure 3-3) provides locations of all roads (motorways, A-roads, B-roads and unclassified roads) in Great Britain (GB). Prior to 2017 the Ordnance Survey's Meridian 2 (OSM2) road network was used, but this has been superseded by OSOR and the NAEI has adopted this new OS product as part of the continual improvement of the mapping process. OSOR is more detailed and accurate than OSM2 and links to the definitive OS MasterMap Highways Network products. For Northern Ireland (NI) a dataset of roads was obtained from Ordnance Survey of Northern Ireland, part of Land & Property Services Northern Ireland.

Figure 3-3 Illustration of the major road network and DfT count point data for the Greater London area



Traffic flow data for major roads (A-roads and motorways) are available on a census count point basis for both GB[26] and NI[27]. The data comprise counts of each type of vehicle as an Annual Average Daily Flow (AADF), aggregated up to annual flows by multiplying by 365. These AADF statistics take account of seasonal variation using 'expansion factors' applied to single day counts based on data from automatic counts for similar roads and vehicle types. These expansion factors are developed and applied by DfT[28] directly to the released AADF statistics.

Differences between GB and NI datasets should be noted. The census count point coverage of roads in GB is considerably denser than that for NI. Additionally, in NI, some count points record total vehicles, rather than a split of different vehicle types. An average vehicle split has been applied to these records.

[26] Map Road traffic statistics - Road traffic statistics (dft.gov.uk)
[27] Traffic and travel information (incorporating annual traffic census and variations in traffic flow) | Department for Infrastructure (infrastructure-ni.gov.uk)
[28] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/524848/annual-methodology-note.pdf

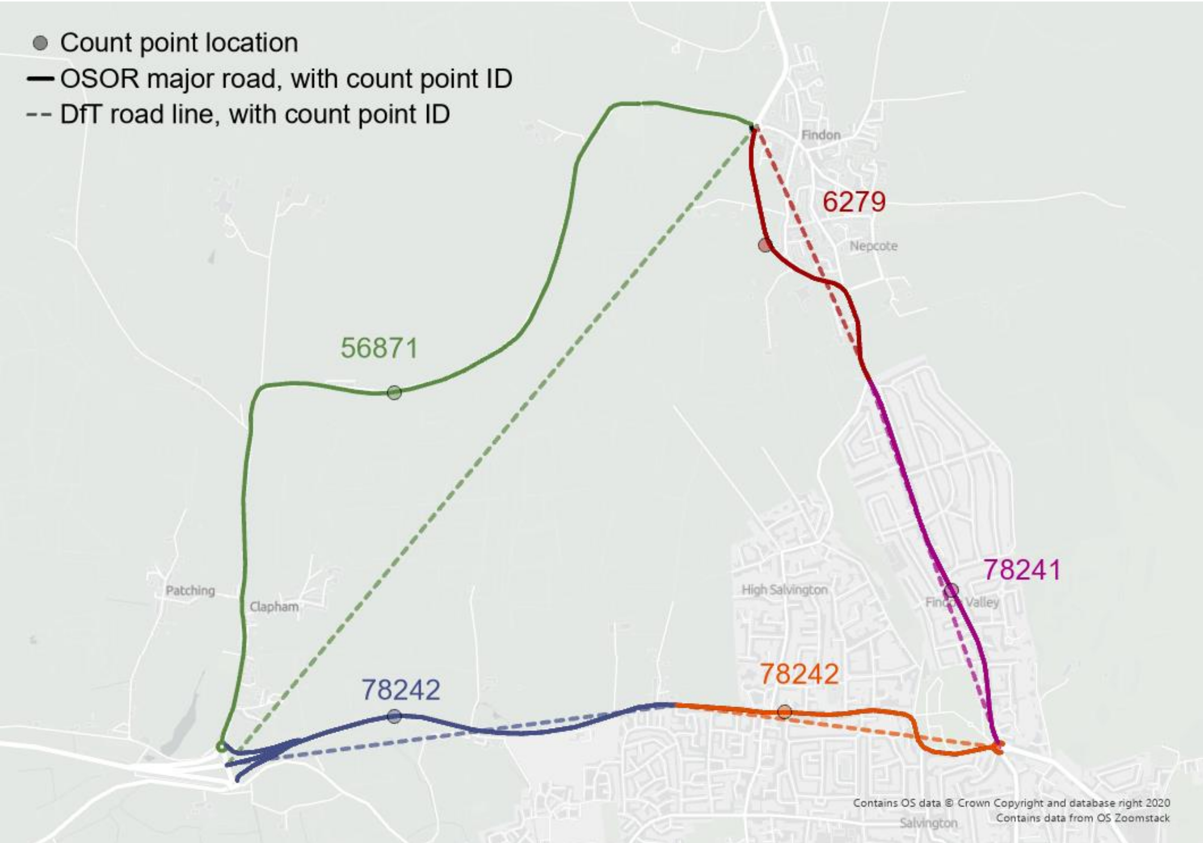
The NI traffic data provided by Northern Ireland's Department for Infrastructure (DfI) from 2018 and following reporting year has a different vehicular classification from previous years. Specifically, the LGV class was omitted and the LGV count was merged with the Car class. As a result, and in order to be consistent with the previous vehicular classification (as well as the data for Great Britain), historic traffic pattern data by road type and urban status was utilised to generate a LGV-to-Car ratio.

In addition, DfI in Northern Ireland has provided a lower number of traffic count points than they did in previous years. From a total of 367 count points only 89 were updated with 2018 data. This has led to adopting a scaling factor using historic traffic counts for Northern Ireland. This enabled the scaling of 278 traffic points to fill in the gaps.

For NI, traffic counts were allocated according to the proximity of the point where the count was made and major roads with the same road number – i.e. each link has the nearest count point with the same road number assigned to it – using a computer script.

For GB, the OSOR network is more complex than the NI road network, and count point allocation required a different approach. Here, count points were allocated to a section of the major road network according to shared road number and spatial proximity to the stretch of road that each count point covers (Figure 3-4). This was done by using a highly simplified, straight line, Department for Transport (DfT) representation of the start and end of each count points' coverage ('count point lines'). A series of computer-based processes were used to automatically perform this allocation. Where count point lines overlapped Local Authority boundaries, OSOR roads were split at that boundary and each split assigned to the relevant LA. Automated allocation was followed up with manual checking and verification.

Figure 3-4 Traffic flows are assigned to the road network (Ordnance Survey Open Roads) by selecting OSOR sections that fall between the start and end points of traffic census count point coverage (DfT road line)



The urban or rural classification of a section of OSOR road covered by a count point (here called a 'count point road') was determined through the following logic:

1. Count point roads that have at least two-thirds of their DfT defined length[29] as urban: classify as urban.
2. Count point roads that have at least two-thirds of their DfT defined length[30] as rural: classify as rural.

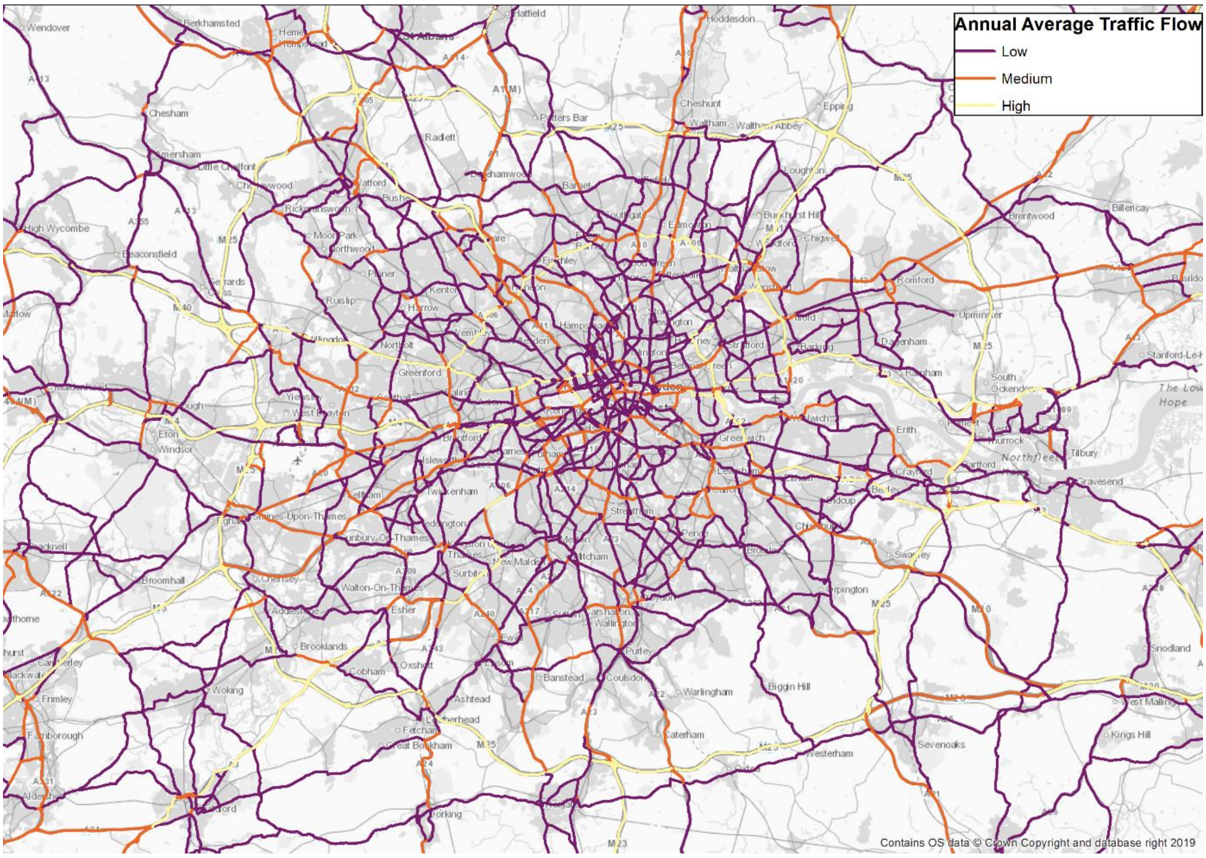
Count point roads not captured by cases 1 or 2 were split at the urban boundary and further logic applied:

3. Count point roads intersecting the boundary once were split into two count points: one urban and one rural. Any new count point road of less than 100m was given the urban or rural classification of their counterpart and splits of less than 15% of the total count point road length were manually inspected for validity.
4. Count point roads intersecting urban areas more than twice were classed based on the majority urban or rural length of the whole road section.

Due to the variety of reasons that a road may cross a boundary twice, these were manually assessed and classified as urban or rural accordingly.

Urban areas for England and Wales are defined as built-up areas[31] with a population of at least 10,000, or for Scotland[32] a population of at least 3,000 (according to 2011 Census data). Figure 3-5 shows the traffic flows that are assigned to the road links after count point allocation.

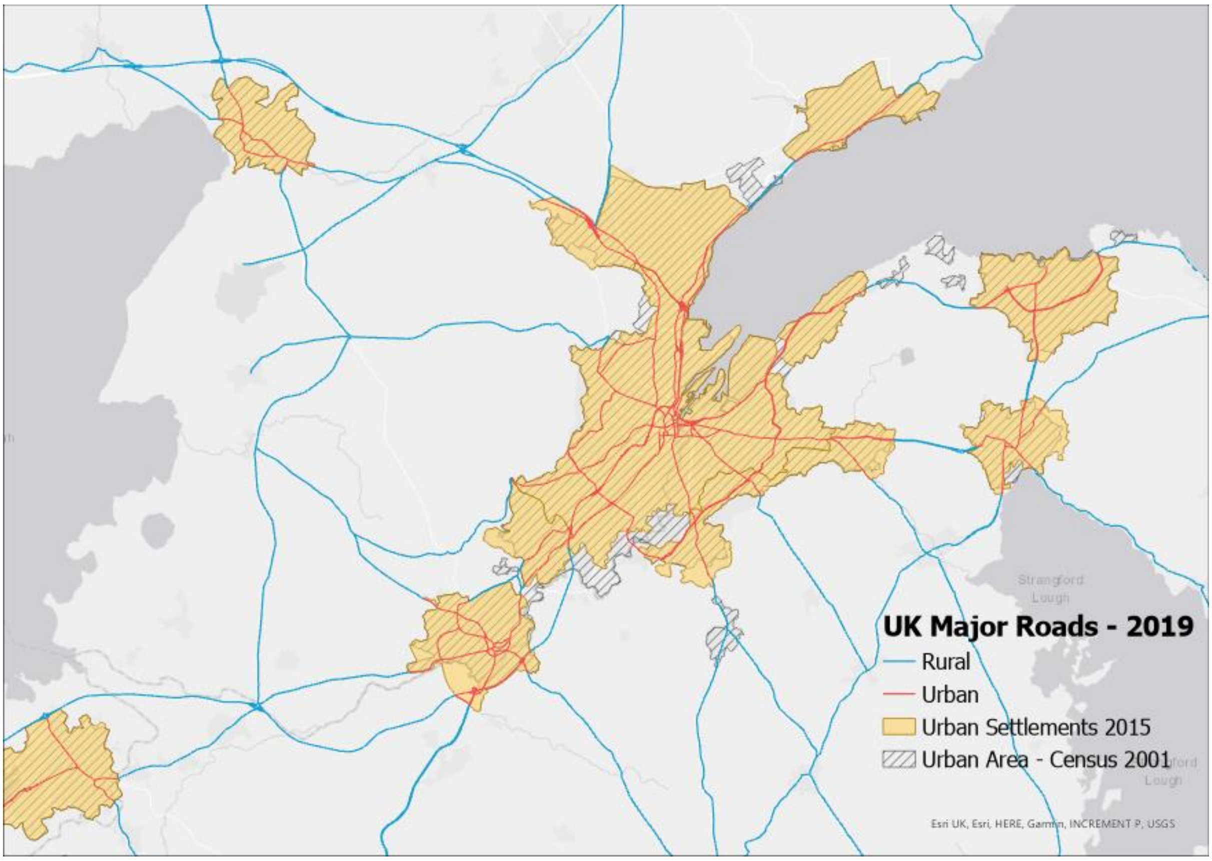
Figure 3-5 Traffic flows are assigned to the road links after count point allocation



[29] This length is provided directly by DfT and therefore further analysis is not necessary
[30] This length is provided directly by DfT and therefore further analysis is not necessary
[31] http://geoportal.statistics.gov.uk/datasets/built-up-areas-december-2011-boundaries-v2
[32] https://www2.gov.scot/Topics/Statistics/About/Methodology/UrbanRuralClassification

An improvement in the 2019 NAEI were the updated urban/rural boundaries used in Northern Ireland (from the historic urban boundaries to the 2015 settlement development limits[33]). This means that some roads have changed status or have different urban/rural lengths. This affects fuel use as the urban status of a road changes the assumed average speed and therefore the fuel consumption factors applied. Any changes in urban status are reflected in the entire time series. Figure 3-6 shows the updated boundaries used along with the status assigned to major road.

Figure 3-6 Urban boundaries update in Northern Ireland



Traffic flow data are not available on a link-by-link basis for the majority of minor roads. But where these data are available, they have been used to enhance the accuracy of the mapping. Minor road count points were allocated to minor roads from the OSOR dataset by using the 2016 OSM2-based allocation. These allocations were transferred by matching the spatial extent of OSM2 road sections to comparable OSOR road sections.

Traffic flows in the majority of minor roads have been modelled based on average regional flows and fleet mix (data from DfT) in a similar way to previous years. Regional average flows by vehicle type have been applied to each type of minor road – B and C roads or unclassified roads. DfT have carried out their routine benchmarking exercise for their estimates of road traffic on minor roads; this exercise happens approximately every 10 years and aims to reduce incremental errors. The result of this exercise was an increase in their estimates of traffic flow on minor roads for historic years. Full details of the benchmarking exercise can be found on gov.uk[34].

[33] https://www.nisra.gov.uk/support/geography/urban-rural-classification
[34] https://www.gov.uk/government/publications/road-traffic-statistics-minor-road-benchmarking

For Northern Ireland, vehicle-specific minor road flows have been calculated from data in the *Annual Road Traffic Estimates: Vehicle Kilometres Travelled in Northern Ireland*[35] which provides information on vehicle kilometres travelled for vehicle types and by road types.

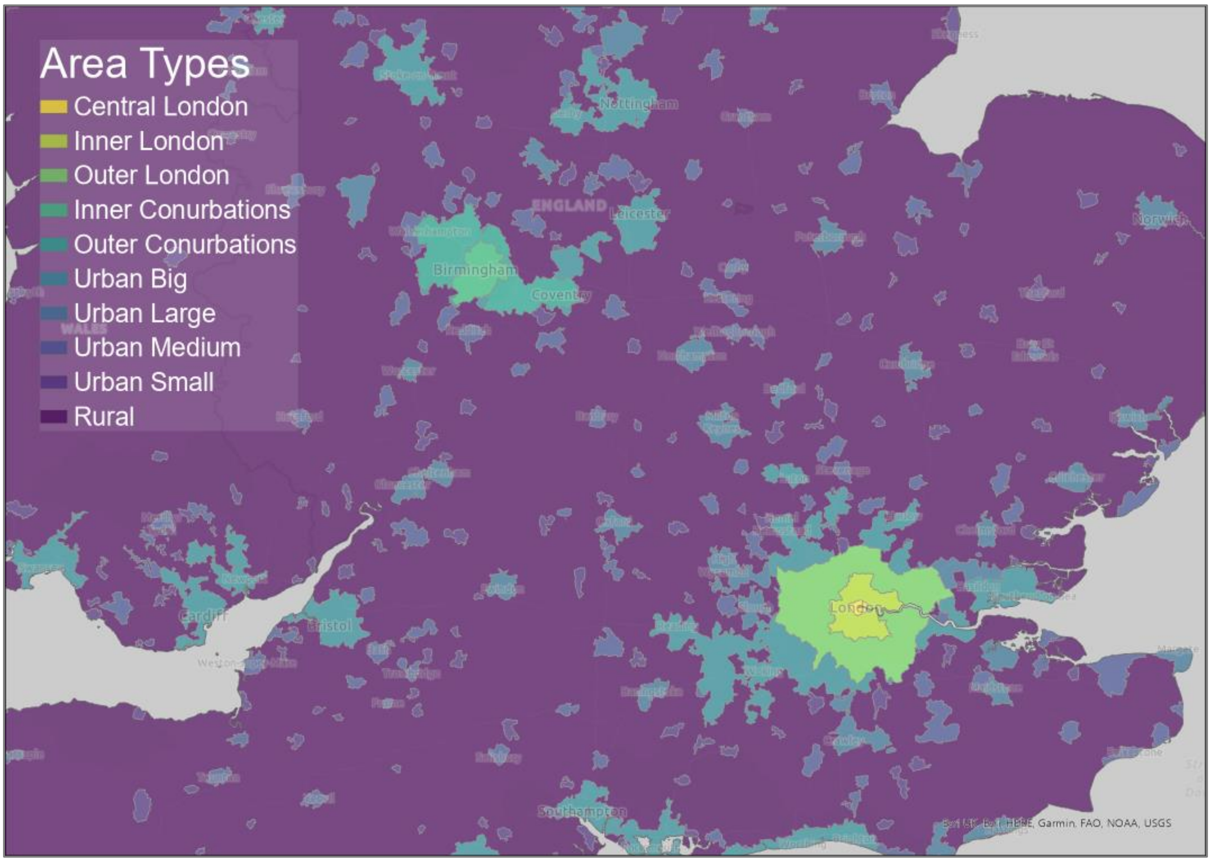
County-level vehicle kilometre estimates from DfT (unpublished) have been provided to ensure consistency between the NAEI and DfT modelling and have been used to correct at County level the estimates of vehicle kilometres in the NAEI mapping.

