Project 2: Review of Carbon Factors for Fuels

Greenhouse Gas Inventory Improvement Programme

On behalf of DESNZ

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With support from

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Executive Summary

This study was commissioned by the UK Government's Department of Energy Security and Net Zero (DESNZ) to improve the carbon emissions factors (CEFs) and sulphur emission factors of selected fuels used in the National Atmospheric Emissions Inventory (NAEI) for major fossil fuels. This study has been delivered by Aether, SGS Engineering and Mott MacDonald, with support from National Physical Laboratory (NPL). The fuels covered in this report are:

- Petrol
- Diesel (a.k.a. Diesel engine road vehicle fuel; DERV)
- Gas oil (a.k.a. red diesel, excluding marine applications)
- Liquified petroleum gas (LPG)
- Aviation turbine fuel (ATF; a.k.a. jet kerosine); and
- Solid fuels (coal, anthracite, coke, manufactured solid fuels).

This research project reviewed and synthesised information from: publicly available statistical data including the UK NAEI and Digest of UK Energy Statistics (DUKES); UK Emissions Trading Scheme (ETS) data provided by DESNZ; literature from previous NAEI reviews, industry reports, fuel specifications, academic literatures, and national inventory reports from comparable European Parties; stakeholder data and industry expert consultation. In addition, a fuel sampling and analysis campaign was undertaken for petrol and DERV used in road vehicles.

Availability of data to inform updated emission factors varied between fuel types. Based on the findings presented in the main body of the report, the recommended updates (either to change or retain) to the carbon and sulphur emissions factors for each fuel are presented in **Tables ES1 and ES2** below.

Table ES1 Summary of proposed carbon emission factor updates

Fuel	Current NAEI carbon content/ CEF (2021)	Recommended carbon content / CEF (2021)	% difference recommended vs. current	Impact on emissions at national level (kt) in 2021	Impact as % of 2021 inventory total
Petrol	85.5% or 0.01916 kt/TJ	86.17% or 0.01931 kt/TJ	+0.78%	+250 kt	+0.06%
DERV	86.3% or 0.02005 kt/TJ	85.54% or 0.01988 kt/TJ	-0.88%	-612 kt	-0.14%
Gas oil	87.00 – 87.44 % or 0.02044 kt/TJ	No change proposed.	No change.	No change.	No change.
LPG	0.01742 kt carbon/TJ 63.89 tCO_2/TJ	64.82 tCO2/TJ	+1.46%	+48 kt	0.01%
ATF	85.9%	No change proposed.	No change.	No change.	No change.
Solid Fuels	Ranging from 0.024 - 0.030 kt/TJ	No change proposed.	No change.	No change.	No change.

Table ES2. Summary of proposed sulphur emission factor updates

Fuel	Current NAEI sulphur content/ energy-based EF (2021)	Recommended sulphur content / energy-based EF (2021)	% difference	Impact on emissions at national level (kt) in 2021	Impact as % of 2021 inventory total
Petrol	0.245 g/GJ or 5.48 mg/kg	No change proposed.	No change.	No change.	No change.
DERV	0.334 g/GJ or 7.19 mg/kg	No change proposed.	No change.	No change.	No change.
Gas oil	0.28 – 3.80 g/GJ or 5.95 -80.9 mg/kg	No change proposed.	No change.	No change.	No change.
LPG	Domestic: 0.3 g/GJ or 6.9 mg/kg Industrial: 0.67 g/GJ or 15.4 mg/kg (stationary), 0.01 g/GJ or 0.22 mg/kg (mobile)	No change proposed.	No change.	No change.	No change.
ATF	9.91 g/GJ, or 218 mg/kg	No change proposed in 2021, but changes proposed to historical time series	No change.	No change.	No change.
Solid Fuels	Ranging from 500 – 4186 g/GJ	No change proposed.	No change.	No change.	No change.

In addition, this report makes other recommendations for further research or data supply options to support further improvement of the NAEI, which are summarised below (see main report for more details):

- Undertake an additional (limited) sampling campaign of winter (November – February) **petrol** and **DERV** blends to improve evidence around seasonality for carbon content;
- In any future fuel sampling, include NCV measurement as part of the lab analysis undertaken when scoping out the work;
- Move away from assuming a fixed ratio of propane and butane in energy use for **LPG** in the NAEI, and instead make use of available data on propane and butane consumption for energy uses, to calculate a weighted average varying by year;
- Work with the DESNZ energy statistics team (DUKES), LPG suppliers and other government departments to improve data and reporting on the quantity of fossil **LPG** and **bio-LPG** consumed;
- Revise the historical time-series of SO_2 emission factors for **ATF**, and review consistency of Fuels Industry UK ATF sulphur content data with other data sources on an ongoing basis;
- Consider a sampling campaign on **solid fuels** to complement data available from producers and suppliers, both for carbon and sulphur;
- Work with the DUKES team to review the activity data used for Manufactured Solid Fuel (**MSF**) consumption, to identify options for correctly accounting for biomass contained in MSF;
- For fuel where updated EFs have been recommended, further engagement between the project team and the NAEI team around timeseries consistency.

Section 9 also contains a final cross-cutting recommendation related to data supply, based on the findings for several fuel types. It recommended is for DESNZ and the NAEI team to engage in further dialogue with fuel suppliers to understand whether any of the laboratory analytical techniques applied to prove conformity with fuel specifications could – in principle – yield estimates of fuel carbon content which could form the basis of more efficient emission factor updates in future.

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Glossary

AQDSFS	Air Quality Domestic Solid Fuel Standards (England) Regulations
ASTM	American Society for Testing and Materials
ATC	Additive Technical Committee
ATF	Aviation Turbine Fuel
BEIS	Department for Business, Energy & Industrial Strategy
BS	British Standard
CEF	Carbon Emission Factor
CERT	CO_2 Estimation and Reporting Tool
CO_2	Carbon Dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CPL	Coal Products Limited
DEFRA	Department for Environment, Food and Rural Affairs
DERV	Diesel Oil for Road Vehicles
DESNZ	Department of Energy Security and Net Zero
DIN	Deutsches Institut für Normung
DUKES	Digest of UK Energy Statistics
EEA	European Environment Agency
EF	Emission factor
EFDSF	Emission Factors for Domestic Solid Fuels
ESD	Effort Sharing Decision
ETBE	ethyl tert-butyl ether
EU	European Union
EU ETS	EU Emissions Trading System
FAME	Fatty acid methyl ester
FSII	Fuel System Icing Inhibitor
GHG	Greenhouse gas
GHGI	Greenhouse gas inventory
GHGIIP	Greenhouse gas inventory improvement programme
GCV	Gross Calorific Value (a.k.a. higher heating value)
HMRC	His Majesty's Revenue & Customs
HVO	Hydrogenated Vegetable Oil
ICAO	International Civil Aviation Organisation
IPCC	Intergovernmental Panel on Climate Change

KP	Kyoto Protocol
LPG	Liquified Petroleum Gas
MSF	Manufactured solid fuels
MTBE	methyl tert-butyl ether
NAEI	National Atmospheric Emissions Inventory
NCV	Net Calorific Value (a.k.a lower heating value)
NIR	National Inventory Report
OEM	Original Equipment Manufacturer
RED	Renewable Energy Directive
RTFC	Renewable Transport Fuel Certificates
RTFO	Renewable Transport Fuels Obligation
SAF	Sustainable Aviation Fuel
SI	Statutory Instruments
SO_2	Sulphur Dioxide
SSF	Smokeless Solid Fuels
UKPIA	UK Petroleum Industry Association (now Fuel Industry UK)
UNFCCC	United Nations Framework Convention on Climate Change

1 Introduction

1.1 Background and need for the project

The Department of Energy Security and Net Zero (DESNZ) appointed a Mott MacDonald led consortium to deliver the greenhouse gas (GHG) Inventory Improvement Programme (GHGIIP). This report covers research into the carbon emissions factors (CEFs) and sulphur emission factors of selected fuels used in the UK National Atmospheric Emissions Inventory (NAEI) for major fossil fuels and has been delivered by Aether, SGS Engineering and Mott MacDonald, with support from National Physical Laboratory (NPL). The fuels covered in this report are:

- Petrol
- Diesel (a.k.a. Diesel engine road vehicle fuel; DERV)
- Gas oil (a.k.a. red diesel, excluding marine applications)
- Liquified petroleum gas (LPG)
- Aviation turbine fuel (ATF; a.k.a. jet kerosine); and
- Solid fuels (coal, anthracite, coke, manufactured solid fuels).

The NAEI contains a comprehensive estimate of the UK's GHG and air quality pollutant emissions since 1990.

Updates to the UK NAEI are informed by the GHGIIP, which identifies methodological and data improvements to the quantification of GHG emissions across the different sectors of the NAEI. The aim is to maintain a scientifically robust NAEI and to improve the transparency, accuracy, consistency, comparability, and completeness of the inventory.

Each year the inventory is updated to include the latest data available. Improvements to the methodology are made and, as necessary, emissions are back-calculated to ensure a consistent time series. Methodological changes are made to take account of new research and data sources. Incremental improvements are made routinely to ensure the inventory uses the most accurate activity data and emission factors.

1.1.1 Previous Inventory Improvements and Reviews

CEFs currently used in the UK NAEI are published as an annex to the 1990-2021 National Inventory Report (NIR) submitted to the UNFCCC and published on the NAEI website[1]. The existing NAEI uses multiple sources to define the CEF of various fuels, including data from industry specific bodies. For the fuels listed above, the two key data sources are:

- Data provided by the UK Petroleum Industry Association (UKPIA, now Fuel Industry UK) (1989)
- Carbon Factors Review (Netcen, 2004)

UKPIA, now Fuel Industry UK, provided many of the CEFs for the UK NAEI for 1990. These data are not available to be reviewed as part of the analysis for this report.

The Carbon Factors Review conducted in 2004, hereafter referred to as the 2004 Review[2], focussed on the CEFs for natural gas, coal and the liquid fuels from 1990-2002.

[1] Spreadsheet annex “2304171442_Energy_background_data_uk_2023.xlsx” (tab NCV) to the UK National Inventory Report (https://uk-air.defra.gov.uk/reports/cat09/2304171442_Energy_background_data_uk_2023.xlsx)
[2] Available at https://naei.beis.gov.uk/reports/reports?report_id=417

Fuel Industry UK were the key provider of data on carbon contents of liquid fuels for this work. After reviewing a range of literature and sample analysis, new CEFs were introduced for the 2004 National Inventory Report. It should be noted that Fuel Industry UK historically collected data on fuel carbon content, however, they no longer do so as refineries and suppliers are not obliged to test for it. On requesting any data post 2003, Fuel Industry UK stated that paper-based data was no longer available.