The next step after mapping vehicle movements was to apply the emissions and fuel consumption factors discussed earlier.

Each major road link was assigned an area type using the DfT definitions of urban area types shown in Table 3-2 and

Figure 3-7 below. Within each one of the 10 area types vehicle speeds were assigned to different road types (built up and non-built up A-roads and motorways)

Figure 3-7 Road transport urban area type classification map



[35] https://www.infrastructure-ni.gov.uk/publications/annual-road-traffic-estimates-vehicle-kilometres-travelled-northern-ireland-2014

Table 3-2 Road transport urban area type classification

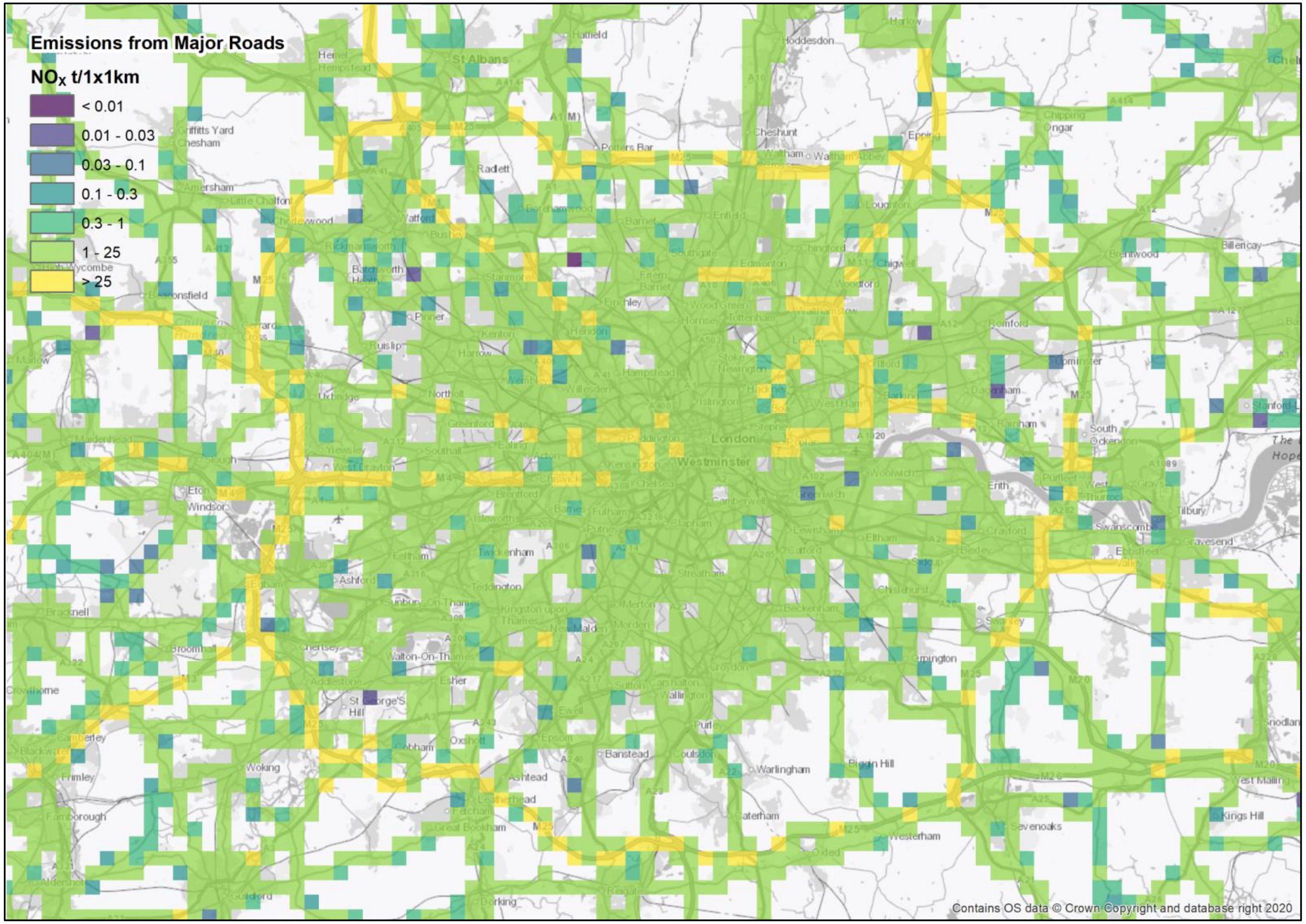
Area Type ID	Description	Population
1	Central London	N/A (Geographically defined)*
2	Inner London	N/A (Geographically defined)*
3	Outer London	N/A (Geographically defined)*
4	Inner Conurbations	N/A (Geographically defined)**
5	Outer Conurbations	N/A (Geographically defined)**
6	Urban Big	> 250,000
7	Urban Large	100,000 – 250,000
8	Urban Medium	25,000 – 100,00
9	Urban Small	10,000 – 25,000
10	Rural	N/A

* Unique areas, which are defined on a geographic basis by Transport for London (TfL).
** Conurbations include the Greater Manchester and West Midlands built-up areas.

Vehicle kilometres (VKM) estimates by vehicle type for each road link were multiplied by fuel consumption or emission factors taking into account the average speed on the road of concern and the vehicle and fuel type and the national fleet composition in terms of the mix of each Euro emission standard of vehicles on the road for the inventory year. These calculations were performed for each major road link in the road network, resulting in maps of fuel use by fuel type and emissions by pollutant. Each road link was then split into sections of 1 km grid squares which enabled the mapping of emissions and energy estimates (for example for London in Figure 3-8).

A similar calculation is performed for minor roads estimates using average speeds for different types of minor roads and applying the relevant fuel consumption factor for that road type to the VKM data modelled as described above. Calculations for minor roads are undertaken at a resolution of 1x1 km across the UK.

Figure 3-8 2019 NO_X road transport emissions on major roads aggregated to 1x1 km resolution



3.3.3 Other road transport emissions

Cold start emissions are produced by vehicles before the engine has reached normal operating temperature. Estimates of the distance travelled by vehicles whilst operating under cold start conditions are available in the NAEI for cars by average trip length and trip type. Cold start conditions in Northern Ireland are assumed to have similar characteristics to those in Great Britain. These data enable estimates of the associated emissions to be determined at the UK level.

The trip types used in the mapping of cold start emissions are classified as 'home to work', 'home to other locations' and 'work based' trips. 'Home to work' related emissions were distributed across the UK using detailed population data from the 2011 census on whether people use their car as their method of transport to work. Emissions for trips from home to other locations were mapped using data on car ownership, once again collected from the 2011 census. Work based cold start emissions were mapped on a distribution of all employment across the UK. These were reconciled with the outputs from DfT's TEMPRO model (DfT, 2013). Predicted population movements by mode of transport in the TEMPRO model were produced through reconciling the National Trip End Model (NTEM) version 6.2 (April 2011) datasets[36], which contains a long-term travel response to demographic and economic trends within Wales, Scotland and the 9 regions of England. A comparable NTEM dataset representative of current socioeconomic conditions in Northern Ireland was recently commissioned by the Department for Regional Development and is expected to be included in future releases. The ratio of Northern Ireland to UK cold-start emissions, for each pollutant, was calculated from the NAEI road transport model. These emissions estimates are based on the COPERT III model for cold-starts (Ntziachristos & Samaras, 2000).

Evaporative emissions of benzene and NMVOC from petrol vehicles were distributed using a map of petrol fuel use on all roads derived using the method described in section 3.3.2 above.

PM_{10} and $PM_{2.5}$ emissions from brake and tyre wear and road abrasion were distributed using a 1x1 km resolution map of estimated total vehicle kilometres on major and minor roads.

There are two other small sources of emissions from road traffic included in the inventory - combustion of waste lubricants and emissions from Liquid Petroleum Gas (LPG) vehicles. Both sources were distributed using estimates of total vehicle kilometres calculated from the NAEI maps of traffic flows.

3.4 Domestic

3.4.1 Natural gas

Sub-national energy statistics were used to generate domestic gas use spatial distribution for England, Wales and Scotland. Gas consumption has been aggregated from the bottom-up gas meter point level to 1x1km resolution. For Northern Ireland, gas connections information for domestic properties was provided by SSE Airtricity[37] and Firmus Energy[38]. Residential use of LPG is allocated in off gas grid output areas, where census returns gas central heating.

3.4.2 Oil and solid fuels

Domestic oil and solid fuel use distributions were created by spatially resolving detailed local information on central heating and house type data from the 2011 census with data from the BEIS National Household Model (NHM), which provides average household energy consumption estimates across the 13 regions of England, Wales and Scotland. Regions within England and Wales follow the regional classification scheme[39], with Scottish regions aligned with the Met Office's 3-tier regional climate (Northern, Eastern and Western) classification to represent the spatial shifts in climate[40]. The census

[36] https://www.gov.uk/government/publications/tempro-downloads/tempro
[37] http://www.airtricitygasni.com/at-home/
[38] http://www.firmusenergy.co.uk/
[39] http://www.ons.gov.uk/ons/guide-method/geography/beginner-s-guide/maps/index.html
[40] http://www.metoffice.gov.uk/climate/uk/regional-climates

data were combined with full-address matched dwelling locations from Ordnance Survey data to give a more accurate distribution of households at 1x1km resolution. The following data series were used in the domestic model:

1. **Ordnance Survey (OS) AddressBase products**

   a) OS AddressBase Premium
   The AddressBase data links any property address to its location on the map. It was created through matching the Royal Mail's postal address file (PAF) to building locations contained in the OS Topography Layer, to provide precise coordinates for each of the 24.7 million residential properties in Great Britain.

   b) Ordnance Survey of Northern Ireland (OSNI) Pointer
   The Pointer address product is the most comprehensive and authoritative address database for Northern Ireland, containing location data for just under 740,000 residential address records. Each record adheres to the OS common address standard.

2. **2011 Census returns on dwelling type and central heating fuel types**

   a) Office for National Statistics (ONS) – cross-tabulated records[41]
   - Census table 'CT0213' provided 2011 estimates classifying all occupied households by type of central heating by dwelling type at the Lower Super Output Area (LSOA) level in England and Wales on census day (27th March 2011). A household's accommodation is classified according to the presence and type of central heating if it is present in some or all rooms (whether used or not).
   - Output Area (OA) information of dwelling type (only) contained in census tables 'KS401EW' for the 10 regions of England and Wales allowed for a more spatially detailed analysis.[42]

   b) National Records of Scotland (NRS)[43] - cross-tabulated records
   Census table 'CT_0043_2011' provided 2011 estimates classifying all occupied households by type of central heating by dwelling type at the Output Area (OA) level in Scotland on census day (27th March 2011). These data were provided to Ricardo Energy & Environment by NRS in June 2015.

   c) Northern Ireland Statistics and Research Agency (NISRA) - cross-tabulated records
   Census table 'CT0084NI' provided 2011 estimates classifying all occupied households by type of central heating by dwelling type at the Small Area (SA) level in Northern Ireland on census day (27th March 2011).[44]

3. **BEIS National Household Model (NHM) regional energy consumption estimates per household by house type by fuel type**

   Regional energy consumption estimates of a detailed build form/type (subsets of census dwelling type) and in the presence of central heating were created by BEIS on 31st March 2014 from the NHM scenario "GHG_Emissions_Data_Request" version 3. Coal and oil have been calibrated to DUKES; gas and electricity have been calibrated to metered readings.

4. **BEIS Residential Wood Survey**

   BEIS undertook a survey of residential wood use during 2015 and this provides estimate of wood users for 2014 at regional level as well as data on technology splits of these users, among other statistics. The Number of Wood Fuel users by Region from the summary results[45] allowed additional assessment of the wood use mapping.

A summary of how these datasets were utilised in the process is given in Table 3-3.

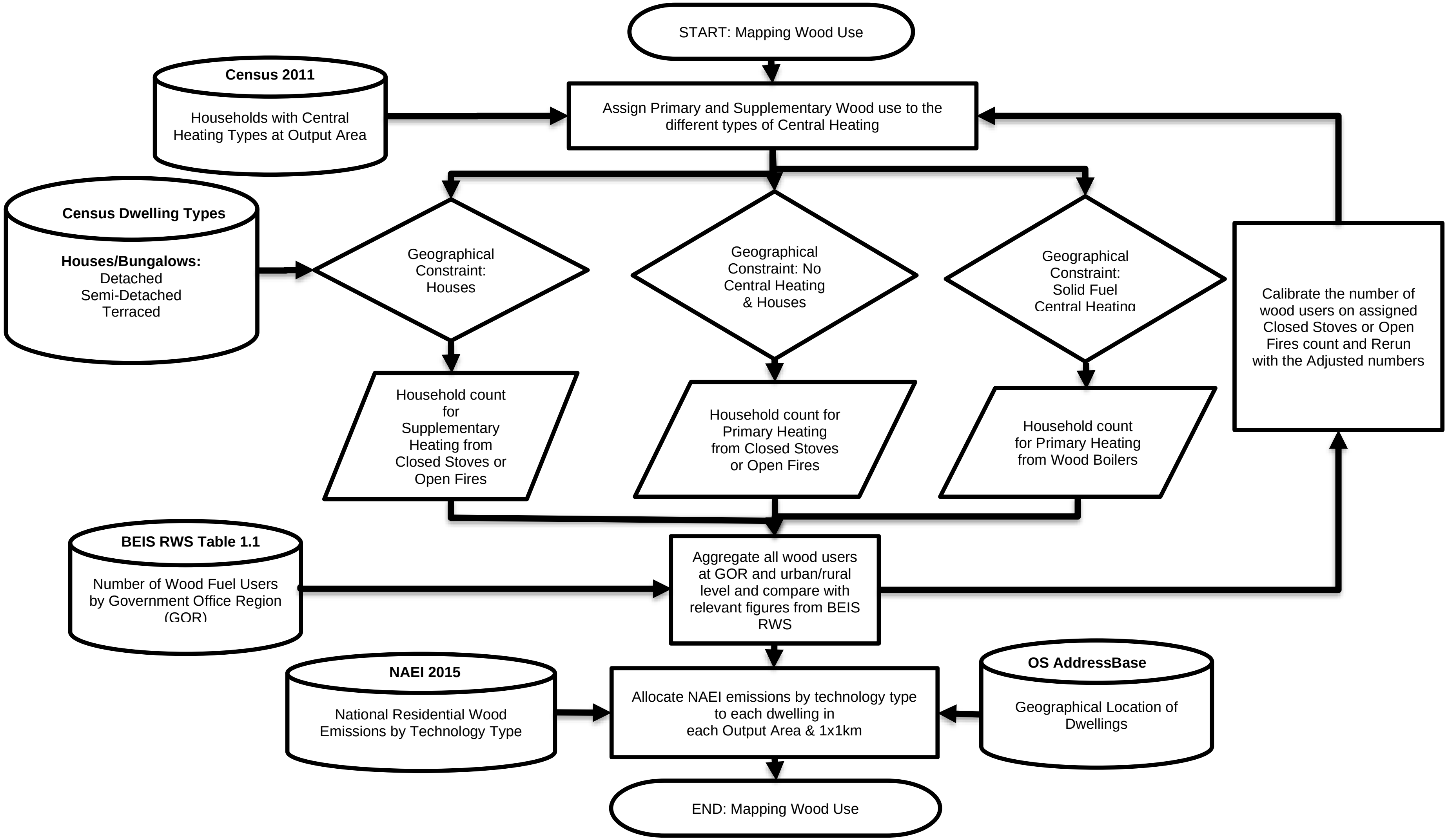
[41] www.ons.gov.uk/ons/guide-method/census/2011/census-data/2011-census-data-catalogue/commissioned-tables/index.html
[42] http://www.ons.gov.uk/ons/datasets-and-tables/index.html
[43] http://www.nrscotland.gov.uk/
[44] http://www.ninis2.nisra.gov.uk/public/Theme.aspx
[45] https://www.gov.uk/government/publications/summary-results-of-the-domestic-wood-use-survey (Table 1.1)

Table 3-3 Description of methods using the above data series

Task and data series used	Application
1	OS AddressBase Premium geographies were used to generate a spatially resolved database of ONS/NRS 2011 census dwelling types distributed within the Census output area boundaries by unique address level coordinates of residential structures within each of England, Wales and Scotland's Output Areas (OA). For Northern Ireland, a fully standardised geo-referenced address layer was retrieved from the OSNI Pointer dataset and combined with NISRA 2011 census household type returns at the Small Area (SA) level. SAs on average contain 155 households a figure comparable to OA's within England / Wales which on average contain 125 households.
2	For England & Wales, ONS cross-tabulated census data provided a breakdown of dwelling type (Detached, semi-detached, terraced, flat/other) by central heating characteristics (gas, electricity, oil, solid, and multiple) at the census Lower Layer Super Output Areas (LSOA)[46]. Fuel splits for a given dwelling type were then applied to OA central heating type counts, based on geographic nesting. NRS & NISRA data across Scotland and Northern Ireland provided a complete breakdown of dwelling type by central heating characteristics at the OA & SA level, respectively. As such, no additional data processing was required.
3	BEIS NHM Regional energy statistics by dwelling type and heating type were used to generate spatial distribution databases for domestic gas, oil and solid fuel consumption across England/Wales and Scotland. Households characterised as having a central heating system operating with multiple fuel types were assumed to have an even split of the gas, electricity and solid fuel central heating returns occurring in matching house types of that OA. The BEIS NHM is a domestic energy policy and analytical tool constructed from the national housing surveys (English Housing Survey and Scottish House Condition Survey) to characterise Great Britain's housing stock. The Welsh housing stock model is derived from a reweighting of the English Housing Survey, with insufficient information available for the inclusion of Northern Ireland. Energy statistics for 'Western Scotland' were adopted by the NAEI as the most appropriate (with regard to building forms and climate) to represent the domestic energy factors within Northern Ireland.
4	Solid fuel use was assigned to solid fuel burnt in boilers and non-boiler appliances (such as open fireplaces, closed stoves). It was assumed that solid fuel activity for boilers was used in properties which, according to Census 2011, had Solid Fuel Central Heating. Solid fuel activity for non-boiler appliances was assumed to be used in houses and bungalows with No Central Heating. Supplementary heating from the same technologies was considered more likely to be located in houses and bungalows only. Apartments were excluded for solid fuel use to be in line with BEIS NHM assumptions on wood use. The number of supplementary heating users for wood was calibrated at Regional level by comparing the total wood user count (as derived from all the above assumptions) against the regional count from the BEIS Residential wood survey. Figure 3-9 presents a summary of how wood use was mapped. Emissions were mapped from the NAEI estimates for residential boiler and non-boiler technologies.

[46] https://data.gov.uk/dataset/c481f2d3-91fc-4767-ae10-2efdf6d58996/lower-layer-super-output-areas-lsoas

Figure 3-9 Domestic wood use allocation process



3.5 Agriculture

Emissions of PM_{10} and $PM_{2.5}$ from agricultural livestock and poultry sources were distributed using agricultural census data 2014. Detailed, farm/holding level data within England was obtained from Defra for this purpose and was used to generate 1x1km resolution datasets for different livestock types. For Scotland, Wales and Northern Ireland agricultural census data 2014 were only available for larger spatial units – Parishes in Scotland, Districts in Northern Ireland and Small Areas in Wales. Therefore, land use data were used to generate a distribution of emissions within these spatial units. The land cover maps of grass land was used to allocate livestock. The resulting distributions for England, Scotland, Wales and Northern Ireland were combined and weighted according to the relevant regional statistics on the number of livestock or poultry in these regions.

The distributions of ammonia, methane and N_2O emissions from agricultural sources were mapped by the UK Centre for Ecology and Hydrology (UKCEH). Agricultural census/survey data for 2019 were acquired at the holding level from the four UK countries' statistical authorities, i.e. Defra (England), the Scottish Government (Scotland), Welsh Government (Wales) and DAERA (Northern Ireland). Aggregated cattle population data were supplied to and processed by Cranfield University from cattle tracing system (CTS) data. The holding level data for the different countries were aggregated to a common set of emission source categories used by the agricultural emission inventory model to ensure compatibility between the different countries' systems and consistency. The emission estimates are based on a model jointly developed and first implemented for the 2016 inventory by Rothamsted Research, ADAS, UKCEH and Cranfield University. The 10x10 km estimates from the emissions model have been spatially resolved to produce non-disclosive high-resolution 1x1km emission maps.

A small proportion of emissions from the incineration of animal carcases were mapped as a point source. For the majority of national total emissions, however, little is known about the location of this activity. As a result, the residual was mapped as an area source across all UK arable land.

Land Cover Map 2007 data from CEH was used to map a variety of other agricultural emissions. These were distributed evenly across the arable land cover map for the UK:

- Emissions of VOCs from agrochemical use
- CO_2, emissions from fertiliser application
- Dioxin and Benzo[a]pyrene emissions from agricultural waste burning.

Agriculture stationary combustion was also mapped using the IDBR employment data and the UK agriculture energy consumption by fuel (ECUK Table 5.1c)[47]. The distribution of solid and liquid fuels was made based on the location of smoke control areas[48] and the geographical distribution of gas availability. The method used is explained in summary in section 3.2 and further detailed in the supporting document *Employment based energy consumption mapping in the UK[49].*

Agricultural off-road emissions were distributed using a combination of arable, pasture and forestry land use data. Each of these land cover classes were weighted according to the off-road machinery activity on each land use. This data on the number of hours of use of tractors and other machinery on the land use types were sourced by Ricardo to improve the UK inventory in this sector.

3.6 Rail

The UK total diesel rail emissions are compiled for three journey types: freight, intercity and regional. The rail mapping methodology was updated for the 2011 emission maps. The emissions were spatially disaggregated using data from the Department for Transport's Rail Emissions Model (REM). This provided emission estimates for each strategic route in Great Britain for passenger and freight trains. The emissions along each rail link were assumed to be uniform along the length of the rail link, as no information on either load variation or when engines were on or off is yet available. The most recent

[47] https://www.gov.uk/government/collections/energy-consumption-in-the-uk
[48] These did not incorporate the updated SCA locations
[49] Employment Based Energy Consumption Mapping in the UK: A report of the National Atmospheric Emissions Inventory 2019 (publishing.service.gov.uk)

year in REM is 2009/10 and therefore the emissions for each strategic route have had to be scaled appropriately, as described in the UK Informative Inventory Report (Richmond, et al., 2021), using trends from national statistics on fuel consumption by rail operators. These were then distributed across Great Britain with the use of GIS data provided by Network Rail, containing the Strategic Routes Sections (SRS) as those have been defined in 2012.

Rail emissions are distributed across Northern Ireland using 2012 data from Translink[50] on amounts of fuel used on different sections of track aggregated to LA. These data are for passenger trains only as there is no freight activity in Northern Ireland.

Coal based rail emissions have been accounted for by extracting station, line and operating information from the latest version of the 'UK Heritage Railways' website[51]. This information was then verified against additional independent UK heritage railway guides[52], and dedicated webpages for specific lines. National coal-based rail emissions have been proportionally allocated based on the number of days a line operated per year (consistent across all sections of a lines track). In total, 86 operational heritage lines were identified, and their main station coordinates plotted. Those stations with track lengths >5 miles were mapped with the assistance of route schematics alongside the aerial imagery and OS Open Background map services provided by ESRI. For the remaining 48 stations activity was assigned to a single 1x1km grid.

3.7 Shipping

A revised, more sophisticated, method has been used to map UK shipping emissions starting from NAEI 2016. This approach is described in Scarbrough et al. (2017) and gives a higher resolution and greater accuracy to emissions estimates (through improved coverage of various vessel types), as well as enabling a deeper understanding of the spatial pattern of emissions.

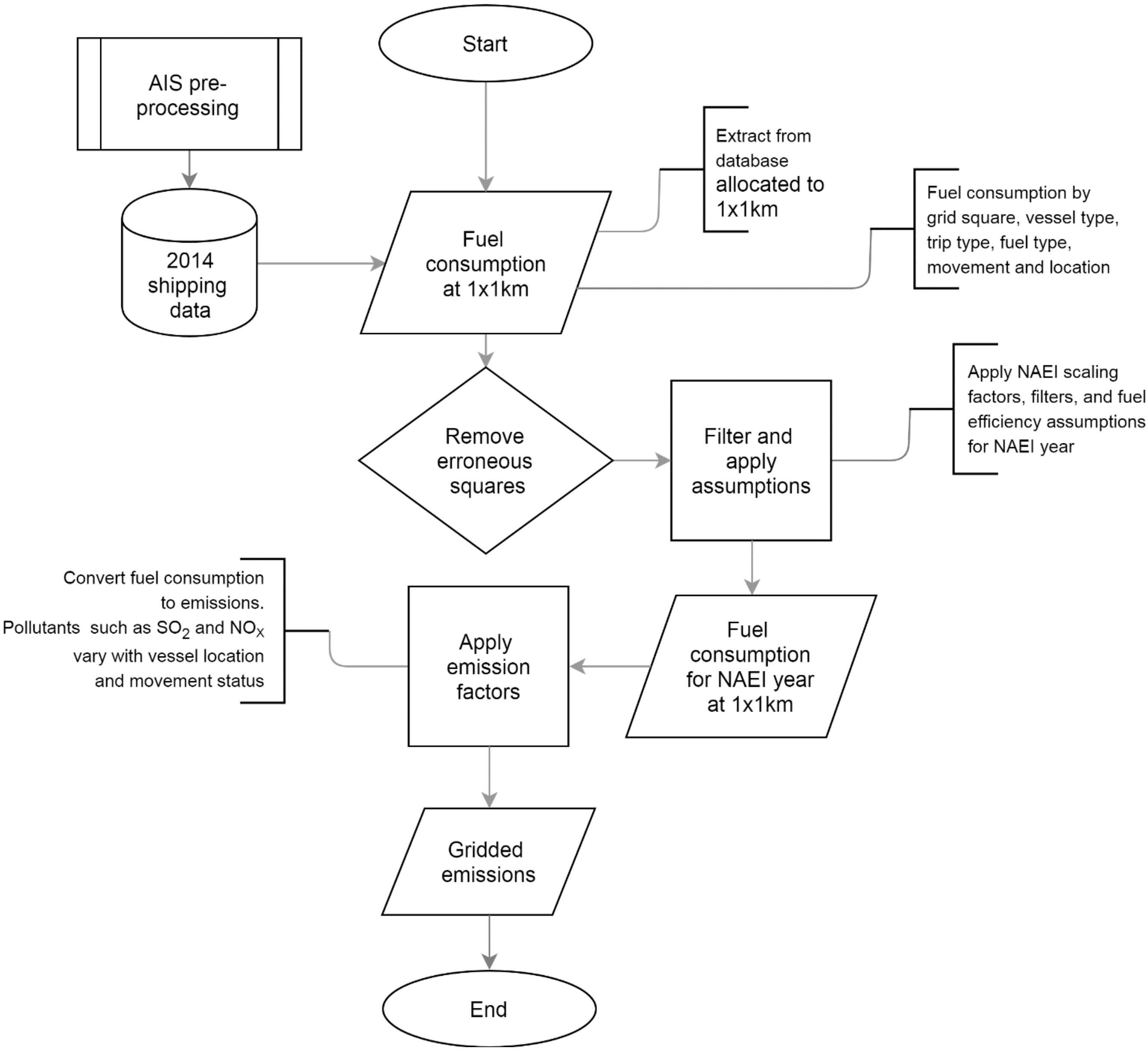
The revised method has been developed using Automatic Identification System (AIS) data supplied by the Maritime and Coastguard Agency. AIS is an on-board ship system that transmits a message containing a vessel's position - and other information such as speed - every few seconds, to be received by other vessels, onshore or by satellites[53]. A complete set of one year's worth of AIS data received by terrestrial UK receivers was obtained and processed to give a dataset that records shipping activity at five-minute intervals for the whole of the year 2014. This was then used to calculate fuel consumption and emissions for each vessel for the year 2014 in conjunction with a second dataset of technical characteristics of individual vessels. The estimates for year 2014 were then forecast to the current NAEI year accounting for activity changes over time, the 2015 sulphur emission control area change in sulphur content limit, fleet-wide efficiency gains and additional NOx emission factor changes to account for fleet turnover.

A detailed discussion of the methodology used to develop a shipping emissions inventory from AIS data can be found in Scarbrough et al. (2017). The mapping process closely followed this approach and is summarised in Figure 3-10. However, differences in reporting requirements between the UK inventory and NAEI maps, and the requirements of the air quality modelling community, necessitate that the map production process diverges from National Inventory compilation in several key ways.

The process of inventory mapping seeks to spatially disaggregate NAEI inventory totals in a way that represents how those emissions are geographically distributed in the real world. AIS data are inherently spatial as they record a vessel's position, and so emissions from each ship can be easily attributed to a $1km^2$ grid using the longitude and latitude accompanying each AIS message. A small number of messages are erroneously located upon terrestrial grid squares (Scarborough et al., 2017, p. 10) or are legitimately in non-UK water bodies within the NAEI mapping area (e.g. vessel movements within major rivers in north-eastern France). These emissions should not exist within the UK shipping map and have been removed.

[50] http://www.translink.co.uk/
[51] http://www.heritage-railways.com/index.php
[52] http://www.heritagerailwaysmap.co.uk/
[53] http://www.imo.org/en/OurWork/Safety/Navigation/Pages/AIS.aspx

Figure 3-10 Shipping emissions mapping process

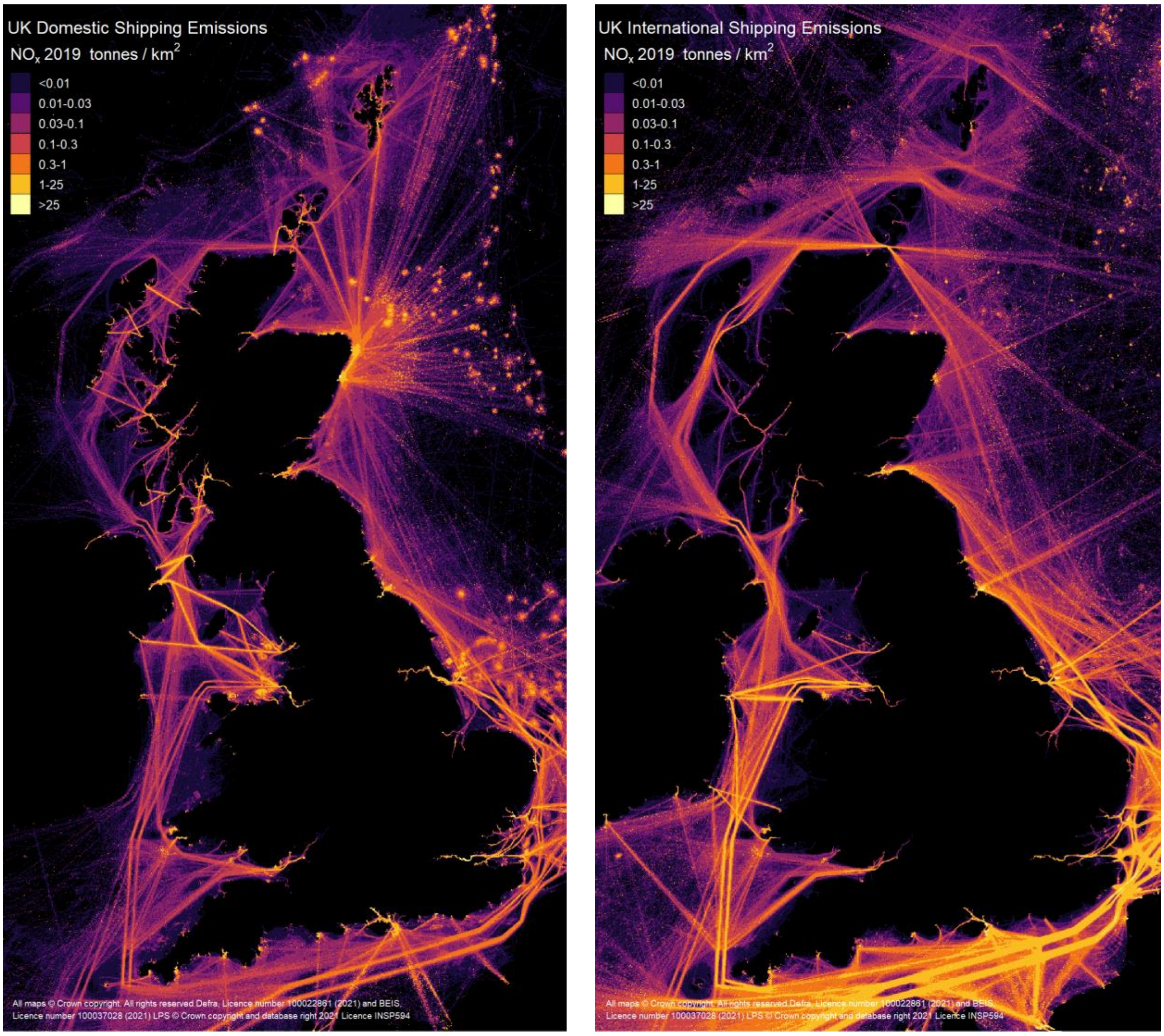


Other differences between mapping and inventory production processes are listed in Table 3-4, along with the reason why the two datasets differ and a description of how this may influence interpretation. The effect of one of these differences is illustrated in Figure 3-11, which shows NO_x emissions from different trip types included in the NAEI maps. More specifically, the map on the left indicates domestic activity (including fishing vessels), whereas the map on the right shows all remaining activity such as vessels travelling to international ports, vessels traveling from Crown dependences and any passing through activity (e.g. navigating through the English Channel).

Table 3-4 Differences between shipping emissions represented by NAEI mapping and the NAEI

Difference	Description		Motivation for difference	Consequence(s) of difference
	NAEI	NAEI maps		
Vessels 'passing through'	Emissions from vessels passing near the UK but not calling at the UK were excluded.	Emissions from vessels passing near the UK but not calling at the UK are included.	The NAEI maps aim to provide as complete an evidence base as possible of pollution sources that affect concentrations in the UK, and is not bound by adherence to the reporting requirements of the NAEI.	Including this category of activity will lead to higher intensity of emissions in certain geographic areas and is a better representation of the total emissions burden from all shipping sources.
UK international emissions	Emissions for UK international shipping based on fuel sales records from DUKES.	Emissions for UK international shipping based on AIS data (same method as domestic and non-UK shipping).	As above.	As above. Additionally: Emissions for UK international shipping based on AIS data (fuel consumption basis) is higher than that estimated from DUKES (fuel sales basis). But these two estimates are not directly comparable as UK international shipping also uses fuel not sold in the UK.
AIS message gaps	Emissions calculated from gaps between consecutive AIS messages of >24hours were included as "domestic" for selected vessel types.	Emissions calculated from gaps between consecutive AIS messages of >24hours have been excluded	To avoid allocating a large emission estimate representing >24 hours vessel operation to a single 1km grid cell, which would misrepresent the location of emissions. There was no need to exclude this from the NAEI as that inventory is not spatially disaggregated.	Lower emissions included in the NAEI maps than in the National inventory total. However, the emissions not included in mapping are far from the UK coastline and not expected to have a large impact on pollutant concentrations in the UK.
Geographic limits	Emissions from vessels were calculated from AIS data, which were limited by the distance from shore-based AIS receivers, without an additional imposed geographical limit.	Emissions from vessels were calculated from AIS data, which were limited by the distance from shore-based AIS receivers, and with an additional imposed geographical limit of the NAEI grid extent.	To align with the technical specification of the NAEI mapping outputs.	As above.

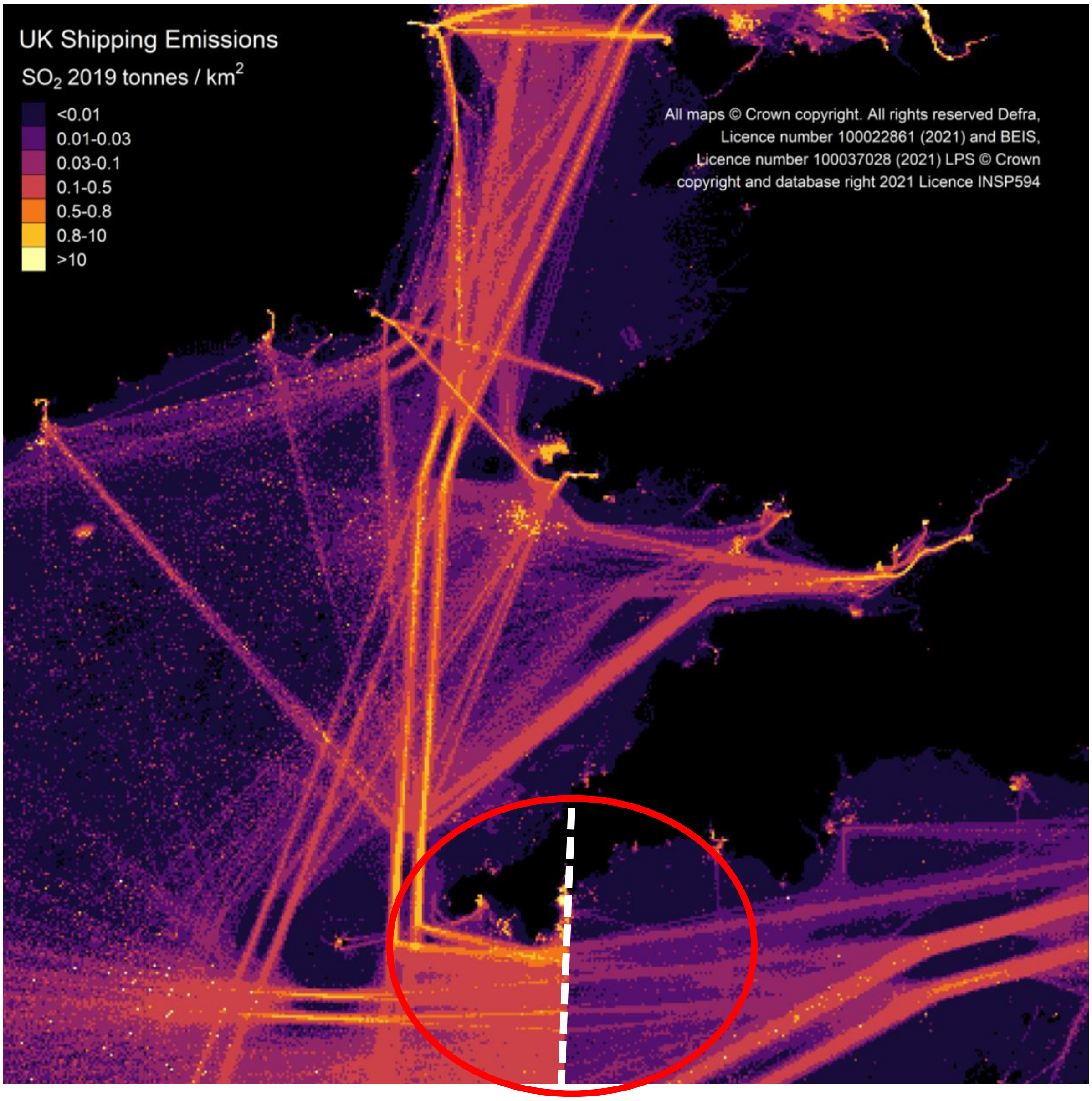
Figure 3-11 NOx shipping emissions by trip type for 2019



Although differences exist between NAEI maps and the National Inventory, mapping outputs also illustrate how key features of the inventory compilation process affect the geography of emissions. One such example is the impact emissions control areas have on the pattern of SO_2 emissions. From 2015 onwards, vessels within emission control areas are assumed to switch from fuel oil to gas oil[54]. The boundary of the Sulphur Emission Control Area (SECA) around the UK is clearly visible in maps of SO_2 from shipping emissions. Part of the SECA boundary is present off the coast of south-west Britain, and this is shown in Figure 3-12. Along the length of the SECA boundary (dotted white line) a pronounced linear drop in emissions can be seen from west to east. This reflects the fuel switching process, as vessels burn cleaner gas oil when within the SECA (to the east of the boundary) but burn fuel oil when outside its limits, emitting greater amounts of SO_2.