Another carbon factor review was undertaken in 2017 by Ricardo, hereafter referred to as the 2017 Review[3]. The 2017 Review analysed factors contributing to uncertainty for a particular fuel, including:

- Contribution of fuel to total inventory emissions
- Potential for trends in emission factor over time not yet captured in the inventory
- Relevance of the current emission factors to actual fuels or applications
- Reliability and transparency of the evidence used for current emission factors
- Likely variability of fuel composition
- Uncertainty values used in the inventory
- Deviation from IPCC default emission factors

The 2017 Review also set out recommendations for a future data collection needs and approaches to determine carbon content of different fuels (covered in more detail in subsequent chapters). The choice of fuels specified by DESNZ to be covered in this report (listed above) was largely informed by the findings 2017 Review. For these fuels the current UK evidence base on CEF is limited or has not been recently updated, contributing to the overall NAEI uncertainty.

Carbon emission factors per unit energy are influenced by the carbon content of fuels, and also the net calorific value (NCV). Carbon content of fuels in particular was identified as the key data gap by the 2017 Review, because representative NCV data for each fuel type is systematically collated each year by DESNZ for the Digest of UK Energy Statistics (DUKES) publication.[4]

1.1.2 CEFs and biofuels

A key trend in recent years since the 2004 review has been the blending of fossil petroleum products with biofuels. In the NAEI, the Digest of UK Energy Statistics (DUKES) is the primary source of activity data for energy balances and fuel consumption. In DUKES, as far as possible fossil (mineral) and biogenic portions of blended products are presented separately (but see **Section 6.5.1** in relation to LPG), and accordingly emissions are reported separately in the NAEI. Therefore, the current CEFs used for liquid fuels in the NAEI (all fuels listed above except for solid fuels) are applied to the quantity of 100% fossil fuels consumed, rather than to the quantity of final blended fuels sold on petrol station forecourts, for example.

Due to this separation of fossil fuels and biofuels in activity data and emission factors in the NAEI, in this work it is important that new CEFs developed or taken from the

[3] Available at https://uk-air.defra.gov.uk/assets/documents/reports/cat07/1711280843_Carbon_Emission_Factors_Update_v01_04.pdf

[4] https://www.gov.uk/government/collections/digest-of-uk-energy-statistics-dukes

literature also respect this separation. The main focus of the report is therefore on CEFs for the fossil portion of fuels only, where the separation can be made.

1.2 Aims of the project

The aims of this project were to:

- Assess the evidence for carbon emission factors of key UK fuels that contribute most to uncertainty of fuel combustion GHG estimates;
- Selective sampling and analysis to address key data gaps where there is insufficient data available from literature or from industry / fuel supplier contacts;
- Make recommendations on the suitability of existing carbon emission factors used in the NAEI;
- Where appropriate, provide recommendations for updated carbon content values, and for incorporation into the NAEI; and
- In addition to the above aims relating to carbon emission factors, this project also aimed to achieve the same goals for sulphur dioxide (SO_2) emission factors.

As with CO_2 emissions, unabated SO_2 emissions are largely determined by the fuel composition (i.e. the sulphur content by mass), not combustion conditions. It was therefore deemed efficient to evaluate evidence for sulphur content alongside the CEF review, as information on both carbon and sulphur content could be analysed from the same samples, gleaned from the same literature and requested simultaneously from the same stakeholders consulted.

1.3 Structure of this Report

Section 2 provides and brief overview of methodology used in this project, including cross-cutting elements. **Section 3** provides a brief overview of the contribution of different fuels to total GHG and SO_2 emissions**.**

Sections 4 to 8 are specific chapters for the work undertaken on each fuel in scope, covering the following aspects:

- **Definition and Contribution to GHG Inventory** - defines each of the fuels within the scope of this review, clarifies relevant terminology and presents the fuels' contributions to the UK's GHG emissions in 2021;
- **CEFs in the existing GHG Inventory** - explains how the CEF of the fuel was calculated in the most recent UK NAEI;
- **Previous Inventory Improvements and Reviews** - summarises previous data collected or reviews on the CEF for the fuel;
- **Methodology** - sets out how this review has considered existing data and/or sought new data from industry or relevant stakeholders;
- **Findings** - outputs of the review; and
- **Recommendations and Implications for Inventory for carbon and sulphur** - recommendations for the next steps for use of the findings of this review and quantification of impacts of those recommendations.

Section 9 provides a brief recap overview of recommendations for each fuel.

2 Methodology overview

The methodology and data sources used in this project differed for each of the fuels considered. Detailed descriptions of the data sources and methodology are provided in the specific chapters covering each separate fuel (**Sections 4 to 8**), but a brief overview is provided in this section, as well as a description of some cross-cutting methodological issues.

2.1 Overview of methodologies and data sources

Data were sought from a wide range of sources:

Statistical data

- The UK NAEI itself provides a wealth of information on the carbon and sulphur emission factors currently used and the data sources underlying these.
- In addition, the DUKES – which is a key source of activity data for the NAEI – was another key source of statistical information for this work on fuel consumption and calorific values for fuels.
- The UK Emissions Trading Scheme (ETS) database of site-level CO_2 emissions was examined, to extract relevant emission factor information for fuels used in non-ETS activities (see **Section 2.4**).

Other literature

- Reports from previous similar review work undertaken to improve the NAEI, provided by the NAEI team or DESNZ.
- Review of available literature relevant to the UK, such as industry association reports, fuel specifications, and academic literature.
- Review of national inventory reports and inventory improvement reports from other comparable countries in Europe.

Stakeholder data and expert judgement

- A wide range of government and industry experts were consulted to obtain insights into the market structure, any available data, expert judgment, and pointers towards useful data sources (see **Section 2.2**).

Fuel sampling and analysis

- Where existing data is lacking, fuel sampling and analysis was carried out (where practicable), to obtain a current snapshot of fuel composition and emission factors.

Each of these sources of information was evaluated regarding their applicability and representativeness for the UK, in terms of the temporal coverage, spatial completeness, market completeness etc. The findings were then compared quantitatively (where possible) to the current NAEI emission factors, considering the uncertainty present in both the NAEI emission factors and the alternative source of information.

On the basis of these comparisons recommendations have been made taking into account as much of the information as possible.

More detailed descriptions of the data sources and methodology are provided in the specific chapters covering each separate fuel (**Sections 4 to 8**).

2.2 Summary of Stakeholder Engagement

Table 1 summarises the key areas of consultation undertaken for this project.

Table 1 Summary of stakeholder engagement

Organisation	Fuel	Data requested	Response received (Y/N)
DESNZ (DUKES team)	Petroleum products	Information on conversion factors, carbon content, calorific value and biogenic fractions of fuels; Contacts for other key stakeholders	Y
DESNZ (DUKES team)	Solid fuels	Information on carbon content and calorific value of solid fuels; Contacts for other key stakeholders	Y
Ricardo	All fuels	General queries on existing inventory calculation methods and ETS data	Y
Fuel Industry UK	All fuels	Whether any recent research was undertaken, data on carbon and sulphur content and change over time of fuels	Y
Stopford	Petrol/ DERV	Data on carbon and sulphur content of additives and change over time	Y*
Innospec	Petrol/ DERV	Data on carbon and sulphur content of additives and change over time	Y*
Additive Technical Committee	Petrol/ DERV	Data on carbon and sulphur content of additives and change over time	Y
Greenergy	Petrol/ DERV	Seasonal differences and trends over time in fuel composition; biogenic content	Y
Certas Energy	DERV	Composition of red diesel	Y
Nationwide fuels	DERV	Composition of red diesel	N
UK LPG	LPG	Information on carbon content, biogenic content, and mixing ratios of propane/ butane	Y*
Calor	LPG	Information on carbon content, biogenic content, and mixing ratios of propane/ butane	Y
SKYNRG	ATF	Carbon and sulphur content of fuels and change over time.	Y*
Q8 Aviation	ATF	Carbon and sulphur content of their fuels and change over time.	Y
Shell	ATF	Carbon and sulphur content of their fuels and change over time.	Y
Total Energies	ATF	Carbon and sulphur content of their fuels and change over time.	N

Organisation	Fuel	Data requested	Response received (Y/N)
Energy Institute	ATF	Carbon and sulphur content of ATF from their routine surveys	Y*
Coal Authority	Solid fuels	Carbon and sulphur content of coal, calorific value and change over time	Y*
DEFRA (Air Quality and Industrial Emissions team)	Solid fuels	Proportion of carbon in fossil vs biological in origin and change over time	Y
Coal Products Limited (CPL) / Invica Industries	Solid fuels	Carbon and sulphur content of domestic coal and manufactured solid fuels, calorific value, bio-content and change over time	Y
M&G Solid Fuels	Solid fuels	Carbon and sulphur content of coal, calorific value and change over time	N
HMRC	Solid fuels	Data on imports of coal and sources	Y

* where organisations responded to communications but were not able provide data or suggest other more appropriate contacts.

2.3 Units of carbon and sulphur emission factors used in this report

The published CEFs for fuels used in the UK NAEI are expressed as mass of carbon emitted as CO_2 per unit of fuel energy consumed (kilotonnes C as CO_2 / TJ (net))[1]. This aligns with the units of fuel carbon emission factors provided in the IPCC 2006 Guidelines[5]. These energy-based emission factors are derived from several different quantities and assumptions about the fuel and the combustion process:

- the carbon content of the fuel;
- the NCV of the fuel per unit mass; and
- assumptions about the fraction of carbon in the fuel oxidised during combustion (usually assumed to be 100%).

The same kind of information is required to estimate sulphur emissions as SO_2. In some cases in this report, the published carbon and sulphur emission factors on an energy basis have been converted back to emission factors or carbon/sulphur content on a mass basis (e.g. tonnes of C as CO_2 / tonne of fuel) using the net calorific values also published as an annex to the NIR alongside the CEFs, in order to compare with other data more readily available in units of fuel carbon content. It should be noted that understanding the basis of mass/ mass composition is important when making comparisons, in particular for solid fuels.

2.4 Emission Trading Scheme data analysis

For several fuels, the project team explored the extent to which data reported to the UK ETS by industrial facilities could be used to inform carbon emission factors. Some installations obliged to report emissions do so using Tier 3 methods to estimate

[5] https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_1_Ch1_Introduction.pdf

emission factors[6], which provides an accurate estimate of the carbon content and net calorific value of fuel burned in those installations. Through consultation with the NAEI team in Ricardo, it is clear that much of this high-accuracy data is already used in the inventory directly for the relevant sectors. In many cases, the fuels used by the (usually large) installations undertaking measurement methods may not be representative of other sectors. However, for some relatively standardised fuels there may be some opportunity to generalise the measurements made at ETS facilities to non-ETS sectors where there is higher uncertainty. The results of summarising measured data in the ETS from 2022 by source and fuel type are included in **Appendix C (Tables C.1 – C.3)**, and specific values referred to in the individual fuel-specific chapters.