[54] The International Maritime Organisation (IMO) framework of the International Convention for the Prevention of Pollution from Ships (MARPOL) has regulated in MARPOL Annex VI to limit the sulphur content of fuels used by ships and allow the introduction of emission control areas.

Figure 3-12 SO_2 emissions from all shipping around the south-west of the British Isles. The SECA (Sulphur Emission Control Area) to the east of the dotted white line (bottom centre) can be seen as a reduction in emissions.



3.8 Inland waterways

Emissions from inland waterways were first included nationally in the 2010 inventory. These were previously not reported in the UK inventory because there are no national fuel consumption statistics on the amount of fuel used by this sector in DUKES. However, as all fuel consumed by all sources in the UK was captured by the inventory, emissions from inland waterways were effectively captured, but were previously misallocated to other sectors using the same types of fuels.

Emissions from the inland waterways class are now calculated according to the following categories and sub-categories:

1. Sailing Boats with auxiliary engines;
2. Motorboats / Workboats (e.g. dredgers, canal, service, tourist, river boats);
    a. recreational craft operating on inland waterways;
    b. recreational craft operating on coastal waterways;

c. workboats;
3. Personal watercraft i.e. jet ski; and
4. Inland goods carrying vessels.

A bottom-up approach was used based on estimates of the population and usage of different types of craft and the amounts of different types of fuels consumed. Estimates of both population and usage were made for the baseline year of 2008 for each type of vessel used on canals, rivers and lakes and small commercial, service and recreational craft operating in estuaries or occasionally going to sea. For this, data were collected from stakeholders, including British Waterways (now the Canal and Rivers Trust), DfT, Environment Agency, Maritime and Coastguard Agency (MCGA), and Waterways Ireland. Various proxy statistics were used to scale activities from 2008 to other years, as described in the UK Informative Inventory Report (Churchill, et al., 2021).

Sparse data were available to estimate the distribution of emissions from this sector. As a result, total emissions from the inland waterways sector were mapped using datasets of vessel activity for a limited number of Great Britain and Northern Ireland's waterways. Lock passage information for Northern Ireland were provided by Waterways Ireland for the Shannon Erne Waterway and the five Locks on the Lower Bann Navigation as well as a geospatial dataset. Data for GB, including geospatial data, were provided by the British Waterways. Where data gaps were identified, additional activity data were taken from the 'Members' area of the Association of Inland Navigation Authorities website[55].

The activity data were used in combination with geospatial information to calculate the product of boat activity and distance. This was subsequently combined with the UK's emissions data.

3.9 Aircraft

The NAEI estimates national total emissions from aircraft operating on the ground and in the air over the UK, up to an altitude of 3000 feet (equating to the take-off and landing cycle). Emissions estimates are calculated from the number of movements of aircraft by type at UK airports (data provided by the Civil Aviation Authority) and from estimates of fuel consumption for component phases of the take-off and landing cycle. Emissions from aircraft at cruise are also included in the NAEI, although these emissions are not mapped.

The locations of airports and their ground level footprints were revised and mapped with the use of satellite imagery. Take-off and landing emissions were allocated to the individual airports based on the modelled emissions at each airport using the CAA data outlined above. In addition, at larger airports emissions from aircraft on the ground (e.g. whilst taxiing or in a holding pattern) have been separated from emissions whilst in the air (e.g. climb and approach phases below 3000 feet) as such activities tend to be more prevalent at larger airports, where greater movement by aircraft on the ground is often required. The former was mapped evenly over the airport apron and runway, the latter over a 4 km strip adjacent to the end of the airport runways representing emissions from aircraft at climb or descent below 3000 feet. For smaller airports, all emissions were mapped evenly over the airport footprint. Unlike the rest of the airports, emissions from Heathrow were distributed based on the geographical aircraft activity as this is reported by the Heathrow Airport Emission Inventory (Walker, 2018).

The maps for aircraft emissions provide a useful split of emissions occurring on the ground and in the air for the air pollution modelling community.

3.10 Industrial off-road

Industrial off-road emissions derive from a range of machinery used in agriculture such as tractors and combine harvesters; industry such as portable generators, forklift trucks and air compressors; construction such as cranes, bulldozers and excavators; domestic lawn mowers; and aircraft support equipment. These emissions have historically been mapped based on employment in heavy industry. In earlier studies, modelling artefacts have resulted in emission estimates being disproportionately

[55] https://www.aina.org.uk/

allocated to city centres because of the location of the headquarters of many companies associated with heavy industry and therefore employees in such areas. The NAEI team have reviewed the employment dataset for the maps to identify and remove those instances where high industrial employment in urban areas did not correlate well with expected heavy industry activity.

3.11 Accidental fires and small-scale waste burning

The distribution of accidental fires across the UK is particularly uncertain. Distribution maps were made using the Land Cover Map 2007 supplied by CEH[56]. The land cover type was matched to the type of accidental fire as shown in Table 3-5. Classes were added together on an equal basis to make aggregated land cover maps for each NAEI sector.

The 'Accidental fires - dwellings' and 'Accidental fires - other buildings' sectors have been mapped using the ONS population estimates[57].

Table 3-5 Land cover data used to distribute emissions from fires

NAEI Source sector	Land Cover classes
Accidental fires - forests	Broad leaved/mixed woodland Coniferous woodland
Accidental fires - straw	Arable cereals Arable horticulture Arable non-rotational
Accidental fires - vegetation	Set-aside grass Natural grass Calcareous grass Acid grass Bracken Bogs (deep peat) Dense dwarf shrub heath Open dwarf shrub heath
Accidental fires - vehicles	Suburban
Small scale waste burning	Suburban
Bonfires	Suburban

3.12 Landfill sites

Emissions from landfill sites feature in the NAEI in two different source sectors. The first is landfill gas combustion which is used for electricity generation and/or heating, which are allocated to the energy sector. These emissions are mapped as point sources. The second sector comprises emissions from the landfill sites themselves, which are allocated to the waste sector. This sector was mapped as an area source as gas release has the potential to occur across these open-surface waste sites (uniform release rates are assumed across individual sites due to limitations in the spatial information).

The information on the location and scale of landfill activity varied across the UK and it is based on 2010 datasets. Information on the geographical extent of landfill sites in England and Wales was available from the Environment Agency in GIS format. In Scotland and Northern Ireland, the geographic locations of landfill sites were available from SEPA and DAERA, but not the spatial extent. SEPA figures, however, also provided estimates of infill received by each landfill in 2008. Using this information, estimates of the Municipal Solid Waste (MSW) arisings received by each landfill site were

[56] https://www.ceh.ac.uk/services/land-cover-map-2007
[57] https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/

made and used as a proxy for the emission rates for landfills in the UK. Distributions were calculated using:

- Regional MSW waste arising by Devolved Administration;
- Actual infill rates for landfills in Scotland for 2008; and
- Area of landfill as a proxy for infill rate for sites in England, Wales and Northern Ireland (information on the area of landfill was absent for Northern Ireland, hence all operations were assumed to be of similar size).

For the methane emission maps, a set of landfill site boundaries was generated for the NAEI 2017 to allow a more accurate representation of methane emissions from current and historic sites. The information on the location and scale of landfill activity varied across the UK. Information on the geographical extent of landfill sites in England and Wales was available from the Environment Agency and Natural Resources Wales in GIS format. In Scotland and Northern Ireland, only the geographic locations of landfill sites were available from SEPA and DAERA. Approximate spatial extents for each site location were created based on a combination of aerial images, OS MasterMap and/or OpenStreetMap. For England and Wales, where all or part of a historic site had been re-opened, this part was removed where it overlapped the new site boundary data to avoid double counting. An age band was assigned to each landfill site boundary based on current or historic site details and Waste Return Notices. Each band was allocated to a proportion of the total annual emissions recorded per Devolved Administration as shown in the table below.

Table 3-6 Proportions of the 2017 landfill methane emitted from sites operated in different periods

Site class	Waste deposited in years	Methane generated in 2017
1	1945-1979	4.5%
2	1980-1989	7.5%
3	1990-1999	19%
4	2000-2009	35%
5	2010-2017	34%

3.13 Upstream oil and gas

Emissions from offshore installations are provided by BEIS, based on information supplied by the operators of those installations. These include:

- Use of gas oil;
- Use of fuel oil;
- Use of natural gases;
- Flaring;
- Venting of gases;
- Loading of crude oils into tankers;
- Fugitive emissions from valves, flanges etc.;
- Direct process emissions.

These estimates are aggregated for the UK totals. For the UK emission maps, the reported emissions by installation were split into emissions from fixed platforms and mobile units such as diving support vessels and drill rigs. The position of wells is known, and so the location of the well that led to the discovery of each field is then used as the location of all fixed platforms associated with that field. It is unlikely that the position of these initial discovery wells will exactly coincide with the position of the platforms intended to exploit those discoveries. However, it was assumed that they will be in that vicinity and, in the absence of better information, this is the best compromise that can currently be achieved. In some cases, this will inevitably lead to platforms being mapped some distance away from their actual position. This is more evident in large fields with multiple platforms that clearly cannot all be located at the same place. For example, the Brent & Forties fields have multiple platforms that are located some kilometres apart but are mapped at the same location. However, for the purposes of modelling long range air pollution from these sources, this is not a significant problem. Similarly, there is no population exposure to released pollutants from these sources within their vicinity, other than workers present on the platforms themselves, as there might be for terrestrial industrial installations. Other platforms are used to exploit multiple small fields and so are likely positioned between those fields. For the moment though, they are mapped by allocating to a single field and therefore located using the discovery well for that field.

In response to NECD inventory review findings, a recalculation was made to the UK inventory and also in the point sources dataset to correct an over-report for NMVOC from oil-loading at an oil terminal.

3.14 Other sectors

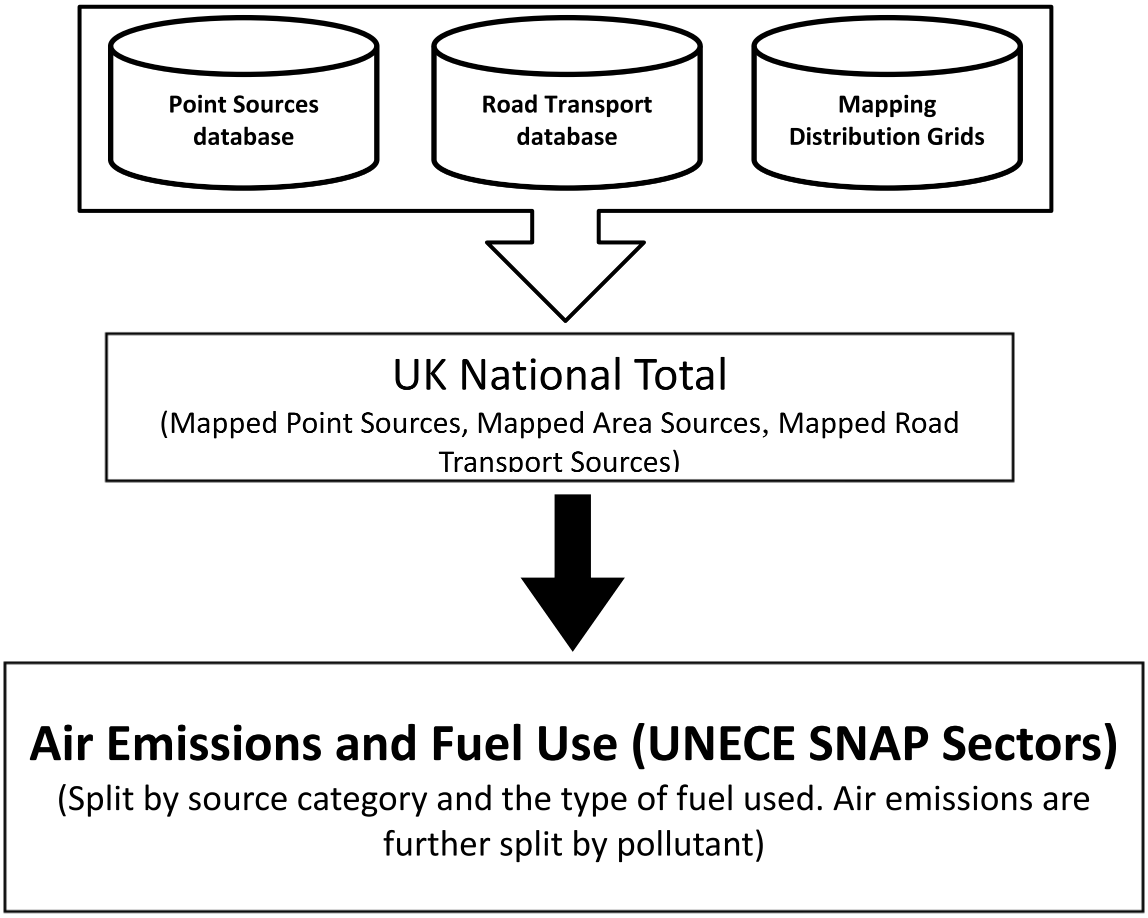
Emissions of PM_{10} from mines and quarries were distributed using data from the British Geological Survey on the locations of mines and quarries in the UK. This data set includes the location of the site and a brief description of products and commodities. There are no data on actual production amounts for each mine or quarry. Regional production statistics for the various commodities were therefore distributed across the sites in each region on an equal weight basis. Only open cast mining and quarrying activities are included. The production statistics were aggregated to 1 km^2 grid and PM_{10} emissions distributed on this basis.

4 Emission maps and data products

4.1 Compilation of maps

The 1x1km[58] resolution maps are compiled in a GIS environment. Maps for each sector are generated by summing the spatially distributed proportions of the NAEI national total (see Figure 4-1).

Figure 4-1 GIS based methodology



Area and road transport source emissions are aggregated for the 11 UNECE source sectors and (GNFR[59] sectors for international reporting), and point source emissions aggregated to a 1x1km grid are added to the area source emissions to calculate a UK total emission map such as those shown in Figure 4-2, Figure 4-3, and Figure 4-4 below for PM_{10}, SO_2 and CO_2 emissions respectively.

A full set of maps is available at: https://naei.beis.gov.uk/data/map-uk-das

and through an online interactive GIS tool at: https://naei.beis.gov.uk/emissionsapp .

[58] Mapped outputs for ammonia (NH_3), methane (CH_4) and nitrous oxide (N_2O) are produced under the same framework, but some sources are limited to 5x5 km resolution due to non-disclosure constraints
[59] http://www.ceip.at/fileadmin/inhalte/emep/doc/AnnexIII_Aggregation_gridded_data_300909.doc