[6] For ETS reporting, different methods can be used to monitor emissions, with different levels of sophistication and accuracy (so-called "Tiers"). These are described in Annex II of the Monitoring and Reporting regulation (https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A32018R2066). "Tier 3" methods are the most accurate methods to estimate emission factors, requiring sampling and analysis of fuels or flue gases used.

3 Contribution of fuels to UK emissions

3.1 Greenhouse gas emissions

Figure 1 below shows UK emissions from fuels in 2021, adapted from the NAEI GHG Pivot Table Viewer[7].

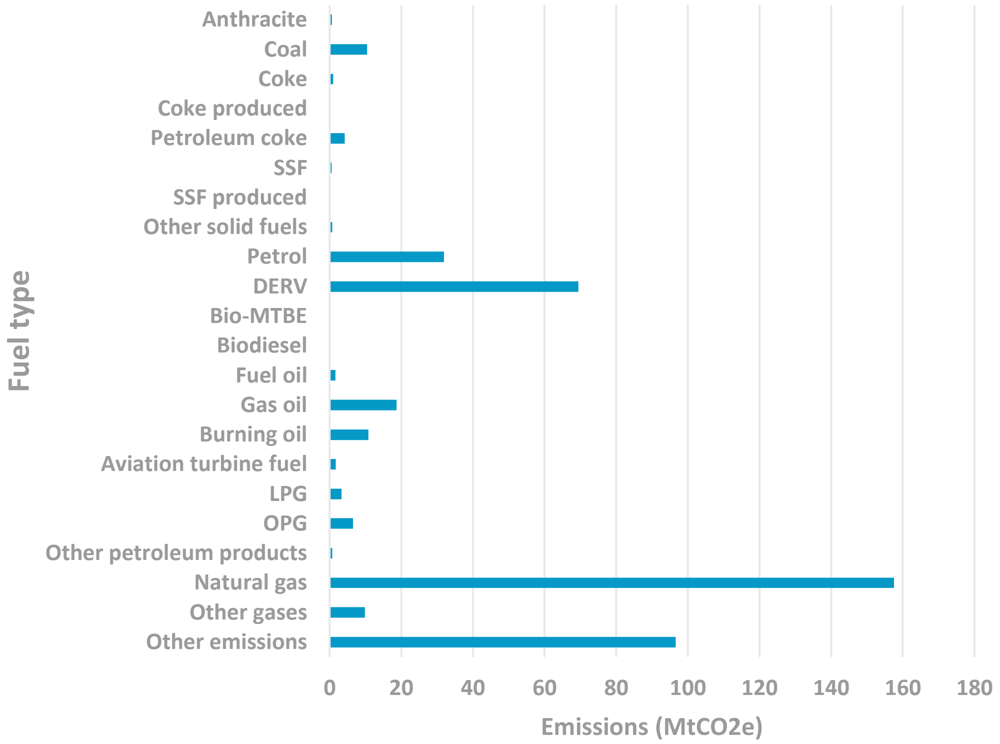

Figure 1 UK Greenhouse Gas Emissions from Fuels in 2021, per Fuel Type

Of the fuels in scope in this project, DERV and petrol contribute the most to overall GHG emissions at 16.3% and 7.5% respectively of total UK GHG emissions in 2021 (excluding LULUCF emissions and removals). The emission factor uncertainty of these two fuels reported in the 1990-2021 NAEI inventory report (Annex 2, table A 2.3.1) is low, at 2%, but due to their high contribution to the inventory they have a large impact on overall inventory uncertainty.

The contribution of solid fuels such as coal and petroleum coke to total GHG emissions is much lower (2.4% and 1% of emissions respectively), but the emission factor uncertainty is much higher at 10% and 15% respectively.

It should be noted that some fuels with a high contribution of emissions to the inventory - such as natural gas, burning oil and other gases - are outside the scope of the study.

[7] The latest version of the NAEI GHG and Air Pollution Pivot Table Viewers available on the NAEI website is for 1990-2020 (https://naei.beis.gov.uk/data/), but Ricardo Energy and Environment provided the latest versions for 1990-2021 (PivotTableViewer_2023_GHG_ForBEIS_Jan_REC.xlsx and PivotTableViewer_2023_AQ_Final_v1_REC.xlsx) to the project team for use in this project.

3.1.1 Sulphur

Figure 2 below shows UK SO_2 emissions by fuel type in 2021, adapted from the NAEI Air Pollution Pivot Table Viewer[7].

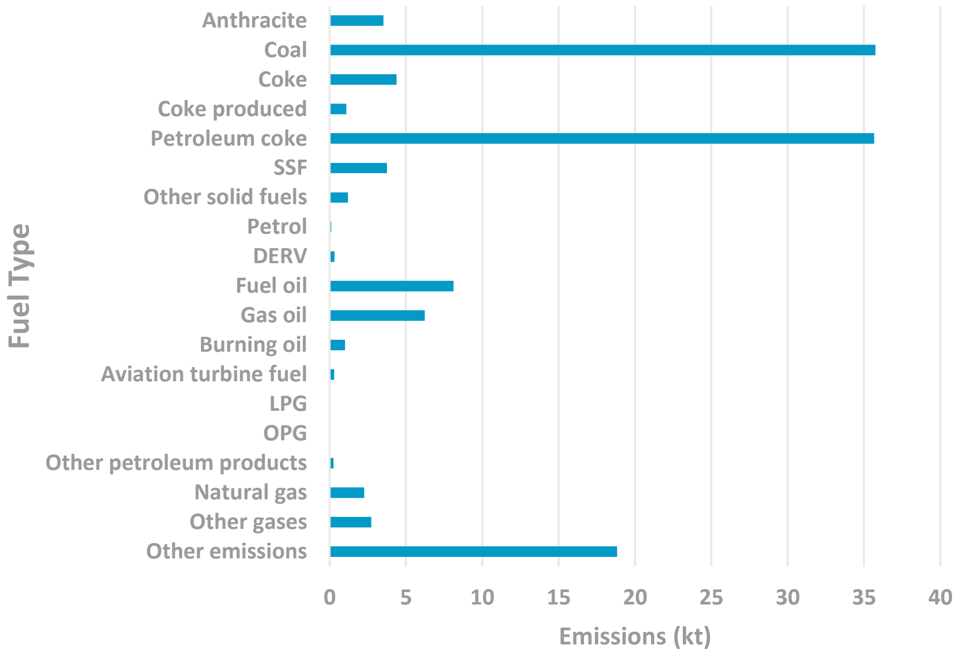

Figure 2 UK Sulphur Emissions in 2021 per Fuel Type

In contrast with GHG emissions, solid fuels are the main contributors to total SO_2 emissions, with DERV and petrol being very insignificant sources. The UK 1990-2021 informative inventory report[8] does not provide fuel-specific estimates of uncertainty. However, section 1.7.6 of the IIR notes that uncertainty in SO_2 emissions is highest for those sectors where there is less regulation and less data on the fuels burned, for example coal and petroleum coke burned as a domestic fuel. These fuels now dominate the overall inventory uncertainty.

[8] https://naei.beis.gov.uk/reports/reports?report_id=1109

4 Petrol

4.1 Definition and Contribution to GHG Inventory

The 2017 Review provided definitions of fuels, which have been reused in this report and updated as necessary.

Petrol (gasoline) is a light distillate primarily used in road vehicles. Petrol in the UK must conform to the standards set out in BS EN 228[9]. The base gasoline is often blended with other products that modify fuel properties. Historically, petrol was blended with lead-based additives until they were phased out in the 1990s. Other products, mostly oxygenates like methyl tert-butyl ether (MTBE), ethyl tert-butyl ether (ETBE), ethanol and reformate were used to replace the function that the lead-additives had on fuel. The fraction of ethanol blended into petrol has increased over time, and E10 (up to 10% ethanol) is now the standard blend in the UK having been introduced in 2021 and 2022 in Great Britain and Northern Ireland respecitvely. Petrol has slightly different "summer" and "winter" blends, in order to maintain suitable fuel characteristics at different temperature extremes. One of the key differences is the quantity of butane, which must be reduced during summer to manage the fuel's volatility.

In 2021, petrol accounted for 9.7% of total GHG emissions generated from combustion of fuels, and 7.5% of total GHG emissions in the UK overall. Bio-MTBE accounted for <0.001% of emissions of fuels in the UK.

4.2 Existing Inventory

4.2.1 Carbon emission factors

The CEFs for petrol used in the NAEI are derived from the following sources:

- Data provided by UKPIA (now Fuel Industry UK) (2004)
- 2004 Review (Netcen, 2004)

The 2004 Review did not provide an updated CEF, and therefore the CEF was left equal to the values in the 2002 GHG inventory of **855 kt C as CO_2/Mt** of petrol, itself based on Fuel Industry UK 1989 data. This was supported by Fuel Industry UK 2004 survey results.

Appendix A (**Table A.1**) sets out the CEFs for petrol in the 1990-2021 NAEI timeseries. The CEF for petrol is consistent across all sources (i.e., road transport, sailing boats, agriculture etc.). The energy-based CEF varies slightly over time due to year-to-year variation in net calorific value (NCV), as published in DUKES. Once the NCV fluctuations have been accounted for, the emissions per mass of fuel remains the same across the timeseries at 855 kt C/Mt fuel.

4.2.2 Sulphur emission factors

Limits on sulphur content in petrol have become progressively lower over time, which is reflected in the NAEI emission factors displayed in **Table 2** below.

[9] https://www.en-standard.eu/bs-en-228-2012-a1-2017-automotive-fuels-unleaded-petrol-requirements-and-test-methods-1/

Table 2. Petrol SO_2 emission factors and apparent fuel sulphur content used in the NAEI[10], shown to 3 significant figures.

	1990	1995	2000	2005	2010	2015	2021
SO_2 EF used in NAEI (g/GJ)	20.9	16.4	4.93	1.43	0.268	0.228	0.245
Apparent S content of fuel (mg/kg)	466.0	365.4	110.0	32.0	6.03	5.10	5.48

4.3 Previous Inventory Improvements and Reviews

The current carbon factors used for petrol and diesel come from the 2004 Review, so changes in composition (both to the base blend and to the mix of additives used) may have occurred since then, related to increasing biofuel content, for example. The 2017 Review identified this unaccounted-for time dependence of carbon content as being a key reason for further work, as well as the scope for variability implied by the wide default uncertainty range (4%) in the 2006 IPCC Guidelines.