Figure 4-2 UK total PM_{10} emissions in 2019

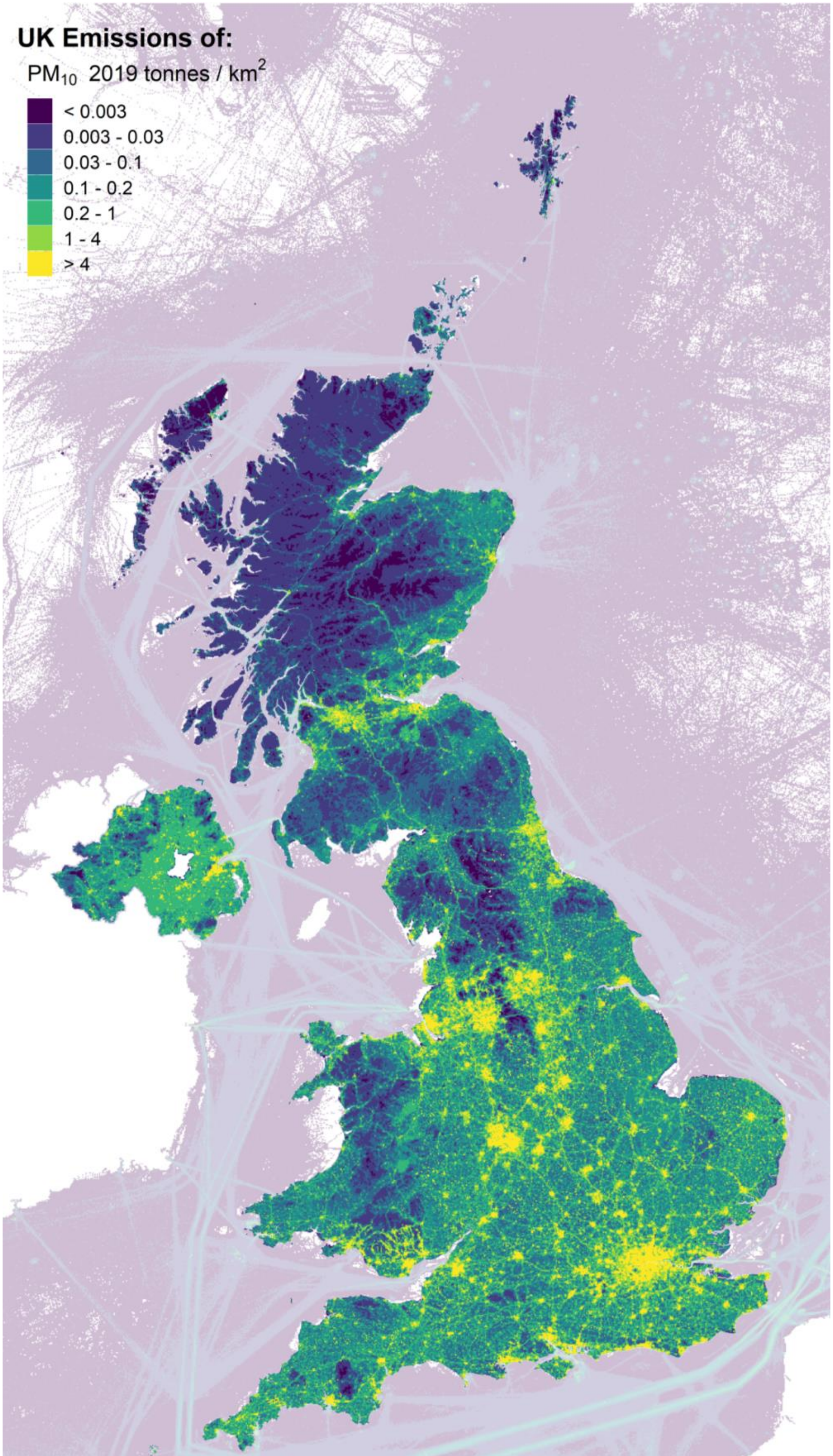


Figure 4-3 UK total SO_2 emissions in 2019

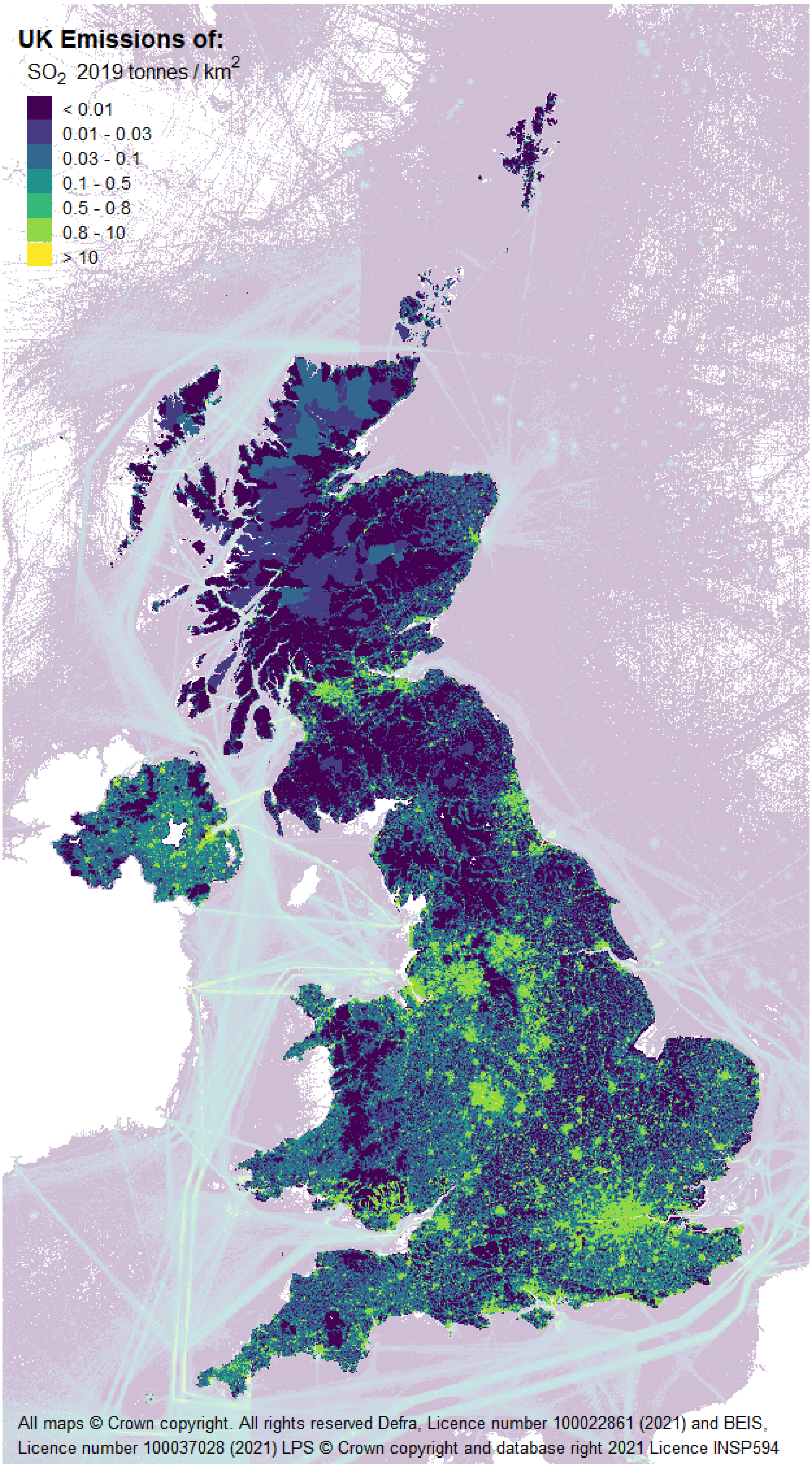
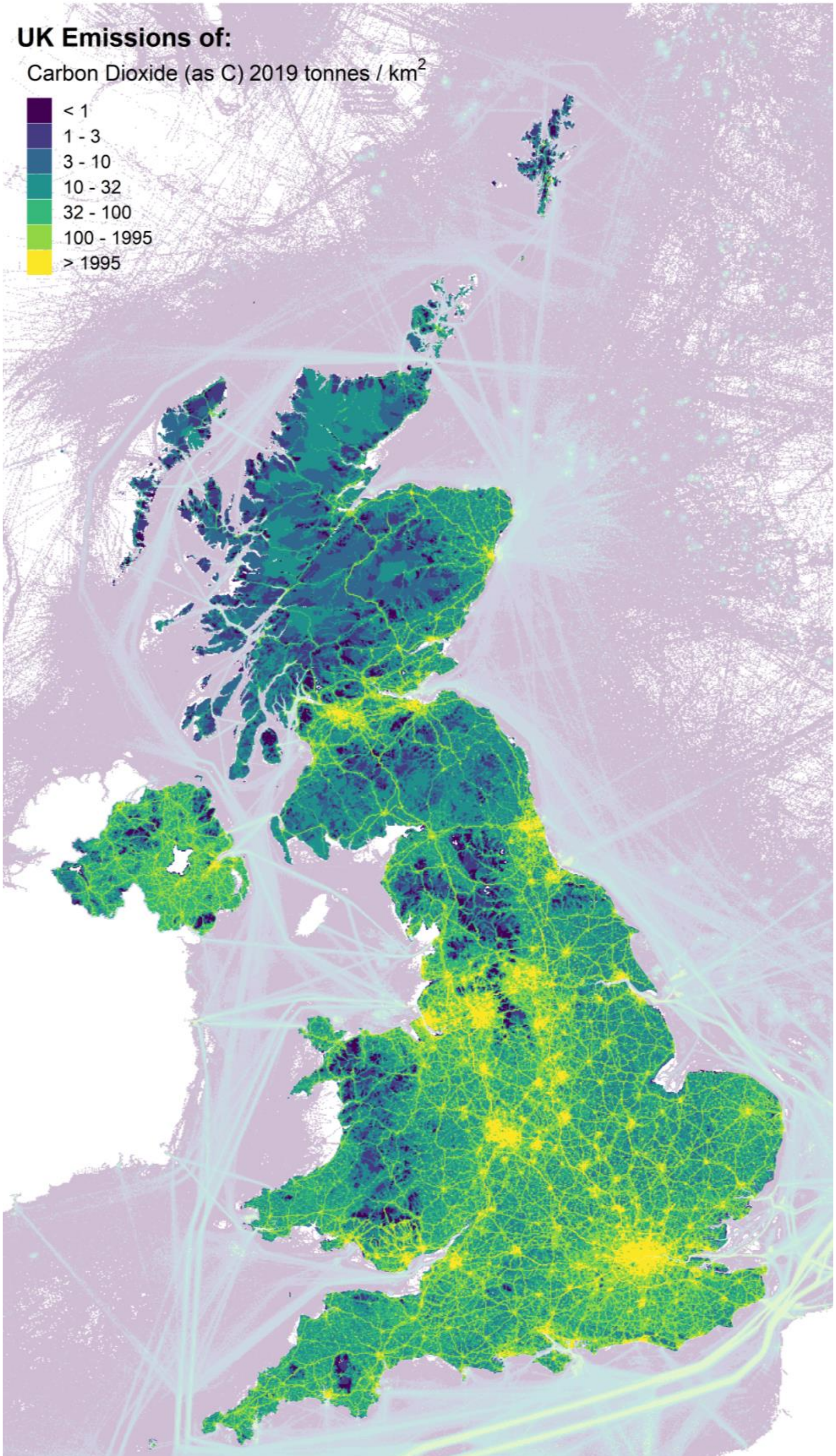


Figure 4-4 UK total CO_2 emissions in 2019 excluding emissions from Land Use Change



5 Uncertainties and verification

The assessment of uncertainties to spatially disaggregate the emissions is achieved via a semi-quantitative and quantitative approach outlined in the following sections. It should be noted that these assessments of uncertainty do not include an assessment of uncertainty of the emissions themselves.

The semi-quantitative approach for assessing the overall emission map quality involves comparing the proportion of emissions, by pollutant, mapped as point or area sources against the national total. Lower uncertainty is associated with emissions from point sources, as the emissions are geographically constrained to a particular location (i.e. industrial stacks). In terms of emission outputs, point sources are often directly monitored by operators and/or have a record of the materials processed on site, used to inform the mapping and therefore are inherently less uncertain.

A quantitative approach for assessing uncertainty in the pollutant maps is subsequently achieved through the application of uncertainty scores to emissions associated with different polluting activities derived from comparison of NAEI and modelled emissions. This better represents the uncertainty in the geographic distribution of emissions of area sources, with area source grids based on actual production/emission data providing a low uncertainty score.

For uncertainties related to the GHG inventory please refer to Brown et al. (2021) and see Annex 2.

Verification, involving the comparison of independently-derived data (i.e. ambient air quality monitoring) and model outputs to provide a 'reality check' on the emissions estimates is briefly outlined, and discussed in further detail by Brookes et al. (2021).

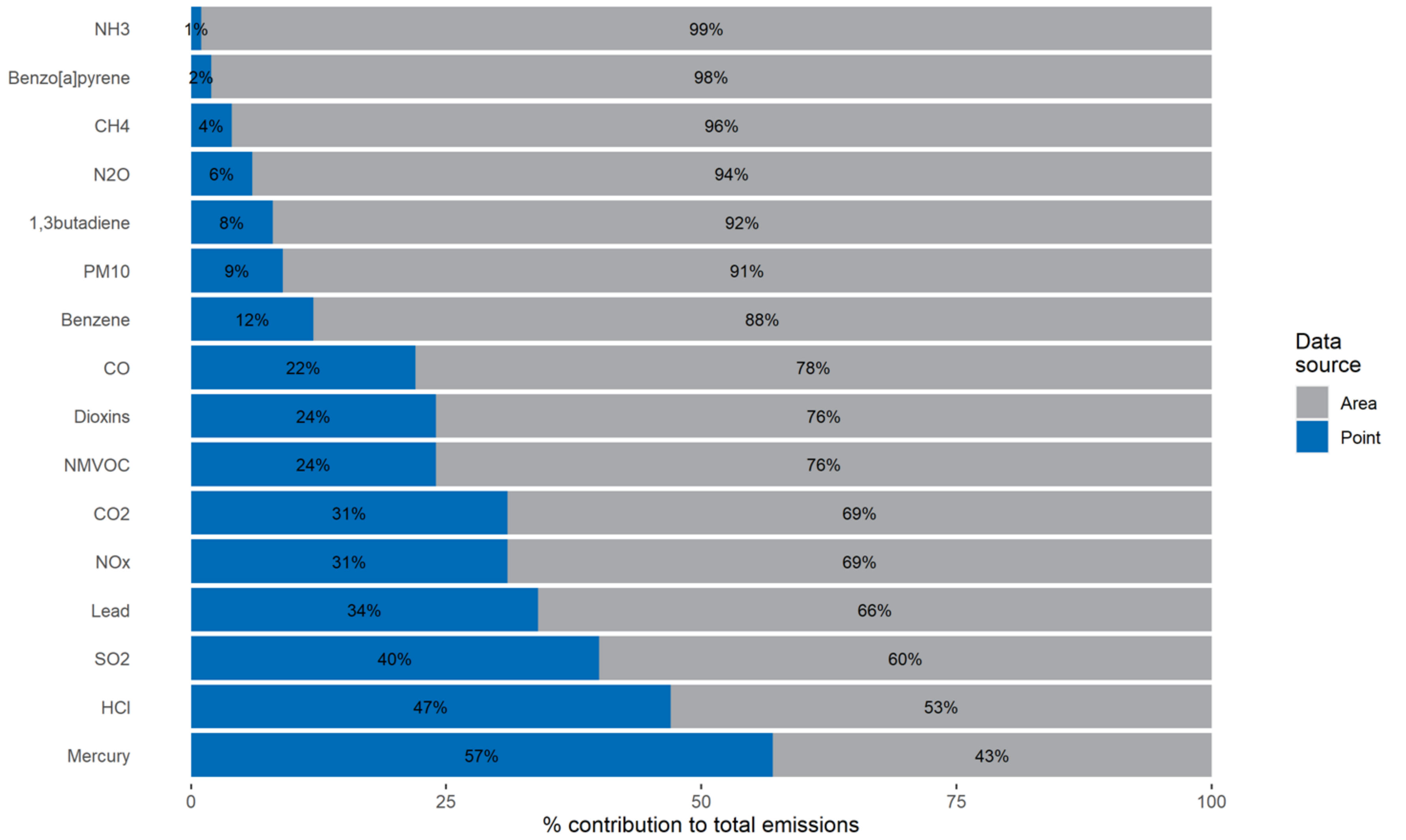
5.1 Estimating uncertainty

Whilst there is an internationally agreed methodology on how to create spatial maps, there is no internationally agreed methodology on how to estimate uncertainty from such maps. Countries develop their own approaches, although many elements are likely to be common between them. Our approach is discussed in this section.

As noted in previous sections, the mapping of emissions has been divided into point and area sources. In general, mapped point source data are expected to be more accurate than those for area sources since they are based upon reliable data produced for regulatory purposes. In contrast, area source emissions are mapped using a variety of surrogate data types of varying quality. Every attempt is made to use the highest quality area source data available (within overall budgetary constraints), and the NAEI team seeks to constantly improve the accuracy of area source mapping by using new, updated, and additional information when this will improve mapping. However, in some cases surrogate statistics used to spatially distribute emissions from a pollutant source may not be ideally suited to this task.

Assessing the overall quality of emission maps is an important component of mapping the NAEI, and the project has approached this in two ways. Firstly, a high-level appreciation of uncertainty can be obtained by comparing the proportion of national total emissions that are mapped as point or area sources. Point sources are generally recognised as superior to area sources in terms of the accuracy and precision of both emissions estimates and their location. The percentage of point and area sources that contribute to pollutant totals is shown in Figure 5-1, and suggests that maps for mercury, dioxins, hydrogen chloride, sulphur dioxide and carbon dioxide are likely to be of higher quality than those for ammonia, benzo[a]pyrene, methane, nitrous oxide and PM_{10} for example. However, this assessment does not differentiate between point source data which are derived from good site-specific emissions data and those which are based on simple modelling, nor does it differentiate between area sources which are mapped using reliable appropriate surrogate statistics and those which use less optimal datasets.

Figure 5-1 Contribution of point sources to mapped emission totals (2019)



A more sophisticated approach to assessing uncertainty in the maps is to use 'data quality ratings' ranging from 1 (highest quality) to 5 (lowest quality) for the mapping of emissions of each pollutant and source. An overall 'confidence rating' can then be calculated for each pollutant map as follows:

$$(\text{Emission}_A \times \text{Rating}_A + \text{Emission}_B \times \text{Rating}_B \text{ etc.}) / \text{Emission}_{Total}$$

where, Emission_A, Emission_B etc. are the emissions of the pollutants from each of the sources in the inventory, and Rating_A, Rating_B etc. are the data quality ratings applied to the mapping of emissions from each of the sources in the inventory.

Some general rules have been applied when defining data quality ratings for mapping procedures. Point source data from industry and regulators are given a rating of 1 because the locations of emissions are 'known' precisely. Modelled point source data are given a quality rating of 2 to reflect the fact that, although all point sources are known, there is uncertainty regarding the distribution of emissions over these sources. Quality ratings for area/line sources are allocated following an assessment of:

- The quality of the spatially resolved data used to make the grid;
- The reliability of the grid as a measure of emissions from a source.

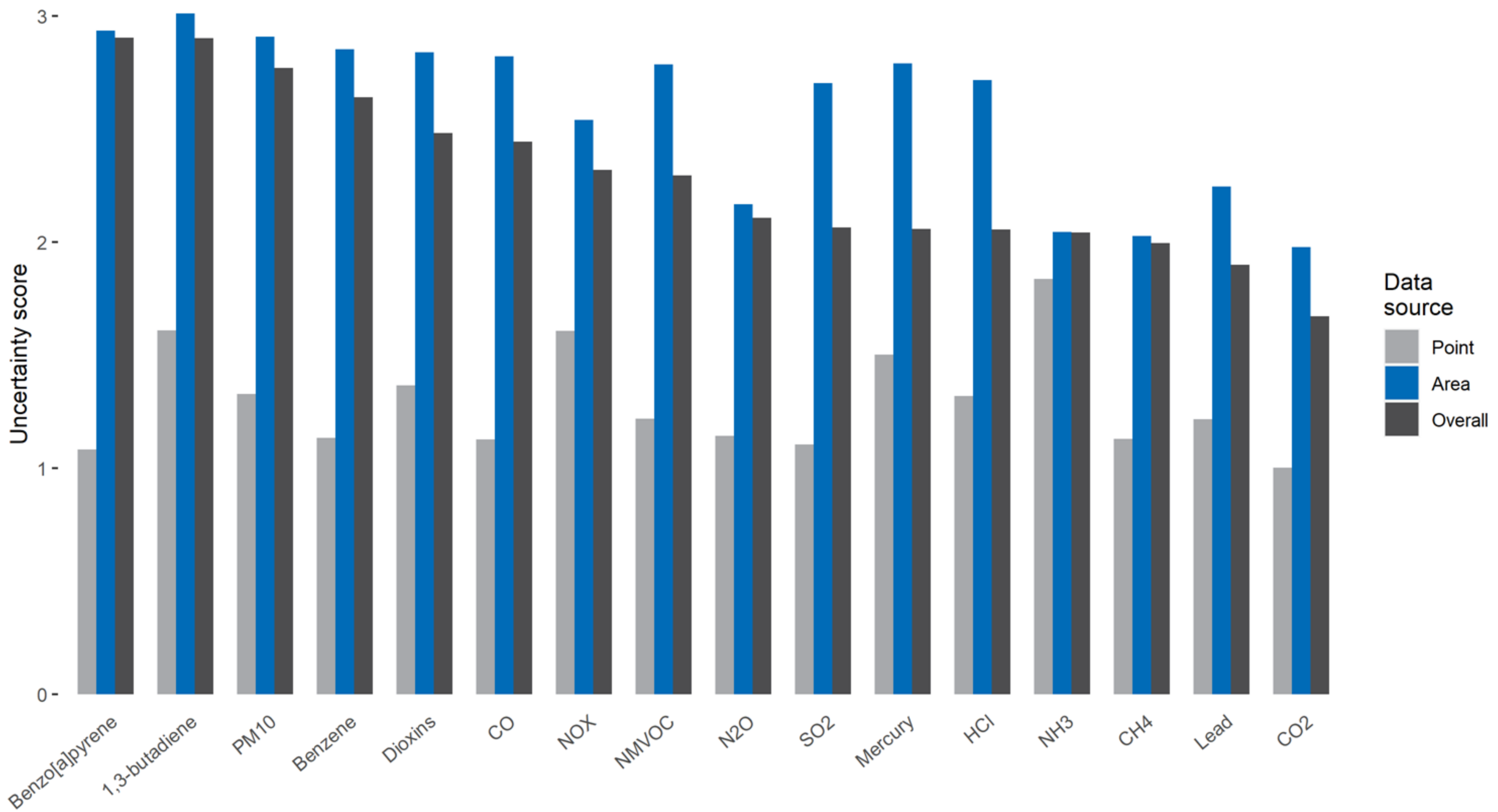
We have not assigned an uncertainty range to each scale point e.g. a score of 1 being equivalent to an uncertainty of <10%. Considerable work would be needed to quantify all the grids sufficiently accurately. In the future, we are considering quoting the uncertainty of spatially disaggregating the emissions based on information such as e.g. activity data, fuel consumption or emissions. This would accompany the information in Table 5-1 and this would provide at least an indication of the underlying uncertainty in the data used for the gridded data. Even though the current uncertainty approach does not generate a full qualitative assessment of uncertainty, the resource efficient semi-quantitative approach still allows methodological improvements of the gridded emissions to be prioritised.