Due to the lack of more recent industry data on petrol and diesel carbon content, one of the recommendations from the 2017 Review was to undertake a sampling and laboratory measurement study for petrol and diesel, in parallel with stakeholder engagement. This was the overall approach specified by DESNZ for this project, and the one undertaken here.

4.4 Methodology

This section includes a short summary of the methodology for both petrol and road diesel (DERV) sampling (to avoid unnecessary repetition across report sections).

4.4.1 Outline and rationale

The overall approach taken was to:

i. Undertake sampling and laboratory analysis of petrol and diesel options from a range of supermarket and oil company-branded petrol station forecourts around the UK, to provide a “snapshot” of carbon and sulphur content of petrol and diesel in 2023; and

ii. Engage with stakeholders and review of literature to obtain information on differences in carbon and sulphur content between summer and winter blends, changes over the years, and also any additional data they may hold to compare against the results of the sampling campaign. A key focus of this was on fuel additives, as it is not known the extent to which these have changes over time, potentially affecting carbon content.

The 2017 Review recommended that samples of the different components of petrol and diesel be taken from refineries, importers, wholesalers or other terminals, prior to blending. If there are differences in the carbon content of fuel produced by these different actors, in order to generate a robust average carbon content, statistically it

[10] SO_2 EFs (g/GJ) taken from NAEI website (https://naei.beis.gov.uk/data/ef-all-results?q=183404, and converted to a sulphur content value using net calorific values published as an annex “2304171442_Energy_background_data_uk_2023.xlsx” (tab NCV) to the UK National Inventory Report (https://unfccc.int/documents/627789), assuming 100% of sulphur is converted to SO_2.

would be most straightforward to approach these actors directly to request fuel samples, and then combine this with data on sales volumes to generate a weighted-average. The decision to sample from forecourts in this project rather than upstream actors was taken for several reasons:

- The difficulty of obtaining sensitive information from refineries, importers and wholesalers directly;
- The importance of understanding the composition of fuel at the point of sale; and
- Practical issues with obtaining samples from upstream suppliers, requiring considerable administrative effort with the risk of a failure to obtain samples. Forecourt sampling gave a greater degree of certainty and speed of sample collection given the short timescales of the project.

Ideally, the sampling campaign would have encompassed both summer and winter blends of petrol and diesel in case there are significant differences in carbon content between them. However, the time constraints of this project and limit on number of samples (100 samples maximum) did not allow for sampling across the course of the year, so only summer blends were sampled. Seasonal variation was instead investigated through literature review and stakeholder engagement.

4.4.2 Sampling methodology (summary)

This section provides a summary of the sampling campaign and laboratory analysis methods. A more detailed description of the sampling methodology and laboratory analysis is provided in **Appendix D**.

Sampling was undertaken by SGS during June and July 2023. A total of 50 samples of petrol and 50 of diesel were taken in 5 geographic areas of the UK, from supermarket fuel stations and major oil company branded fuel stations, covering both regular and premium fuel grades.

The laboratory analysis consisted of quantifying:

- carbon content;
- sulphur content; and
- biogenic content.

The aim of the sampling and analysis campaign was to estimate carbon emission factors which can be applied to the 100% fossil portion of petrol and diesel, to align with the way fuel consumption data is presented in DUKES. For both petrol and diesel, this was calculated from the lab analysis results. Carbon content of the fossil fraction of the fuel (the desired analytical output for carbon) could not be measured directly, but was inferred from the total carbon content and biogenic content.

For sulphur, given the consistent sulphur limits between the biofuels and the fossil fuel blends, the simplest assumption is that sulphur content of the fossil and biogenic fractions are similar. Under this assumption, the total sulphur content values can be applied equally to the separate DUKES statistics on fossil diesel and biodiesel consumption.

Net calorific value (NCV) of the petrol and diesel samples were not measured, which would have been required in order to provide energy-based CEFs on a sample-by-sample basis. The reason for this is threefold:

i) the NCV can only be measured for the whole blend rather than isolating the NCV of the fossil fraction, so assumptions would have to be made to calculate the fossil fraction NCV to combine with the CO_2 emissions from the fossil fraction, which would introduce uncertainty;

ii) DUKES publishes high-quality average NCV values for fossil petrol and diesel each year, so the carbon and sulphur content by mass of the fuel were higher priorities than NCV

iii) Budgetary constraints meant that undertaking NCV analysis would have reduced the number of samples available.

Nevertheless, a recommendation is made to include NCV analysis where possible in future sampling programmes, to allow energy-based CEFs to be derived on a sample-by-sample basis.

4.4.3 Aggregation of results

The average carbon and sulphur content was calculated based on the sampling strategy summarised above and described in detail in **Appendix D**. It should be noted that this does not take account of several factors which may affect the overall representativeness of the average for the UK:

- The lack of winter blend samples
- The non-random sampling, which whilst geographically varied did not cover every part of the UK or every fuel supplier
- Lack of data available on the sales volumes of each specific product, ensure the sampling undertaken was representative of a typical tank of fuel sold.
- Lack of bulk-delivered DERV in the samples

To partially mitigate these factors, for petrol data on the fraction of UK petrol sales by country, by grade (regular vs. premium) and retailer type (supermarket vs. branded retailer) were used to adjust the sampling results to better reflect the fuel sales volume relevant to each sample taken. A weighted-average was calculated for each fuel parameter of interest. For DERV, only DERV sales by country were used to weight results. This is because data on DERV sales by grade were not found, and the data on sales by retailer type were not as suitable as for petrol (due to bulk-deliveries being a larger fraction of the market for DERV).

These adjustments notwithstanding, there still remain caveats which add to uncertainty of the sampling results in a way which is very difficult to quantify.

4.4.4 Literature Review and Industry Engagement

Literature review and stakeholder engagement were the key activities undertaken to search for data on biofuel content, additives, base fuel carbon or sulphur content, focusing on differences between summer and winter blends, and on changes over time since 1990.

The literature review included:

- Key previous review work undertaken on NAEI carbon emission factors by the NAEI inventory team, or specific reports prepared for BEIS/DESNZ
- A keyword search of scientific and grey literature
- Review of the national inventory reports (NIRs) and associated documentation of other countries in Northwest Europe with a relatively similar climate to the UK (France, Germany, Ireland, Belgium, Denmark, the Netherlands).

The principal stakeholders contacted by Aether in relation to petrol (and diesel) were:

- Innospec - due to their key position in additive manufacture and membership of the European Additive Technical Committee (ATC)[11];
- Stopford - who have previously published on carbon content and additives;
- Fuel Industry UK - who have historically undertaken routine testing of various fuels on the UK market and supplied this to the NAEI Inventory team; and
- Greenergy - one of the UK's largest petrol and diesel importers, biofuel suppliers and blenders.

Furthermore, a comparison of CEFs used in international GHG inventories was undertaken, reviewing the time series and summer vs. winter differences. The focus was on countries with a similar climate to the UK, primarily Germany and Netherlands.

4.5 Findings – Carbon

4.5.1 Data related to the fuel market and variations

Petrol in the UK must conform with the specification BSEN 228. This sets minimum and maximum values for important performance and safety characteristics, such as density, flashpoint, calorific value etc., but does not specify a required carbon content. Discussions with Fuel Industry UK[12] have indicated that because there is no regulatory requirement to test or report on the carbon content of petrol, only macro parameters are tested to ensure fuels meet specification, not carbon content.

4.5.2 Results of sampling campaign - Carbon

The results of the sampling campaign of petrol are shown in **Table 3** below. NCV of fuel samples were not determined as part of the analysis, so results are presented primarily in terms of carbon content by mass, rather than an energy-based carbon emission factor. Results are broken down by fuel grade and retailer type, and all results are weighted to reflect relative fuel sales by country, grade and retailer type in 2021/22. The value which can be compared with existing NAEI emission factor is in the bottom right corner with a black border.

The weighted average carbon content of the fossil fraction of petrol, combining the sample data and the fuel sales weighting factors (country, grade and location type; **Table D2** in **Appendix D**) was **86.17%** (the simple average of all samples was 86.19%). As mentioned above, this number only represents summer blends.

[11] https://www.atc-europe.org/
[12] Personal communication via email and teleconference in May-June 2023.

Table 3. Overall summary results (weighted average, min and max) of the sampling campaign for petrol, including overall carbon content, bio-based content and carbon content of the fossil fraction.

Type of location	Weighted average % (Min - max range)		
	Regular	Premium	All grades
Overall carbon content %m/m			
Branded retailer	82.6 (81.5-84.4)	85.1 (83.2-86.2)	83.18
Supermarket	83.3 (81.6-84.4)	85.2 (84-86)	83.72
All retailer types	82.92	85.13	83.42
Bio-based content %m/m			
Branded retailer	9.8 (5.6-12.3)	3.5 (0-8.7)	8.36
Supermarket	9 (5.9-11.5)	3.5 (0.9-5.2)	7.75
All retailer types	9.44	3.51	8.09
Carbon content of the fossil fraction %m/m			
Branded retailer	85.9 (85.1-87.2)	86.3 (85.4-86.8)	86.01
Supermarket	86.4 (84.9-87.4)	86.4 (85.3-86.9)	86.37
All retailer types	86.12	86.33	**86.17**

The clearest differences in carbon content of the overall petrol blend are between regular and premium grades of fuel, due largely to the lower bio-based content (which has a lower carbon content than fossil petrol) of premium grades.

There was less difference between the sample averages for regular and premium grades when considering the carbon content of the fossil fraction of petrol only; the value for premium petrol was on average 0.4 percentage points higher than for regular petrol at branded retailers, but at supermarkets there was no difference.
There were only minor differences in carbon content of the fossil fraction between supermarkets and branded retailers, with the value for supermarkets being 0.3 percentage points higher for regular petrol, and almost identical for premium petrol. **Figure 3.** on the next page shows the sample results graphically.

There was some variability in sample average carbon content in fossil fraction of fuel taken from the 5 different areas around the UK (**Figure 3.,** bottom). For regular petrol, sites around Grangemouth had the highest average carbon content in the fossil fraction, and Belfast the lowest, with a range in average values per region of about 2 percentage points. There was less variability for premium grades, with the average carbon content in the fossil fraction of samples from mainland Great Britain between 86.2% and 86.6%; the Belfast region again had the lowest value at 85.4%. It is unclear from the limited sampling undertaken (in both time and space) whether there is a systematic difference between Northern Ireland and the rest of the UK. Nevertheless, this geographic variability highlights the importance of having sampled widely across the UK and included Northern Ireland in the sample, and weighting by fuel sales in different countries. However, it also implies that there may be additional geographic variability across the UK in regions not captured by the sampling.

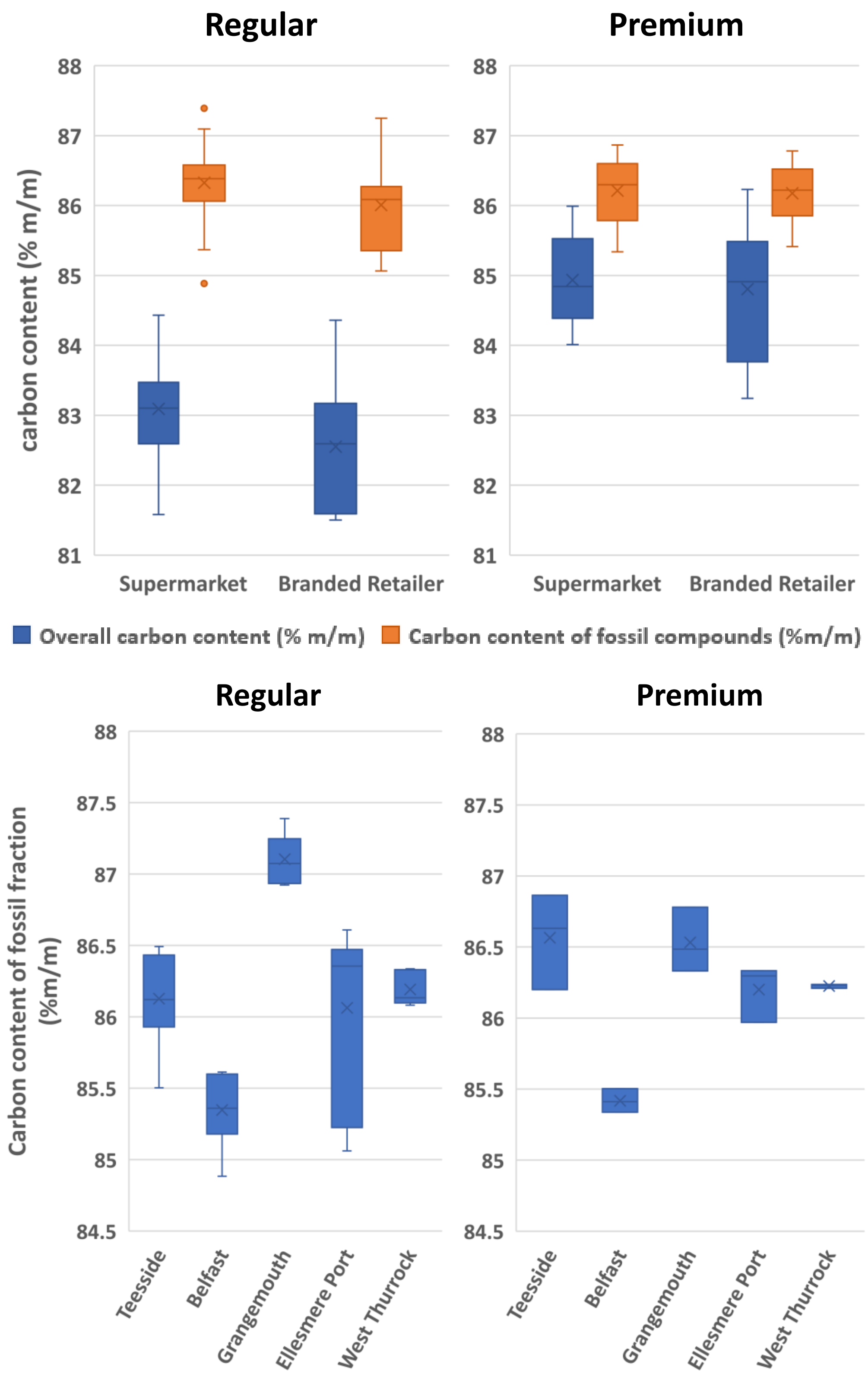

Figure 3. Top: Distribution of carbon content values obtained from the sampling campaign for petrol overall (blue) and for the carbon content of the fossil fraction of petrol (orange), broken down by fuel grade (regular and premium) and type of retailer (supermarket versus branded retailers). Bottom: Carbon content of the fossil fraction of petrol according to area of the UK from which samples were taken.

Seasonal variation

Seasonal variation is present in the properties of petrol blends, which may have an impact on the carbon content of the fossil fraction of the fuel. As the sampling campaign only tested summer blends, information on seasonal variation in carbon content was sought through stakeholder engagement and a review of literature.

Fuel Industry UK stated that, while fuel compositions do change through the seasons, they do not believe this alters the carbon content materially. During the summer, the volatility of petrol must be managed by reducing the amount of light material, such as butane. This could result in a higher carbon and lower hydrogen content during the summer. During the winter, more butane is added so vehicles can cold start.

A 2016 sampling study in the Netherlands[13] compared carbon emission factors and calorific values of summer and winter petrol blends. The carbon content in the fossil fraction (calculated by excluding ethanol) was found to be slightly lower in the winter blend (85.45%) than the summer (85.8%) blend, but due to a higher NCV in the winter blend this translated into a more substantially lower CEF per unit energy.

It is not advisable to extrapolate the seasonal differences from the Dutch results to the results in this study in a quantitative way, due to potential differences in fuel supply between the UK and Netherlands, the age of the study (E10 petrol not yet standard), and some potential issues about how the data has been aggregated in the Dutch study. However, alongside the expert input from Fuel Industry UK, the Dutch study would suggest that the winter blend carbon content would be **similar to (perhaps slightly lower than) the 86.17% average for summer blends**.

4.5.3 Petrol Additives

Through engagement with the Additive Technical Committee (via contacts at Innospec), they provided a recent summary report on common additives in petrol and diesel[14].

Additives are added to gasoline for a range of purposes, although in recent years primarily to improve combustion efficiency and reduce wear and tear on engines. The development of automotive engines was the driver for additive development. Initially this was focussed on improving the octane rating of fuel. However, with improved processes at refineries the octane rating of gasoline has also improved and anti-knocking agents have become less important. Instead additives that protect the functioning of engines have become more important, mainly ones to reduce deposition on surfaces of engines which started to become important in the 1980s. The reduction in use of lead alkyl additives (anti-knocking) led to the development of an additive to prevent wear of the exhaust seat valve in older engines, which were constructed out of metals less suited to substitutes for lead alkyl additives. The introduction of biofuels could further increase the need for additives for deposit control. Common additives are:

- Additives that form films on the metal surfaces of engines to prevent components of fuels being deposited on or interacting with these surfaces (e.g.

[13] TNO, 2016. Available at: https://www.researchgate.net/publication/308201731_Dutch_market_fuel_composition_for_GHG_emissions

[14] Technical Committee of Petroleum Additive Manufacturers in Europe, Fuel Additives: Use and Benefits, ATC, 2020

corrosion from water present in fuel or deposition of partially combusted particles on the hot inlet valve surfaces.
- Antioxidants which prevent the formation of gums during combustion.
- Conductivity improvers which reduce the accumulation of static charge in fuels, reducing the risk of explosion.
- Markers and dyes are also added to both fuel types which can be used to identify fuel type or for inventory control / theft deterrence.
- Demulsifiers which either prevent the formation of or break emulsions within the fuels.
- Additives that bind to metal ions in the fuel, to reduce the oxidation effect of these ions.
- Additives which form a film to prevent corrosion of copper and silver surfaces.
- Additives to form a film to reduce erosion of the exhaust valve seat of older engines.
- Anti-knock agents, although as mentioned these are becoming less important, which improve the octane rating of fuel improving ignition.

Almost all of these fuel additives are organic with carbon content relatively similar to or only slightly higher than the base fuels, with only a small inorganic component (e.g. an oxygen, sulphur or nitrogen acting as the functional group). The exceptions are provided in the table below.

Table 4. Inorganic fuel additives

Fuel additive	Purpose	Treatment rate (mg/kg fuel)
Conductivity improvers	Polymeric sulphur or nitrogen compounds that increase the conductivity of fuel, preventing static charge build up and explosions.	1-40
Anti-Valve Seat Recession	Phosphorous-based compounds or potassium, sodium or manganese organo-metallic compounds that reduce corrosion of the exhaust valve seat	100-200 mg/kg

The additives above have a higher inorganic component and in high enough quantities could impact the carbon content of fuel. However, as shown the treat rates are not significant (100-250 mg/kg = 0.01 – 0.025%) and therefore it could be concluded that additives would not be expected to impact the carbon content of petrol significantly.

A previous report to BEIS on variability in the petrol carbon factor by Stopford Energy and Environment[15] came to a similar conclusion. Discussions with Fuel Industry UK[16] also suggested that, in general, additive content in petrol is low, with the exception of branded petrol which may include a range of performance additives such as octane improvers, or detergents to help the engine run better. Fuel Industry UK indicated that these products represent a small proportion of the market, and that supermarkets may add lower rates of additives.

Overall, it seems that changes in the types or quantities of additives included in petrol over time are likely to have had an insignificant effect on carbon content.

[15] https://uk-air.defra.gov.uk/assets/documents/reports/cat07/1811161339_Carbon_Factors_Petrol_Final_report.pdf
[16] Personal correspondence between Aether and Fuel Industry UK, 23/06/23

4.5.4 Comparison with the NAEI and uncertainties

The carbon content of petrol used in the NAEI (fossil fraction of petrol only) on a mass basis is currently 85.5% (i.e. 855 kt C as CO_2/Mg converted to a %, assuming 100% combustion), which can be directly compared to the value in bold at the bottom right of **Table 3** above.

The NAEI value of 85.5% is slightly lower than the averages of between 85.9% and 86.4% (for different grades and retailer types) found by the sampling campaign for summer blends, and is 0.67 percentage points lower than the indicative overall weighted average of summer blends calculated above (86.17%). However, it does fall close to the minimum carbon content (in the fossil fraction) of samples for all grades and retailer types, which varied between 84.9% and 85.4%.

Fully quantifying the uncertainty of the sampling campaign results has not been possible, as there are many sources of uncertainty as described in **section 4.4.3** which are difficult to estimate. **Indicative** confidence intervals of the mean carbon content in the fossil fraction from the sampling campaign (expressed as 2 times the standard error of the mean, which is commonly used to approximate the 95% confidence interval) are given in **Table 5** below, based on i) the observed scatter of measured values (sampling uncertainty) and ii) the measurement uncertainty associated with the laboratory techniques used. The confidence interval represents the range in which the sample mean value will fall 95% of the time, if the sampling were to be re-done with the same sample size and design. **Appendix D** provides further details on how these were calculated.