Table 5-1 Spatial uncertainty scoring system

Emission	Score		Typical remark
Area	1	Highest	Use of grids based on actual capacity/production/emissions data for a given source
Area	2		Use for grids which is based on good, relevant, data at high level of definition but with maybe some minor shortcomings (e.g. road transport & population emissions)
Area	3		Use of grids which are believed to be fairly good, albeit with some significant shortcomings (e.g. grids based on employment data which define a particular sector)
Area	4		Use of grids which are believed to be fairly poor with major shortcomings (e.g. grids based on employment data where a sector cannot be clearly defined, such as the 'fabrication of metal products')
Area	5	Lowest	Low quality grids (e.g. use of population or general employment statistics to map a specialised sector with limited numbers of processes or highly regionalised presence. These include cider manufacture, marine coating etc.)
Point	1	Highest	Operator data available for some or all points
Point	2	Lowest	Modelled data

A rating is defined for each of the above parameters and the mean is used as the overall data quality rating for the source sector. For example, a grid based on 2019 ONS population estimate data has been allocated a rating of 2 since it is based on very accurate census data which is generalised across the 1x1 km grid. The use of such a grid to map emissions from decorative paint use is considered appropriate and has been assigned a rating of 1. The area source data for decorative paints therefore has an overall quality rating of 1.5. On the other hand, while a grid based on suburban land cover is also good quality and assigned a rating of 2, its use to map emissions from small scale waste burning (bonfires) is considered much less reliable and is given a rating of 4. Area source data for these emissions has an overall quality rating of 3. Figure 5-2 shows the resulting confidence ratings for the NAEI pollutant maps.

Figure 5-2 Confidence ratings for mapping elements of the 2019 NAEI maps



5.2 Verification

Verification can be used to help build confidence in the mapping work and to prioritise future methodological improvements. It is good practice to verify emissions maps, particularly if they are to be reliably used in dispersion models to predict potential exceedances of air quality objectives and European limit values.

Within this context, it is helpful to draw a distinction between emission inventory verification and validation. Validation is the process of checking that emissions have been estimated using the appropriate protocols, while verification involves comparison with independently derived data such as ambient monitoring data and model outputs to provide a 'reality check' on the emissions estimates.

There are no other emission maps which can verify, in other words be directly compared to, the maps which are produced from this work[60]. However, there are steps which can be taken to help verify this work.

The NAEI uses the outputs from Defra's Pollution Climate Model (PCM) maps (produced under the Modelling of Ambient Air Quality, MAAQ project) to help judge the quality of the emission maps generated in this work. Since atmospheric concentrations depend on complex processes of dilution, atmospheric chemistry and dispersion of emissions in the atmosphere there will not be a direct relationship between the atmospheric concentration and emission maps, but concentrations and emissions are interdependent.

The model calibration indicates how well the modelled concentrations, based on the NAEI emission maps, correlate with the measured concentrations at the locations where those measurements are made. The model calibration is completed after the spatial emissions team finishes and reports the NAEI emission maps and methodology report. Therefore, the team does not have this information available when writing the report. The closest alignment of data sets is a comparison of the previous year's MAAQ with the current NAEI emission maps. The spatial emissions team routinely seeks feedback from the MAAQ project in a programme of continuous improvement so that features identified through the application of the emissions data can be challenged and methodologies reviewed.

The annual mean background concentration of air pollutants is made up of three parts:

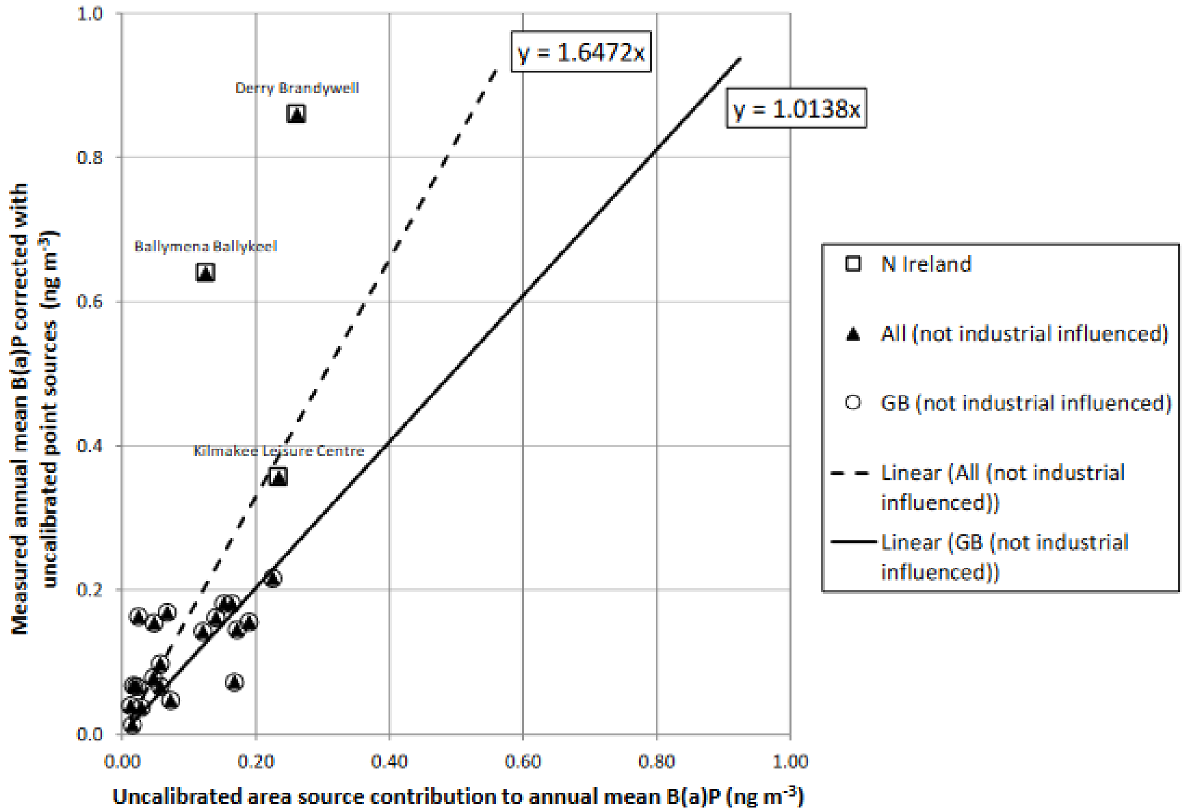
- Contributions from relatively distant major point and area sources such as power stations, large conurbations and transboundary sources. Measurements from monitoring sites well away from local sources, for example from rural stations within the UK's Automatic Urban and Rural Network[61] (AURN), provide good indications of the spatial variation of concentrations arising from distant sources;
- Contributions from local point sources; where for example, concentrations are modelled using dispersion models parameterised using data from individual industrial sites;
- Contributions from more local diffuse sources (area and line sources such as road transport related activity).

The NAEI area source maps are routinely used in air quality models to characterise the local contribution to ambient concentrations of air pollutants. National scale air quality modelling activities use emissions from the NAEI area source maps to model ambient concentrations across the whole UK. As part of this work, a dispersion kernel modelling approach is applied to the area source emission maps within an area of 33 km x 33 km square surrounding each receptor location, to calculate the uncalibrated contribution from area sources to the ambient concentration at a central receptor. Ambient measurements from monitoring sites are then used to calibrate this area source model. The strength of the relationship between measured concentrations and the model results (based on the NAEI emissions) provides an indication of the quality of the emission distribution as it compares actual concentrations measured with predicted concentrations from the mapped emissions. The example shown in Figure 5-3 below indicates scatter in the B(a)P area source calibration as modelled using NAEI 2016 emission maps. The calibration coefficient for Great Britain (1.0138 for the year 2017) has declined over UK wide calibration coefficients for previous assessments using older versions of NAEI (6.434 for the year 2014). The reduction in the coefficients and the reduced scatter in the fit suggests

[60] Some investigatory work has been done for Defra comparing satellite air quality maps with the emission maps generated as part of this work, but the data in these maps are not directly comparable.
[61] http://uk-air.defra.gov.uk/interactive-map

improved understanding of the scale and distribution of emissions from domestic wood combustion first introduced in the NAEI 2015 emission maps.

Figure 5-3 Calibration of area source model for B(a)P for the year 2017



Further information about the comparison of monitoring and mapped area sources is described in the report 'Technical report on UK supplementary assessment under the Air Quality Directive (2008/50/EC), the Air Quality Framework Directive (96/62/EC) and Fourth Daughter Directive (2004/107/EC) for 2019 (Brookes et al, 2021).

The UK GHG inventory uses an inverse modelling approach to help verify estimates of emissions for a selection of GHGs. The approach is described in Annex 6 of Brown et al. (2021). This modelling approach is not spatially resolved. Work is planned to expand this analysis to verify the NAEI maps against atmospheric concentrations from the UK DECC network (UK Deriving Emissions related to Climate Change network[62]).

5.3 Earth observation based verification

Remote sensing using satellites could offer a unique opportunity to verify ground-up emissions estimates from the NAEI against an independently derived dataset. Satellite observations complement surface observations since surface observations are not homogenously distributed over the UK. For some pollutants satellite observations provide better coverage than current ground-based monitoring and thus enable improved spatial distributions of the pollutants. On the other hand, satellite observations may have a coarser horizontal resolution compared to ground-based measurements, and only provide one or two observations per day over the same location. The satellite observations can be influenced by weather effects such as cloud coverage, which may reduce the accuracy of retrievals.

[62] http://www.bristol.ac.uk/chemistry/research/acrg/current/decc.html

The studies on this topic, using satellite-derived data to validate emissions, are in their early stage. Most of the studies use a complex modelling approach which requires a strong technical expertise and significant computing resources to derive the emissions.

Alternative approaches to estimate emissions over large point sources, which can be natural such as volcanoes (e.g. Fioletov, et al., 2020) and anthropogenic such as cities (e.g. Beirle, et al., 2011) and industrial sites (e.g. de Foy, et al., 2015), have started to emerge during the last decades. These approaches are feasible with the satellite observations presented in this report, but it is beyond the scope of this document.

A qualitative comparison of spatial patterns between the NAEI emission maps and the satellite concentration maps can be made. It helps to highlight the main source regions and provide an initial comparison between both distributions. This report considers how well atmospheric measurements of NO_2, SO_2 and NH_3 made by satellite-based instruments compared with maps of these pollutants compiled as part of the NAEI.

5.3.1 Methodology

The approach used in this report is to compare qualitatively the spatial distribution of emissions and the distribution of remotely sensed atmospheric columns of three key NAEI pollutants: nitrogen oxides (NO_x), sulphur dioxide (SO_2) and ammonia (NH_3). This is a raw comparison and further analysis is needed to be established to fully derive emissions from these satellite observations. It is also worth noting that in the satellite observations, the natural sources cannot be been distinguished from the anthropogenic sources, while the NAEI corresponds to the total anthropogenic emissions of each pollutant.

Qualitative assessment is the preferred approach because a number of issues need to be overcome to provide a quantitative assessment of bottom-up NAEI and top-down satellite data. Emissions inventory maps use reported or inferred evidence of activity to spatially represent the amount of a given pollutant produced at source. Satellite instruments measure the spectrum emitted by the Earth's atmosphere or the backscattered solar light from the atmosphere into space. The concentrations are then retrieved from these measured spectra by algorithms. The retrieval algorithms take into account different parameters, depending on the characteristics of the instruments (e.g. angle of atmospheric sounding, instrumental noise) and of the retrieved species such as the influence of the stratosphere (e.g. (McLinden et al., 2014), the interference of other absorbing atmospheric species (e.g. Hurtmans et al., 2012), etc.

In principle, atmospheric measurements of relatively short-lived species such as NO_2 (typical lifetime: 2 to 12 hours), SO_2 (typical lifetime: from 6 hours to several days) and NH_3 (typical lifetime: from 2 hours to 2 days in exceedance conditions) should roughly correspond to the emissions sources. However, the relationship between primary emissions and atmospheric concentrations is more complex. The pollutants can be transported and so well mixed in the atmosphere, and chemical reactions through the atmosphere disrupt the connection between emissions and atmospheric composition. Inverse modelling can be used to reconstruct a source emission from remotely-sensed data (e.g. Streets et al., 2013), but such analysis is beyond the scope of this report.

Despite these differences, atmospheric composition measured by satellite instruments can still be used to check mapped emission sources by estimating the correlations between both distributions and analysing the differences.

To facilitate qualitative comparisons, the concentrations (atmospheric column) maps derived from the satellite observations are averaged within the same projection as the NAEI emission maps. Hence, broad comparisons can be made between both distributions. Units of measurements are not directly comparable with the NAEI emissions, but spatial patterns of pollutant concentrations are indicative.

5.3.2 Satellite data

In terms of data processing, satellite products and data are generally provided at different levels. The Level 0 corresponds to the unprocessed instrument data, the Level 1 corresponds to the calibrated spectra measured by the instrument and Level 3 products are the averaged data. For this report, we have used the Level 2 products, corresponding to the satellite observation per pixel.

The tropospheric NO_2 and SO_2 satellite product from the European Space Agency (ESA) have been used, while the NH_3 from the joint team of the Free University of Brussels (ULB) and the Laboratoire Atmosphères, Milieux, Observations Spatiales (LATMOS) have been used.

The NO_2 and SO_2 are measured by TROPOspheric Monitoring Instrument (TROPOMI) and NH_3 by the Infrared Atmospheric Sounding Interferometer (IASI). While TROPOMI provides data for the year 2019, it is worth noting that the current IASI NH_3 data set only covers the period from 2008 to 2018.

TROPOMI: NO_2 and SO_2

TROPOMI was launched on the ESA's Sentinel-5 Precursor mission on 13 October 2017 (Veefkind et al., 2012). It measures the concentrations at ~13:00-14:00 UK time every day.

Earth observation data appropriate for mapping atmospheric concentrations of NO_2 and SO_2 were freely available from the Copernicus Open Access Hub[63]. The corresponding data set (per orbit) was downloaded over the region covering the latitudes 48°-62°N and longitudes 12°W-4°E for the available dates in 2019. Data comes as a density measure within the troposphere. The "OFFL" (offline) version of NO_2 tropospheric columns and SO_2 0-1km columns have been used.

IASI: NH_3

IASI was launched onboard on the EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites) MetOp platforms, IASI-A on MetOp-A in 2006 and IASI-B on MetOp-B in 2012. We have used pre-release v3R (reanalysed) of the IASI L2 ammonia product (total column) (Van Damme et al., 2021) which are freely available on the Aeris data infrastructure[64]. It is worth noting IASI-C on MetOp-C was launched in 2018 but the version of the data used in this report has not been available yet for this instrument. The instruments measure the concentrations at ~09:00-12:00 UK time every day. We have downloaded the data covering the region within the latitudes 48°-62°N and longitudes 12°W-4°E.

Quality of the data

Table 5-2 summarizes the three data sets presented in this report. It is important to note that, outliers were filtered out of the IASI data. To do so, the IASI-A data for period from 2008 to 2018 have been used. For each grid, the outliers within a radius of 80 km were calculated for this period. Then, the observations of IASI-A and IASI-B for an individual year (e.g. 2018), based on this filter, were used to calculate the annual mean. The combination of both instruments helps to increase the number of observations used to calculate the annual mean. This combination of both instruments is necessary to calculate high-resolution map, as explained in the next Section 3.4, due to the coarser resolution of the IASI pixel (12 km of diameter at the nadir) compared to TROPOMI one (3.5 × 7 km).

[63] https://s5phub.copernicus.eu/dhus
[64] https://iasi.aeris-data.fr/nh3/

Table 5-2 Earth observation datasets used for emission comparisons in this report

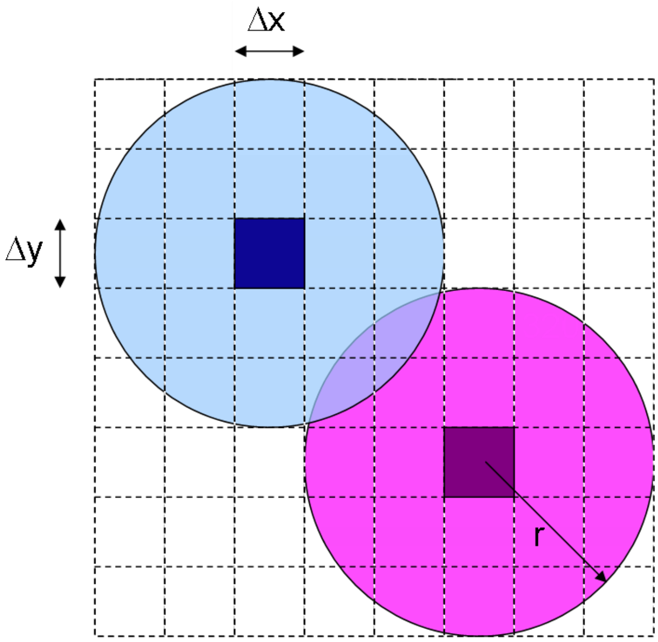
Pollutant	Dataset	Recommended filters	Period used	Measurement unit
NO_2	TROPOMI/Sentinel-5P NO_2 Tropospheric Column L2 OFFL dataset	quality flag ≥ 0.75[65]	01.01.2019 - 31.12.2019	Molecules.cm^{-2}
SO_2	TROPOMI/Sentinel-5P SO_2 1km level Column L2 RPRO dataset	- cloud coverage[66] < 20% - solar zenith angle < 70% - SO_2 0-1 km column > -3 DU	01.01.2019 - 31.12.2019	Dobson unit (1 Dobson unit = 2.69×10^{26} molecules.cm^{-2})
NH_3	IASI/Metop-A and B reanalysis ANNI-NH3-v3R	- cloud coverage < 10%[67] - morning orbit[68]	01.01.2008-31.12.2018 to calculate the outliers 01.01.2018-31.12.2018 for the annual mean	Molecules.cm^{-2}

High resolution maps

To derive high resolution maps of satellite data, the pixel-averaging approach developed by (Fioletov et al., 2011), was applied. This approach slices each satellite pixel into multiple sub-pixels, which are mapped onto a high-resolution grid. With this technique, the average of all satellite pixels centred within a several kilometre radius from each grid point is calculated, as shown in Figure 5-4. This approach exploits the fact that the location, shape and orientation of the satellite footprint on the ground varies from one orbit to another; and helps to artificially increase the resolution of the spatial distribution.

[65] https://sentinels.copernicus.eu/documents/247904/3541451/Sentinel-5P-Nitrogen-Dioxide-Level-2-Product-Readme-File
[66] Fioletov et al. (2020), https://acp.copernicus.org/articles/20/5591/2020/
[67] Van Damme et al. (2018), https://doi.org/10.1038/s41586-018-0747-1
[68] Van Damme et al. (2021), https://doi.org/10.1088/1748-9326/abd5e0

Figure 5-4 Scheme of the pixel averaging technique (source: Pommier et al., 2013). Each value of the Δx × Δy grid corresponds to the mean of each pixels centred within a circle with radius "r".