Table 5. Sampling and measurement uncertainty of the estimates of carbon content of the fossil fraction of petrol, expressed as 2 times the standard error of the mean of the samples.

	2 x Standard error of the mean (percentage points of carbon in fossil fraction)	Lower confidence bound (%m/m)	Upper confidence bound (%m/m)
Sampling uncertainty	±0.17	86.00	86.34
Measurement uncertainty	±0.65	85.52	86.82

The measurement uncertainty values are greater than the sampling uncertainty values, so these larger values were used as an indicative estimate of the confidence interval around the mean (see **Appendix D**), of between 85.52% and 86.82%, when all samples are combined together.

The NAEI value of 85.5% falls just outside bottom of the indicative confidence interval of the overall mean when all fuel grades and retailer types are combined.

The value of 85.5% carbon content is used throughout the time series in the NAEI. Sourcing data was challenging during this project to determine how the carbon content of fossil petrol in the UK has changed over time. However, given that the NCV of petrol used in the NAEI shows changes over time based on ongoing data collection, it seems likely that these changes in NCV would have been accompanied by changes in carbon content. In addition, there have been several changes in the EN228 specification and legislation on fuel quality over the time series, which could also have led to changes in carbon content.

4.5.5 International Inventory Comparisons

A literature review was conducted to compare the CEFs used in the UK inventory against those used in international inventories. The most comparable information came from the Netherlands and Germany, which provided emission factors by year for the fossil-only fraction of petrol. Details of relevant findings from the literature review is provided in **Appendix B.**

For the Netherlands, the NIR annex[17] on road transport methodology stated a mass-based CEF for 2021 of 853.1 g C/kg fuel, which equates to 85.31% carbon, and is slightly lower than the current 85.5% used in the NAEI. The Dutch figure has reduced over time from 86.6% in 1990.

For Germany, a report on CEFs used in the German GHG inventory[18] calculated a carbon content for petrol sampled in 2020 of 86.5% for regular petrol (termed "super / mid-grade" in that report), and 85.6% for premium petrol, with the weighted-average being 86.4%. This is similar to (slightly above) the value of 86.16% for summer blends found in this study, with the carbon content of regular petrol being higher and premium petrol being lower than found in this study. However, it is not clear whether the German results for 2020 relate to summer, winter or annual-average blends. Again, the carbon content of the fossil fraction of petrol has reduced over time for the two grades, from an average of 86.9% and 86.1% respectively measured in 1994. These values are more similar to the new data collected in this study than to the currently used NAEI factors.

4.6 Findings – Sulphur

Discussions with Fuel Industry UK indicate that, while there are seasonal changes to the additives in petrol, sulphur content will remain the same throughout the year. Unlike for carbon, BS EN 228 specification includes maximum limits to sulphur of 10 mg/kg, so sulphur content of petrol is regularly tested by fuel suppliers.

Fuel Industry UK provided fuel quality data for 2021[19] and 2022[20] during the project including sulphur content, summarised in **Table 6** below.

[17] https://unfccc.int/documents/627759, Geilenkirchen et al. (2023) Methods for calculating the emissions of transport in NL_tables_def.xlsx, tab 2.7
[18] Juhrich, 2022: https://www.umweltbundesamt.de/en/publikationen/co2-emission-factors-for-fossil-fuels-0
[19] Fuel Industry UK, 2023, Unpublished data from 2021 based on aggregate samples from the 8 Fuel Industry UK member companies operating the 6 major refineries in the UK and importing fuel.
[20] Provided by DESNZ via DfT, based on Fuels Industry UK sampling programme in 2022

Table 6. Typical sulphur content of petrol in 2021 and 2022 from UK refineries and fuel suppliers affiliated with Fuel Industry UK

Fuel type	Sulphur mg/kg	
	2021	2022
Regular unleaded	5.48	Summer: 5.19 Winter: 4.2
Premium* unleaded	4.92	Summer: 5.8 Winter: 4.8

Source: Fuel Industry UK (2023)[19,20]. Note that the Fuel Industry UK data uses the term "Premium unleaded" to mean 95 RON unleaded, which in this report is referred to as "Regular" unleaded. "Super" is used for the higher RON unleaded which we refer to as Premium in this report.

The figures in the table above are labelled as "indicative" figures, as they are averages of samples tested by Fuel Industry UK member companies rather than following a statistically representative sampling design. They omit imported fuels which are marketed through non-member companies, such as Greenergy. Nevertheless, whilst not fully representative of the UK market, Fuel Industry UK members collectively source over 85% of the transport fuels used in the UK[21], so the numbers supplied are likely close to the true average values.

4.6.1 Results of sampling campaign – Sulphur

Table 7 shows the results of the sampling in terms of sulphur in petrol. Results are broken down by fuel grade and retailer type, and all results are weighted to reflect relative fuel sales by country, grade and retailer type in 2021/22. The value which can be compared with existing NAEI emission factor is in the bottom right corner with a black border.

Type of location	Weighted average sulphur content mg/kg (Min - max range)		
	Regular	Premium	All grades
Branded retailer	6.0 (2.7-7.9)	5.7 (3.8-9.1)	5.90
Supermarket	5.1 (2.6-7)	4.9 (4.4-5.6)	5.02
All retailer types	5.56	5.32	**5.51**

[21] https://www.fuelsindustryuk.org/. Fuels statistics 2023, p.2.

Figure 4 overleaf shows the same results graphically.

Table 7. Overall summary results (weighted average, min and max) for sulphur content (mg/kg = ppm) from the sampling campaign for petrol.

Type of location	Weighted average sulphur content mg/kg (Min - max range)		
	Regular	Premium	All grades
Branded retailer	6.0 (2.7-7.9)	5.7 (3.8-9.1)	5.90
Supermarket	5.1 (2.6-7)	4.9 (4.4-5.6)	5.02
All retailer types	5.56	5.32	**5.51**

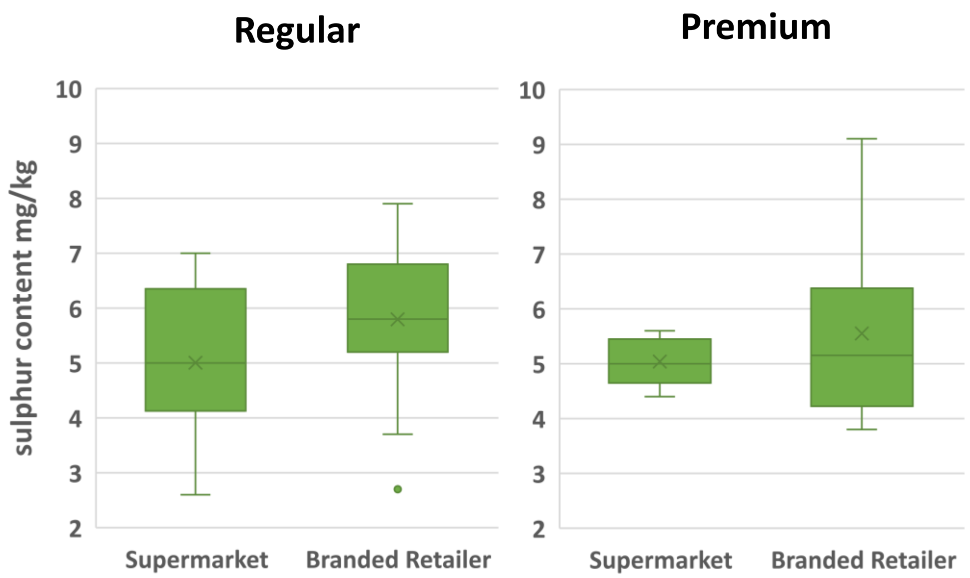

Figure 4 Distribution of sulphur content values obtained from the sampling campaign for petrol, broken down by fuel grade (regular and premium) and type of retailer (supermarket versus branded retailers).

The weighted average sulphur content for summer petrol blends, combining the sample data and the fuel sales weighting factors (country, grade and location type; **Table D2** in **Appendix D**) was 5.51 mg/kg. As mentioned above, there is no reason to expect this to vary significantly seasonally.

4.6.2 Comparison with the NAEI and uncertainties

The sulphur content of petrol used in the NAEI on a mass balance basis currently was 5.48 mg/kg (ppm) in 2021 (**Table 2**). This is very similar to the summer-blend sample average values obtained from the sampling campaign here. It is the same as the Fuel Industry UK figures from 2021 for regular petrol, because Fuels Industry UK data is the source of the NAEI emission factor. The Fuel Industry UK data for 2021 shows that the sulphur content for premium unleaded petrol is slightly lower at 4.92, but as that makes up only around 23% of the market, the average of the Fuel Industry UK data is also likely to be close to the current NAEI value. The 2022 data from Fuels Industry UK shows slightly lower regular petrol sulphur content numbers for 2022 than 2021.

As described in **section 4.5.4** for carbon, a full quantification of uncertainty of sulphur content has not been made in this report. However, **indicative** estimates of confidence intervals around the weighted-mean values based on sampling and measurement uncertainty respectively are presented below in **Table 8**. The confidence interval represents the range in which the sample mean value will fall 95% of the time, if the sampling were to be re-done with the same sample size and design. **Appendix D** provides further details on how these were calculated.

Table 8. Sampling and measurement uncertainty of the estimates of sulphur content of petrol, expressed as 2 times the standard error of the mean of the samples.

	2 x Standard error of the mean (mg S/kg fuel)	Lower confidence bound	Upper confidence bound
Sampling uncertainty	±0.39	5.11	5.90
Measurement uncertainty	±0.17	5.34	5.68

For sulphur content, the larger of the two uncertainty ranges is the sampling uncertainty, and the measurement uncertainty likely contributes to this (assuming it is random), so the sampling uncertainty range can be taken as the indicative confidence interval around the mean.

The NAEI value falls well inside these indicative ranges, being very similar to the weighted mean value found in this study.

As for carbon content, unfortunately no time series of sulphur content data was forthcoming from stakeholders or literature review, to compare with the historical values used in the NAEI.

4.7 Recommendations and implications for the inventory

The proposed changes to the NAEI carbon emission factors and sulphur emission factors for petrol are summarised in **Table 9**. Details of any additional recommendations are set out below.

Table 9. Petrol carbon emission factors and sulphur emission factors proposed changes and impact on the inventory

	Carbon (% mass or energy based-CEF)	Sulphur content (% mass or energy based CEF)
Current NAEI value (2021)	85.5% or 0.01916 kt/TJ	0.245 g/GJ or 5.48 mg/kg
Recommended value (2021)	86.17% or 0.01931 kt/TJ	No change proposed.
% difference recommended vs. current	+0.78%	No change.
Impact on 2021 emissions at national level (kt)	+250.38 kt	No change.
Impact as % of 2021 inventory total	+0.06%	No change.

*Recommended energy-based CEF is calculated using the NCV used in the NAEI for 2021, because NCV was not measured independently as part of the sampling study.

4.7.1 Carbon content

For petrol it is recommended that a carbon content value of 86.17% be used for inventory year 2023 and the following years, until further data are available / studies are undertaken. There are some caveats regarding the representativeness of the sample as an annual average for the UK as a whole, as discussed in **Section 4.4.3, 4.5.4** and **Appendix D**.

Some limited additional sampling of winter petrol blends could be justified to improve evidence around seasonality.

Regarding revisions to the historical time-series for petrol, a steady decrease in carbon content over time since around 2005 is suggested by the Dutch inventory data, but given the lack of concrete time-series data found for the UK this is best left for the NAEI team to decide.

An over-arching recommendation for both petrol and diesel sampling in future would be to include NCV measurement as part of the lab analysis undertaken, to allow sample-by-sample estimation of the energy-based CEF, rather than linking to DUKES NCV data from a completely separate set of samples.

4.7.2 Sulphur content

Based on the information gathered during this project, it has been determined that that the sulphur content of petrol currently used in the NAEI (5.48 mg/kg) is still valid, being very similar to the indicative average of 5.51 mg/kg for summer blends found in the sampling campaign (near the centre of the uncertainty range), and also aligns with data from Fuel Industry UK.

5 Diesel and gas oil

5.1 Definition and Contribution to GHG Inventory

The 2017 Review provided definitions of fuels, which have been reused in this report and updated as necessary.

The NAEI and DUKES distinguish two very similar categories of middle distillate fuels, named DERV and Gas Oil.

DERV

Diesel oil for Road Vehicles (DERV) is a middle distillate used in road engines. DERV has a very narrow range of allowable densities in EU specifications and can be blended with biodiesels, with similar properties, without altering the base fuel. It is also known as white diesel (to differentiate it from "red diesel" – see below). It conforms to the specification EN 590, but there are distinct summer and winter blends in the UK, with different allowable cold filter plugging points[22] (-4°C in summer, -12°C in winter).

In 2021, DERV accounted for 21.1% of total GHG emissions generated from combustion of fuels, and 16.3% of total GHG emissions in the UK overall. Biodiesel accounted for 0.05% of fuel emissions, and 0.04% of UK emissions.

Gas oil / Red diesel

Gas oil is a middle distillate and used in a wide range of industrial engines. There are two grades of gas oil used in the UK conforming to 2 different standards:

- BS 2869 Grade A2 gas oil (max 20ppm sulphur)
- BS 2869 Grade D gas oil (max 1000ppm sulphur)

"Red diesel" is a term which can be used for fuels meeting one of these two specifications but is also used for fuel conforming to road/white diesel specifications (EN 590) to which red dye has been added. A key aim of this project has been to confirm whether the GHG emissions factors for DERV, the two grades of gas oil, and for dyed EN 590 red diesel are the same or different.

Red diesel / gas oil has historically been taxed at a lower (rebated) rate, and its use prohibited in road vehicles. It has mainly been used in the agricultural, marine and construction sectors. The red dye enables law enforcement agencies to identify it as rebated fuel and detect when the wrong sort of diesel is being used, providing a deterrent to fuel fraud. However as of 1st April 2022, more stringent requirements have been introduced[23]. The tax changes are intended to ensure that most users of diesel use fuel taxed at the standard rate, which more fairly reflects the harmful impact of the emissions they produce.

Gas oil (BS 2869) is generally very similar to DERV (EN 590) in its specifications. The main differences (apart from the red dye) are:

[22] The temperature at which the fuel begins to solidify
[23] HMRC, 2021. https://www.gov.uk/government/publications/changes-to-rebated-diesel-and-biofuels-from-1-april-2022/changes-to-rebated-diesel-and-biofuels-from-1-april-2022

- Grade D gas oil has a higher allowable sulphur content
- Typical cetane number is lower for gas oil
- Slightly lower cold filter plugging temperature for EN 590
- There has been no obligation under the Renewable Energy Directive (RED) to blend in a minimum % of biofuel (e.g. FAME) in low sulphur gas oil BS 2869, or in dyed white diesel (EN 590).

In 2021, gas oil accounted for 5.7% of total GHG emissions generated from combustion of fuels, and 4.4% of emissions in the UK overall.

5.2 Existing Inventory

5.2.1 Carbon emission factors

The CEFs for DERV and gas oil used in the NAEI are derived from the following source:

- 2004 Review (Netcen, 2004)

The 2004 Review states that:

Diesel is corrected for changes in sulphur content and density over time using smoothed sulphur contents from the annual UKPIA survey of sulphur contents and density from the previous Department of Trade and Investment (DTI) DUKES.

Gas oil and fuel oil [are] corrected for changes in sulphur content over time using smoothed sulphur contents from the annual UKPIA survey of sulphur contents.

Appendix A sets out the CEF for DERV across the 1990-2021 NAEI timeseries. The CEF is consistent across all sources (i.e., road transport, sailing boats, agriculture etc.), and has remained relatively consistent since 1990. On a mass basis, it is **863 g CO_2 as C/kg** DERV in recent years (implying the fuel is 86.3% carbon by mass if all C is oxidised).

There are three different CEF for gas oil, which broadly fall into the following categories:

- Gas and oil terminal/ production
- Shipping and vessels
- All other uses (i.e., transport, agriculture etc.)

Only the last use is in the scope of this review, which is currently **870 g CO_2 as C /kg** gas oil in the latest year of the inventory (implying the fuel is 87% carbon by mass if all C is oxidised).

5.2.2 Sulphur emission factors

Table 10 below shows the SO_2 emission factors and the fuel sulphur content implied by these over time, for DERV and gas oil. The sulphur content of all fuels has reduced over time, with DERV having low content much earlier in the time series than gas oil. Currently sulphur content values used in the NAEI for gas oil in mobile and stationary applications differ, reflecting the use of different grades of gas oil for these applications.

Table 10. Diesel and gas oil SO_2 emission factors and apparent fuel sulphur content used in the NAEI, to 3 significant figures

Measure	Fuel	Sector	1990	1995	2000	2005	2010	2015	2021
SO_2 EF used in NAEI (g/GJ)	DERV	All	88.2	60.7	1.85	1.44	0.345	0.335	0.334
	Gas oil*	Mobile	98.3	65.6	61.6	68.0	33.9	0.362	0.280
		Stationary	98.3	65.6	61.6	68.0	33.9	7.80	3.80
Implied S content of fuel (mg/kg)**	DERV	All	1900	1300	40.0	31.0	7.40	7.20	7.19
	Gas oil*	Mobile	2100	1400	1320	1450	721	7.70	5.95
		Stationary	2100	1400	1320	1450	721	166.1	80.9

*Note for Gas oil, mobile sources exclude marine diesel, and stationary sources includes only small combustion, as large combustion emissions are out of scope of this work.

**Assuming that 100% of the sulphur is converted to SO_2 following combustion.

5.3 Previous Inventory Improvements and Reviews

Updated emission factors for liquid fuels were obtained from Fuel Industry UK (2004) which describes a survey of the carbon contents of selected fuels: naphtha, aviation spirit, diesel, gas oil and fuel oil. At that date, the CEFs of all other fuels were left equal to the values in the 2002 GHG inventory, obtained from Fuel Industry UK in 1989.

The 2017 Review concluded that the diesel factor should be retained as it was the slightly more conservative of the base diesel factors. Therefore, no new CEF were proposed.

The 2017 Review noted that the biofuel blended into diesel *"has little or no bearing on the base fuel. Thus, it should be safe to assume that the base fuel has a constant carbon factor*". The 2017 Review noted that red diesel was indistinguishable from road diesel other than the red dye used to identify it for tax purposes.

5.4 Methodology

As with petrol, the overall methodology included literature review, stakeholder engagement and fuel sampling.

Fuel sampling was restricted to DERV. A sampling campaign was also considered for gas oil, but in the time constraints of the project this was not considered feasible. Unlike DERV, gas oil is almost exclusively delivered in large quantities, and obtaining samples from a sufficient number of suppliers and geographic range would require a substantial organisational effort.

5.4.1 DERV Sampling

Sampling of diesel was done at the same time as sampling of petrol and carried out using the methodology set out in **Appendix D**.

5.4.2 Industry engagement Data Requests and literature review

Large producers of red diesel were contacted to gain an understanding of how red diesel differed from DERV, if at all, and whether any information was available on the carbon and sulphur content of their red diesel, and changes over time. The producers contacted were Certas Energy, Crown Oil, and Nationwide Fuels, although Nationwide Fuels were unable to respond. As noted above, Greenergy were also contacted as one of the largest fuel importers and blenders.

In addition, a literature review was conducted to compare the CEF used in the UK inventory against those in some similar international inventories, as noted in **Section 4.5.5** above.

5.5 Findings – Carbon

5.5.1 Data related to the fuel market and other data from stakeholder engagement

As with petrol, Fuel Industry UK stated that there is no regulatory requirement to test or report on the carbon content of DERV, and only macro parameters are tested for performance. None of the stakeholders contacted were able to provide information on carbon content of DERV or gas oil.

Fuel specification sheets were available to download from some fuel suppliers' websites[24] for EN 590 white diesel (which can be dyed red), class D gas oil and class A2 gas oil. These all indicated a typical carbon content of 87% (no decimal places). This refers to the carbon content of the blended fuel, but the specification sheets also indicated that the fatty acid methyl ester (FAME) content was typically below 0.1% v/v for all three variants, so the 87% value would also apply to the fossil diesel (the most relevant metric to compare with the NAEI).

Information found regarding the composition and treatment rates of the red dye used to mark gas oil and EN 590 diesel as for non-road use was also limited. Certas stated that the exact dye and quantity used is likely to vary by supplier, but that it is unlikely to affect the carbon content significantly. One of the most common red dye used is Solvent Red 164, which has a carbon content similar to diesel[25].

5.5.2 Results of sampling campaign for DERV – Carbon

The results of the sampling campaign for diesel are presented in **Table 11** and **Figure 5** below. Again, as for petrol results are expressed on a per unit mass basis, because the net calorific value of samples was not analysed. The value which can be compared with existing NAEI emission factor is in the bottom right corner with a black border.