Such maps have been established for global NO_2 and SO_2 concentrations by Mc. Linden et al. (2016) al. (2016) (at 0.05°×0.05° resolution), and for CO concentrations over megacities (Pommier et al., 2013) (at 2 km × 2km resolution). This oversampling method is relevant to highlight sources which are usually hidden by background concentrations and has been recently used to the TROPOMI observations, on NO_2 (Lange et al., 2021) and on SO_2 (e.g. Fioletov et al., 2020)

This method also relies on the original resolution of the satellite pixel. Thus, 1 km × 1km maps could be calculated with the TROPOMI data (original ground pixel of 3.5 × 7 km), while a 2 km × 2km map was prepared with IASI data (original ground pixel of 12km of diameter at the nadir).

5.3.3 Comparison of NO_2

It should be noted that space-based data from TROPOMI measure NO_2 and not NO_x, which is mapped by the NAEI. However, NO_2 data from TROPOMI shows general agreement with regional-level spatial patterns present in the NAEI total NO_x emissions map (Figure 5-5).

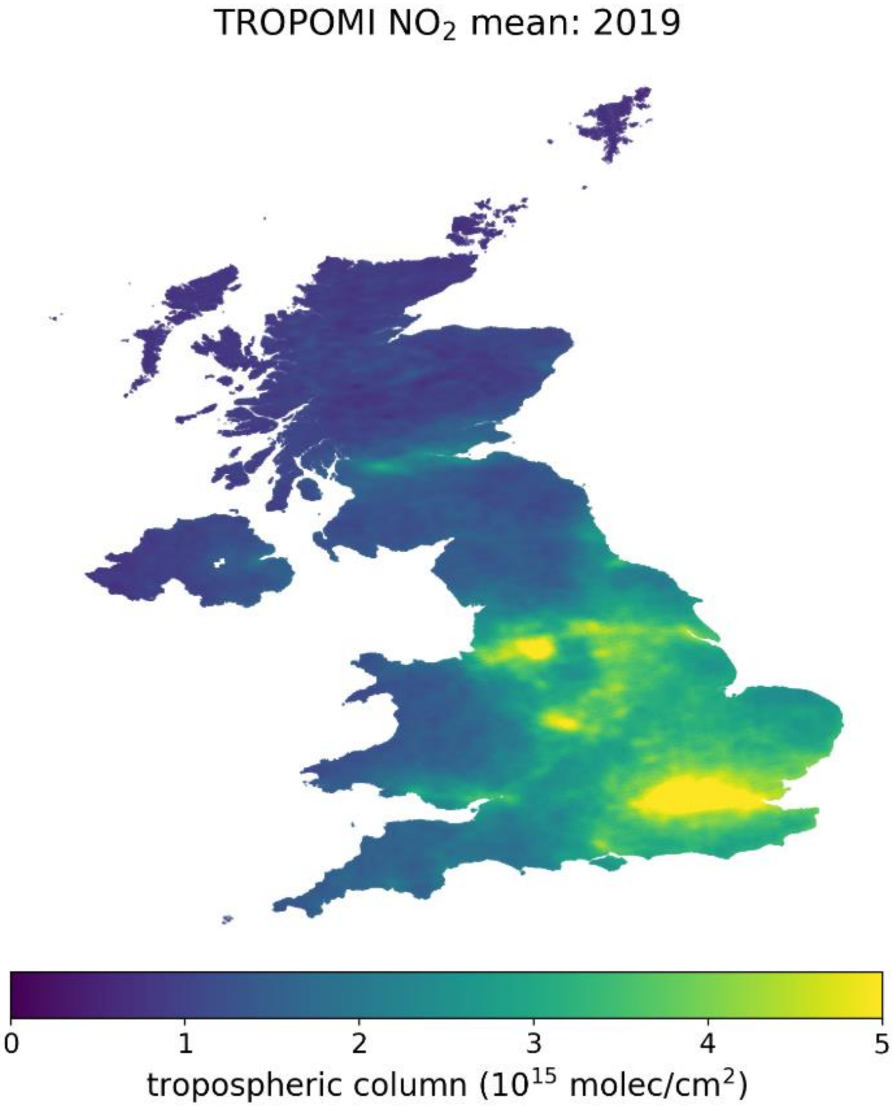
Even with the differences between both distributions in terms of quantity represented, i.e. a mean column with the satellite observations for 2019 (in molec.m^2), and the total NAEI emissions in 2019 (in tonnes), clear similarities are visible in both maps.

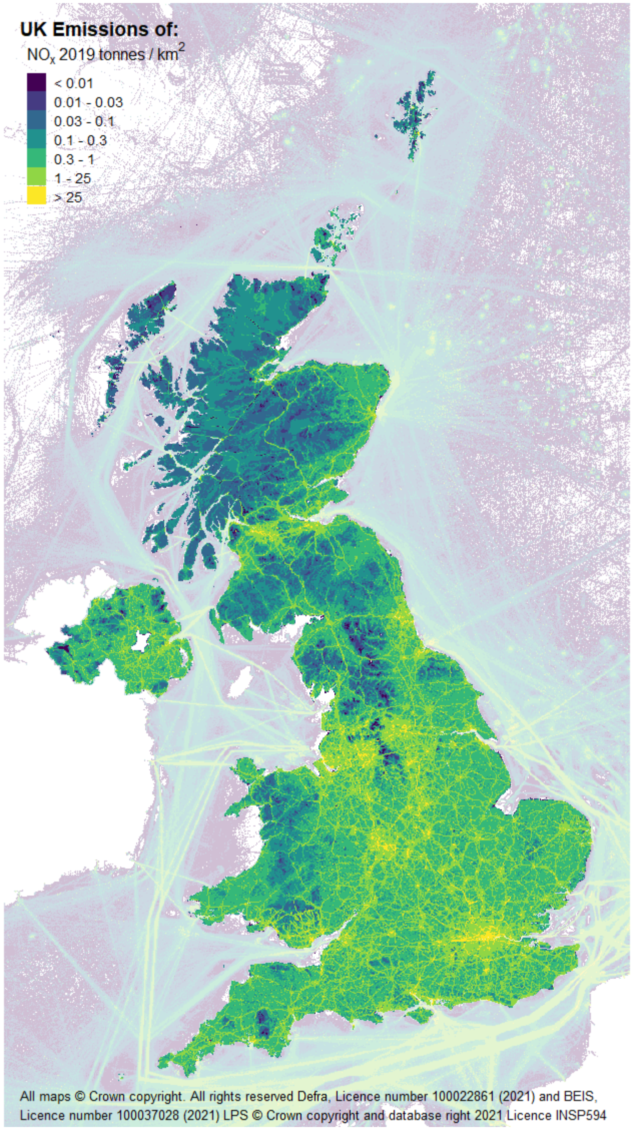
In the NO_2 mean calculated from the TROPOMI observations, large urban areas in the UK are distinguishable, such as London, Glasgow, Manchester, Birmingham, Sheffield and Leicester. Smaller cities are also visible such as the coastal cities of Bristol and Southampton.

There are some differences between both maps. The major roads are difficult to distinguish or are not captured at all through satellite observations. Cities such as Edinburgh, Newcastle, and Middlesbrough have noticeable concentrations such as the emissions shown in the NAEI NO_x map; and cities such as Aberdeen and Carlisle are not captured in the TROPOMI mean.

Overall, the main cities in the UK are visible with the TROPOMI observations and elevated NO_2 concentrations across the Midlands are captured. It is clear, with the satellite map, that London has high NO_2 concentrations during the calculated year. The satellite map also confirms the lower concentrations, and therefore lower emissions, in Northern Scotland, in Wales, in Cornwall and in the region located between Newcastle and Scotland.

Figure 5-5 NO_2 tropospheric column mean in molecules/cm^2 in 2019 (Left). Total NAEI NO_x emissions in tonnes for 2019 (Right). Both maps are plotted in 1x1km





5.3.4 Comparison of SO_2

The Figure 5-6 shows the comparison between the 0-1 km SO_2 columns measured by TROPOMI and the NAEI distribution of total SO_2 emissions for 2019.

To calculate this distribution, an additional step was required. Fioletov, et al. (2020) suggested that the TROPOMI SO_2 product suffers from “large-scale bias” which is a common issue in satellite SO_2 retrievals. To reduce the impact of the large-scale bias, the mean value calculated over a large domain (i.e. in a radius of 300 km) has been subtracted from the mean value calculated for each grid, following the method described in (Fioletov et al., 2011).

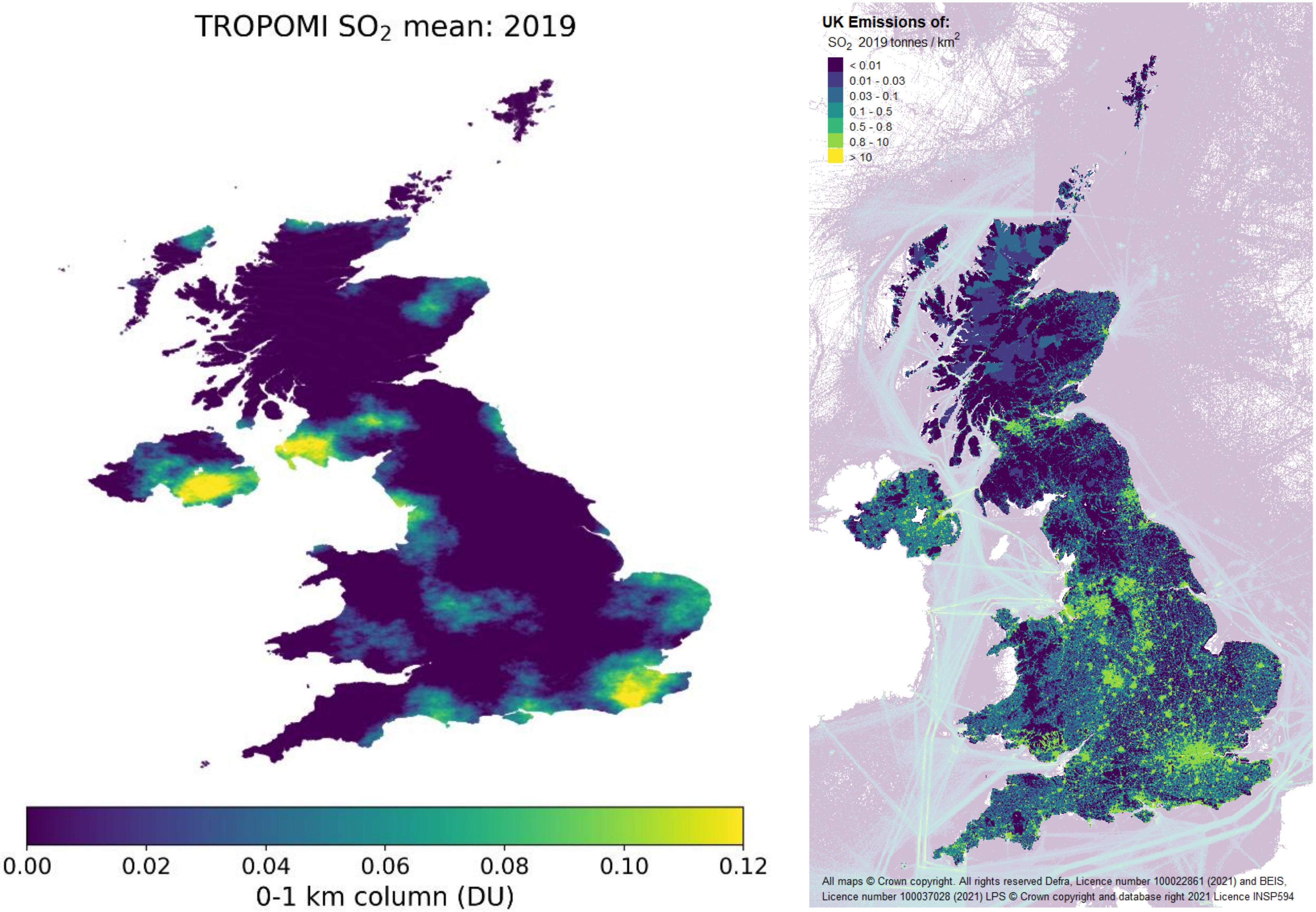
The result of this corrected 0-1 km SO_2 distribution is presented with the total NAEI SO_2 emissions in Figure 5-6.

In the satellite derived concentration map, some of larger concentrations are along some coasts (e.g. Wigtownshire in south-west Scotland). These high concentrations can be related to the existence of local sources, the transport of SO_2 from other sources and also might be related to a natural increase in concentration due to the topography. Indeed, there is more air density in the 0-1km column, and so more SO_2 molecules in the sounded column, close to the sea than over a hill or a mountain. Further investigations are needed to interpret these larger 0-1 km columns.

Despite this impact of the topography, some other regions have larger concentrations. It worth noting, the larger concentrations remain in a limited interval as displayed with the colour scale. Indeed, the larger values plotted in Figure 5-6 are around ten times lower than the higher anthropogenic sources detected in other part of the world (e.g. Fioletov et al., 2020).

There are some differences between both maps, e.g. most of the urban sources are not detected with the satellite observations (such as London, Glasgow). On the other hand, some other source regions are detected by TROPOMI and are not represented in the emission inventory such as the area in East Sussex and Armagh. However, the differences have to be interpreted with caution, since the SO_2 retrieval has been mainly designed for the detection of degassing volcanic emissions at different altitudes.

Figure 5-6 SO_2 0-1km column mean in Dobson unit in 2019 (Left). Total NAEI SO_2 emissions in tonnes in 2019 (Right). Both maps are plotted in 1x1km



5.3.5 Comparison of NH_3

As mentioned in Section 3, the current IASI data only covers the period until 2018. Thus, this section presents a comparison between the IASI distribution of NH_3 in 2018 and the NAEI 2018 emission map reported in 2020 (Figure 6.1). It is also worth mentioning that the IASI map is plotted in a 2x2km grid while the resolution of the NAEI map is 1x1km.

The satellite observations in Figure 6.1 highlight three regions where the concentrations were elevated in 2018: Norfolk-Suffolk, Lincolnshire and Staffordshire-West Midlands. In addition, both maps show consistency in their distribution, such as over Northern Ireland, Devon, and Dyfed. However, the city of London is not observed by the satellite while it is noticeable in the NAEI map. Other differences can be seen such as over the regions around Elginshire, Banffshire and Aberdeenshire. These regions have lower concentrations in the IASI map than the reported NAEI NH_3 emissions might suggest.

Based on the satellite distribution, and by assuming a constant effective lifetime for the whole UK, it is possible to estimate the emission flux for each grid of the satellite map. This approach, named box model, and used in Van Damme, et al. (2018) considers that the distribution of the concentrations matches the distribution of emissions. This assumption, despite the fact that it does not consider the transport or the dilution of the pollutant in the atmosphere, can be considered as reasonable since NH_3 has a lifetime of a few hours.

These emission fluxes are calculated by dividing the total mass (converted from the total column in each grid) with the lifetime. Thus, by considering a lifetime of 6 hours, we can get the emission fluxes as shown in Figure 6.2. The fluxes are theoretically possible to be estimated from emission inventories to produce a map that is directly comparable with the emission fluxes based on the satellite observations (Van Damme et al., 2018).

Figure 5-7 NH_3 total column mean in molecules/cm^2 in 2018 (Left). Total NAEI NH_3 emissions in tonnes in 2018 (Right). The IASI map is plotted in 2x2km while the NAEI map is plotted in 1x1km

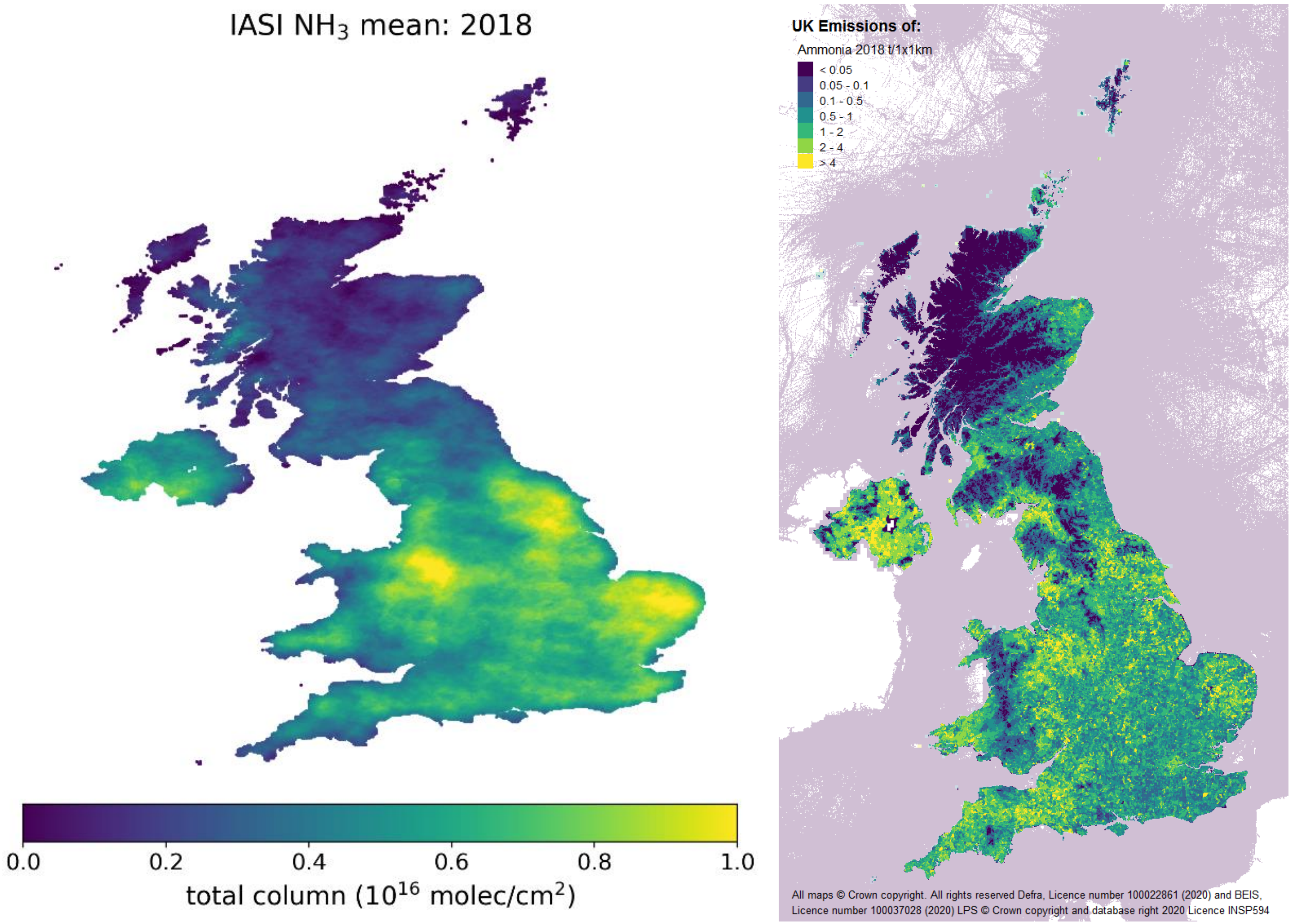
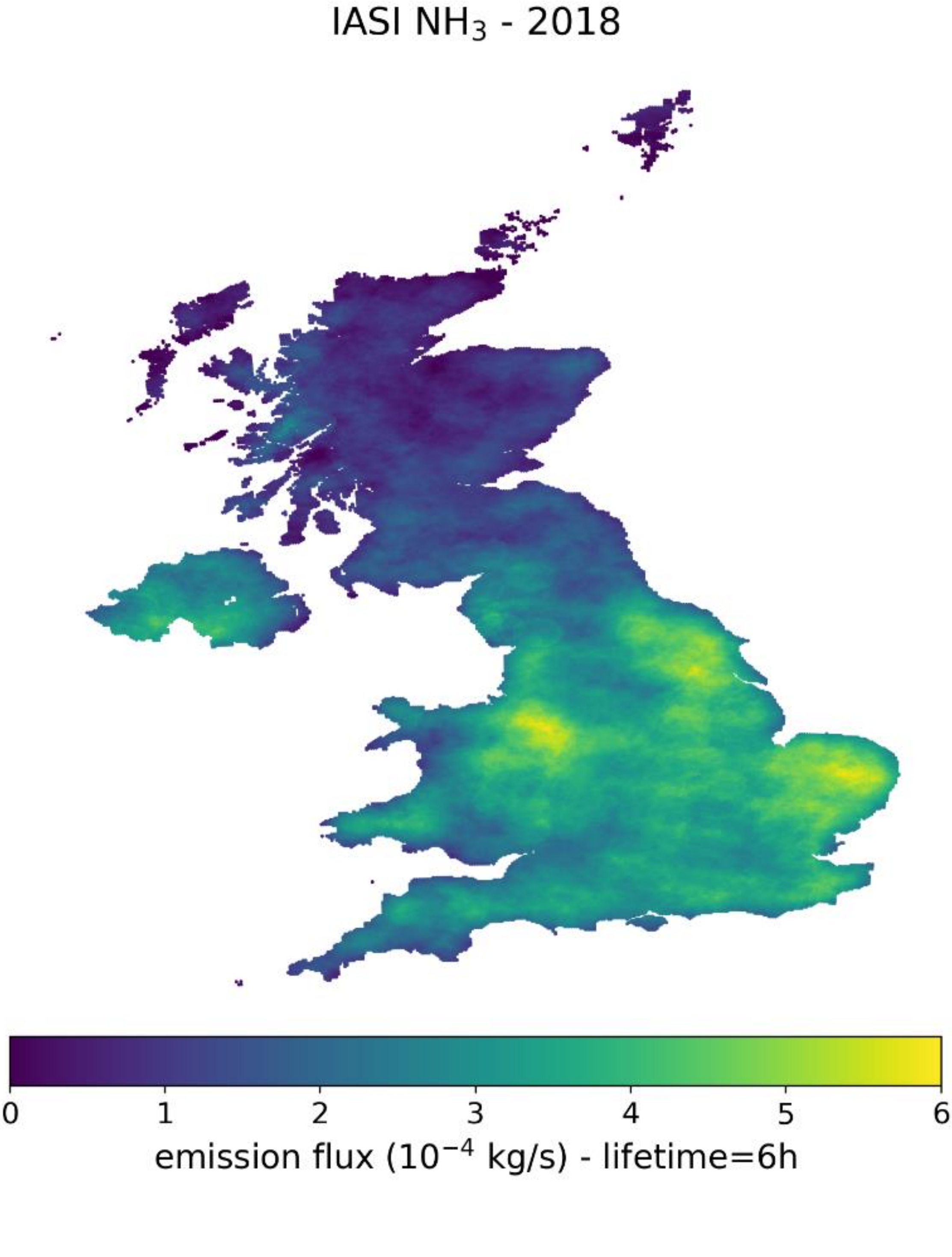


Figure 5-8 NH_3 emission fluxes in kg/s in 2018. The map is plotted in 2x2km



5.3.6 Summary

This section has presented an initial qualitative comparison between the concentration maps from TROPOMI measurements and the NAEI emission maps in 2019. The comparison for NH_3 was not possible since the IASI data for 2019 are not available yet, but a comparison for 2018 has been presented.

Even with the known limitations of the satellite observations, this comparison has shown reasonable agreement in the distributions, especially for NO_2. The more consistent results for NO_2 were expected since the majority of UK NO_2 emissions originate from anthropogenic sources which are well represented in the NAEI. Furthermore, NO_2 is the more mature product among the different pollutants retrieved from TROPOMI. The larger urban areas exhibit the highest NO_2 concentrations and the distribution is in general agreement with the NAEI emission map. However, the high concentrations due to road traffic are still challenging to observe from space on the actual road network, compared to the NAEI maps where the spatial pattern of the roads is noticeable. This is due to the limited resolution of the satellite observation and the impact that the other large sources have in the area.

The comparison for SO_2 remains difficult. Missing sources over the UK might have been detected, but this needs to be investigated by analysing the observations across several years. Regions over Essex have large concentrations, which are not listed in the NAEI emissions. However, cities such as London are not observed in the presented satellite map.

The satellite NH_3 distribution has highlighted three regions with elevated concentrations in 2018: Norfolk-Suffolk, Lincolnshire and Staffordshire-West Midlands. While the resolution of both maps was different (2x2km for IASI, and 1x1km for the NAEI), consistency in both distributions has been shown, such as over Northern Ireland, Devon, and Dyfed. Further studies are required to better understand the differences between the satellite datasets and NAEI spatial emissions.

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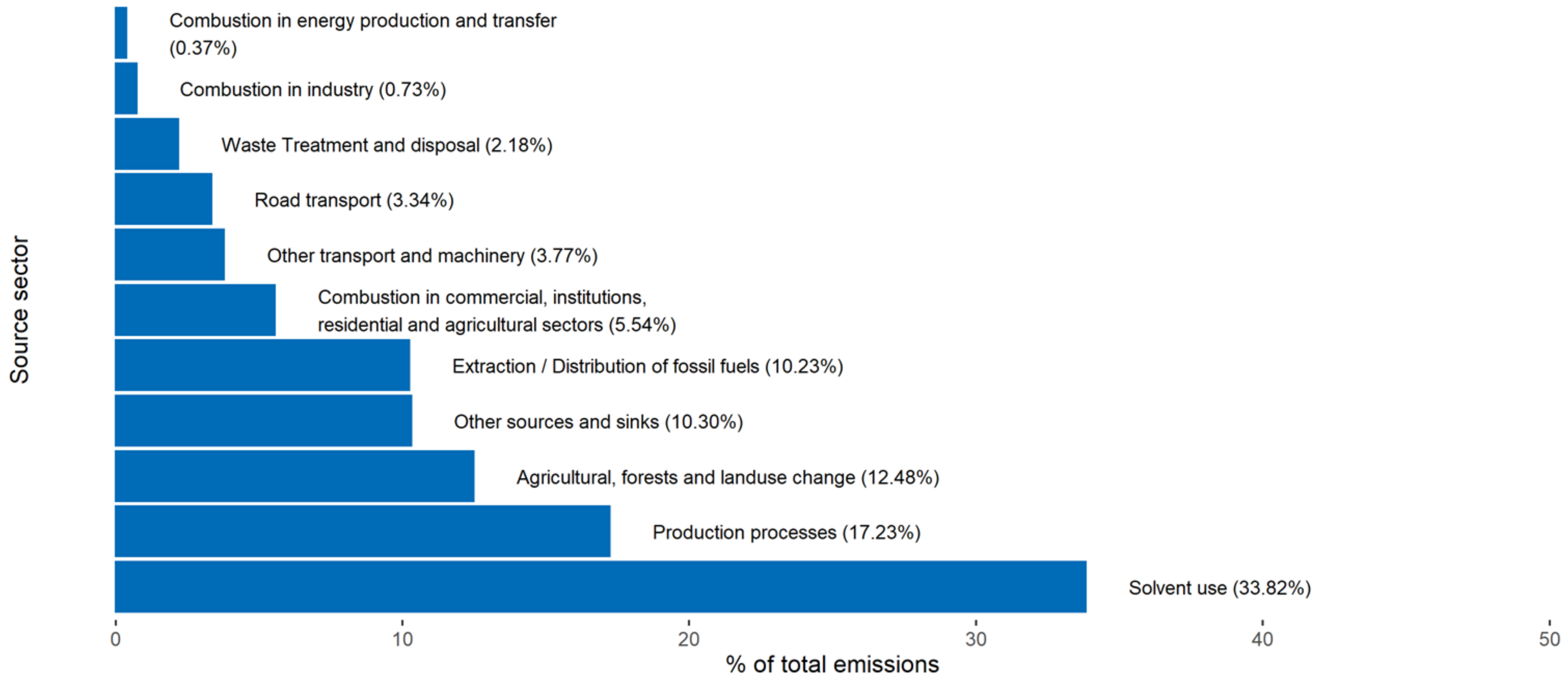
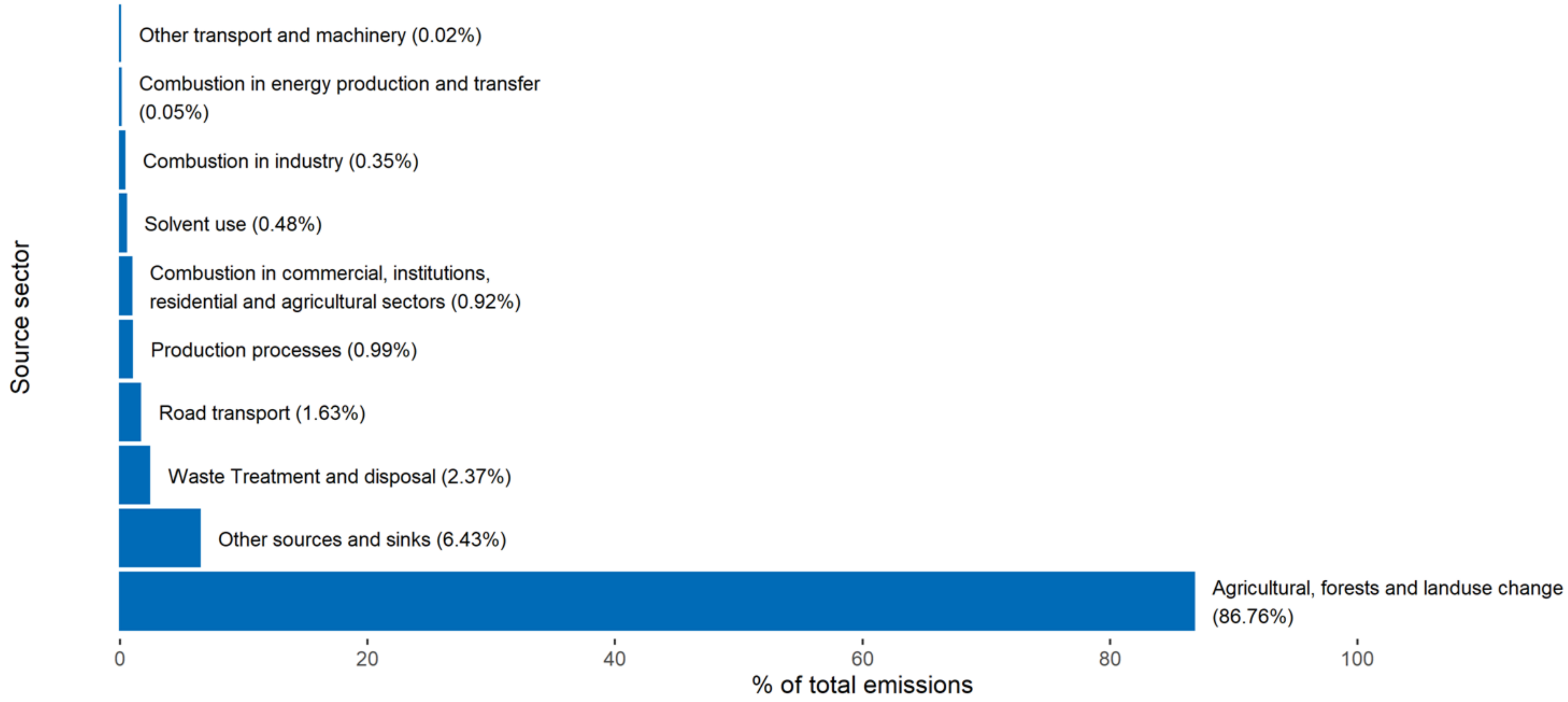
Appendix 1 Bar Charts of UK Emissions split by UNECE Source Sector

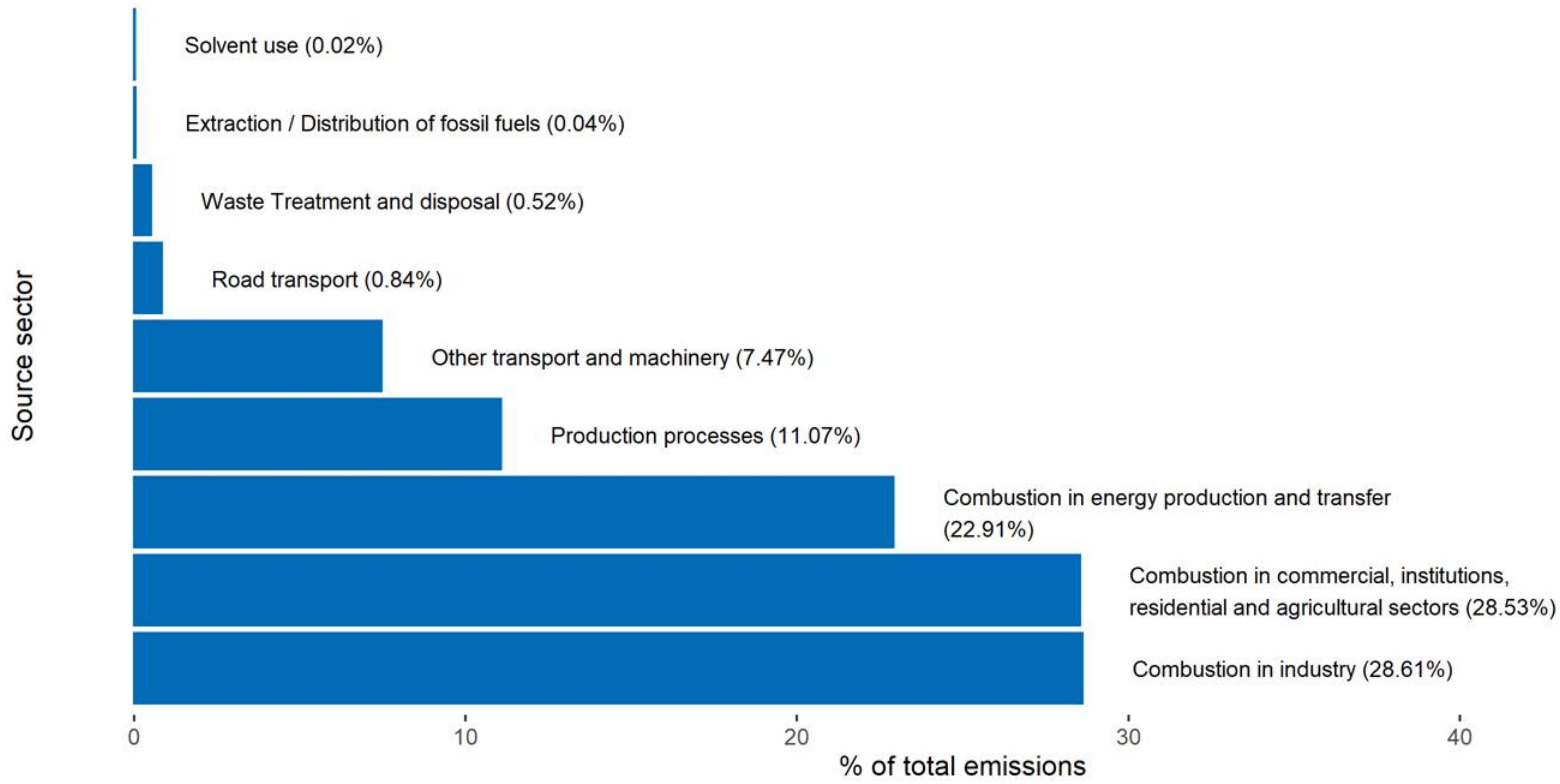
NMVOC Emissions in 2019 by UNECE Source Sector as shown on the NAEI 1x1km maps



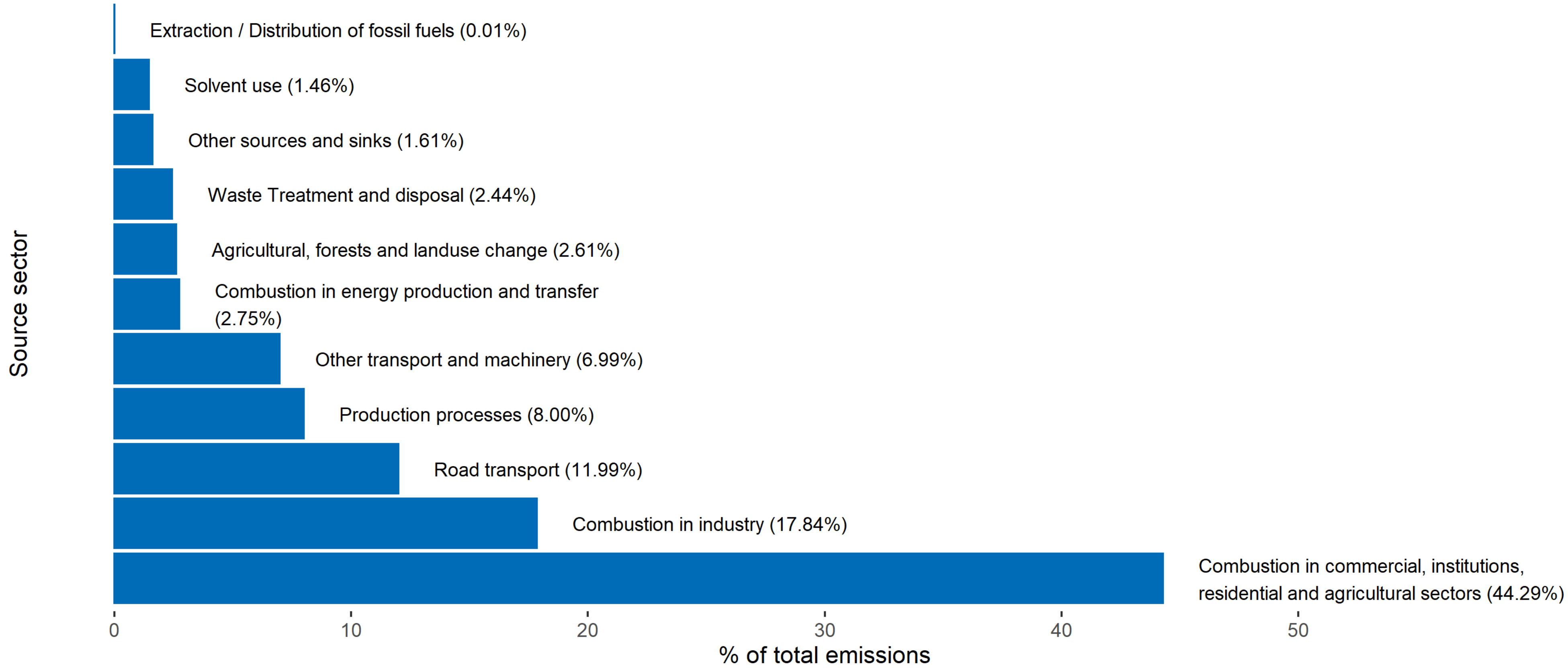
Ammonia Emissions in 2019 by UNECE Source Sector as shown on the NAEI 1x1km maps



Sulphur Dioxide Emissions in 2019 by UNECE Source Sector as shown on the NAEI 1x1km maps



PM2.5 Emissions in 2019 by UNECE Source Sector as shown on the NAEI 1x1km maps



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