For DERV, when aggregating sample results these were weighted only according to fuel sales by country (**Table D3** in **Appendix D**); weighting by fuel grade and retailer type was not implemented for the reasons explained in **section 4.4.3**. The weighted-average carbon content of the fossil fraction from the 50 DERV samples was **85.54 %** (the simple unweighted average of samples was 85.52 %)**.**

In comparison with petrol, there was much less variation in overall carbon content of the blended fuel between regular vs. premium and supermarket vs. non-supermarket products. This reflects the fact that there were no substantial differences in biofuel

[24] https://www.nationwidefuels.co.uk/fuel-specifications/gas-oil-en-590-specifications/; https://www.crownoil.co.uk/fuel-specifications/bs-2869/d-grade-gas-oil/; https://www.crownoil.co.uk/fuel-specifications/bs-2869/a2-gas-oil/

[25] According to https://www.worlddyevariety.com/solvent-dyes/solvent-red-164.html Solvent red's molecular formula is $C_{31}H_{34}N_4O$, equating to 77.8% carbon

content between these categories, and also that FAME and HVO have more similar carbon content to fossil diesel than ethanol does to fossil petrol.

The same homogeneity is also seen for the carbon content of the non-biofuel fraction, where the average values of the different categories are all within 0.2 percentage points.

Table 11. Summary results for overall carbon content, biofuel content and carbon content of the non-biofuel fraction of DERV (weighted average, min and max % m/m) from the sampling campaign.

Type of location	Weighted average % (Min – max range)		
	Regular	Premium	All grades
Overall carbon content %m/m			
Branded retailer	85.0 (84.3-86.0)	85.0 (84.2-85.8)	85.04
Supermarket	85.1 (83.7-86.0)	N/A	85.07
All retailer types	85.06	85.04	85.05
Biofuel content (HVO + FAME) %m/m			
Branded retailer	4.2 (0.1-7.7)	5.9 (0.6-7.8)	5.09
Supermarket	6.7 (3.6-7.8)	N/A	6.66
All retailer types	5.64	5.91	5.72
Carbon content of the fossil fraction %m/m			
Branded retailer	85.4 (84.4-86.2)	85.6 (84.8-86.5)	85.48
Supermarket	85.6 (84.1-86.7)	N/A	85.64
All retailer types	85.54	85.55	**85.54**

There was also much less geographic variation in carbon content of the fossil fraction compared with petrol samples, in particular for regular blends; the mean carbon content of the fossil fraction for regular blends varies by less than 0.5 percentage points across the different areas (compared with 2-3 percentage points for petrol). Nevertheless, despite the lack of systematic variation between locations, supermarkets vs. branded retailers and regular vs. premium products, there was still substantial unexplained variation across samples, with the carbon content of the fossil fraction ranging 2.6 percentage points between 84.1% and 86.7%. Much of this scatter could be due to measurement uncertainty (if this is random rather than systematic), as the standard deviation of results due to measurement error could be as large as 3 percentage points (see **Appendix D** for further explanation).

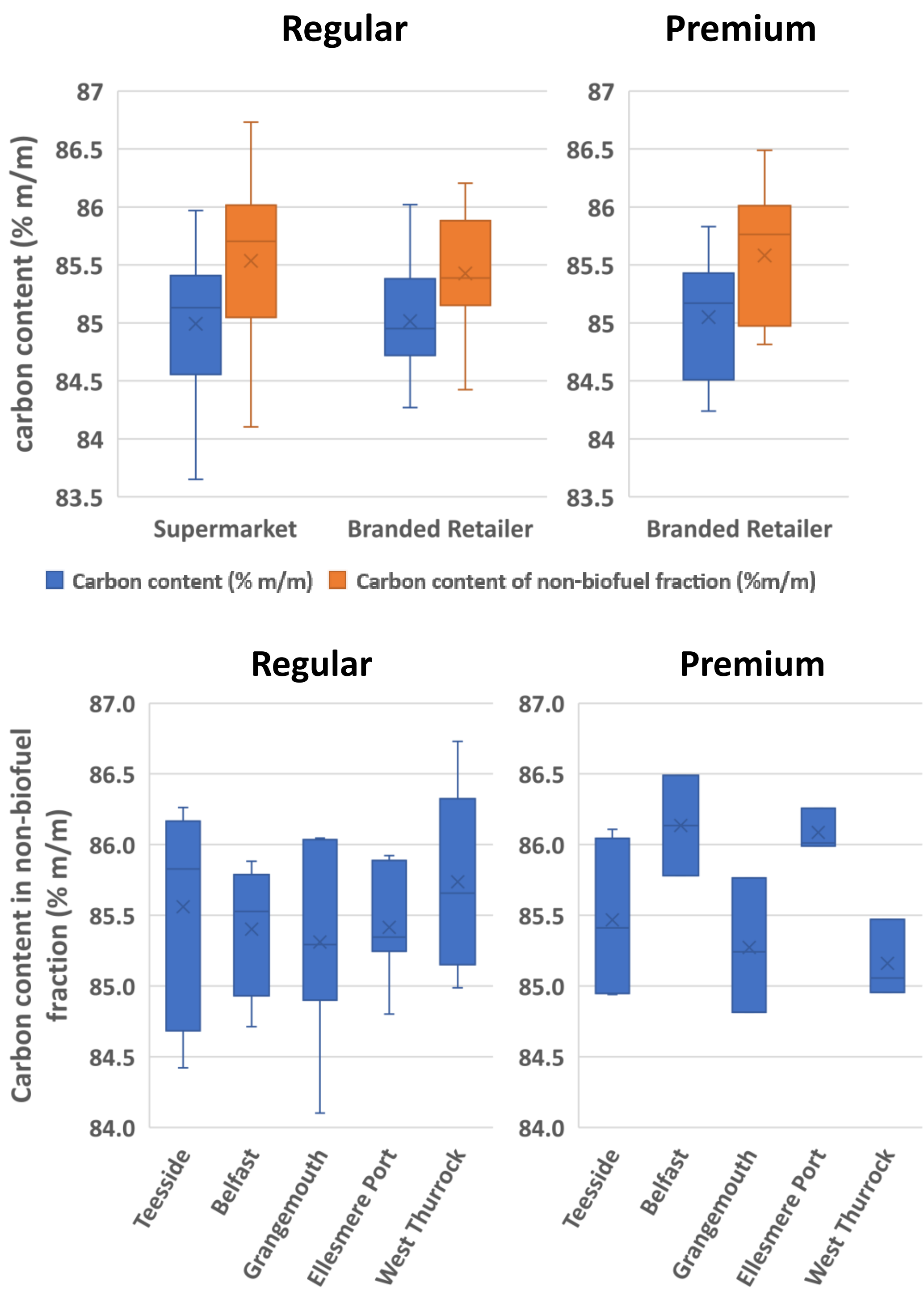

Figure 5 Distribution of carbon content values obtained from the sampling campaign for diesel. Top: carbon content of the total blend (blue) and of the non-biofuel fraction of diesel (orange), for different fuel grades (regular and premium) and type of retailer (supermarket versus branded retailers). Bottom: carbon content of the non-biofuel fraction of diesel, but area of the UK from which samples were taken.

Seasonal variation

As is the case for petrol, the sampling campaign only provides information on summer DERV blends. As mentioned in **section 5.1**, winter and summer blends differ in their resistance to solidifying in cold temperatures.

Discussions with Greenergy[26] indicated that biofuel content of DERV is a key factor which varies seasonally. In winter (November to February), the biofuel content normally ranges from 4-6%, whereas in summer (March to October) the biofuel content will be at around 7%. This is supported by Fuels Industry UK fuel quality data for 2022[20] showing mean FAME content of 5.3 %v/v in summer blends, versus 4.4 %v/v in winter blends. However, neither Greenergy nor the Fuels industry UK data could provide insight on whether there are differences in the fossil component over the year.

A research report on CEFs used in the German GHG inventory[18] provided information on summer and winter blend carbon content of diesel sampled from German refineries in 2002 (tables 14 and 15, pp.38-39 in that report). The average summer and winter blend carbon contents across all refineries were 86.32% and 86.40% respectively; i.e. there was little seasonal variation. At that time, biofuels were not blended into diesel after leaving refineries, so this is a good indication of carbon content in fuel as used for 2002. No more recent data from Germany is available.

A 2016 sampling study in the Netherlands[13] undertook a comparison of the fossil component of summer and winter DERV blends (calculated by subtracting the FAME content). The study found **very little seasonal difference** in carbon content of the fossil component of DERV (summer average of 85.23%; winter average of 85.45%), and NCV of the fossil component was also very similar. It must be noted that there are some potential issues about how the data has been aggregated in the Dutch study, however.

Whilst the results of these studies cannot rule out the possibility of larger seasonal differences in carbon content of fossil diesel in the UK, neither study points strongly towards that conclusion.

5.5.3 Comparison with the Netherlands inventory

The Netherlands' GHG inventory report annex on road transport methodology[17] provides fossil-only emission factors by year for diesel, which can be compared to the values used in the NAEI. The figure for 2021 was 854 g C/kg fuel, which equates to 85.4% carbon. This is slightly lower than the current 86.3% used in the NAEI, but **very consistent with the 85.4% - 85.6% average values for the non-biofuel fraction of summer blends found in the sampling study.** The Dutch figure has reduced over time from 86.4% in 1990, which is very similar to the 86.3% used in the NAEI based on the 2004 emission factor review.

Further detail on relevant findings from the literature review is provided in **Appendix B**.

5.5.4 Additives

Similar to gasoline, additives are added to diesel, for a number of purposes, primarily to improve combustion efficiency and reduce wear and tear on engines. Similar to gasoline, the first additives helps to improve ignition, although unlike gasoline these additives are still commonly used especially as demand has led to lower cetane quality fuel being produced at refineries. With this increased demand as diesel became more popular additives to reduce the crystallisation of diesel into waxes became standard and important for the use of diesel fuel in winter. Similar to gasoline, in the 1980s deposition control became important with new environmental legislation and additives were developed to prevent this. The reduction of the sulphur content of the fuel posed

[26] Personal correspondence between Aether and Greenergy, 08/08/23

additional challenges and additives to improve lubricity and conductivity of the fuel were introduced. However, lubricity improvers became less important following the use of FAME as a renewable diesel blending component as this acted in a similar manner. The most common additive types for diesel are:

- Additives that form films on the metal surfaces of engines to prevent components of fuels being deposited on or interacting with these surfaces (e.g. corrosion from water present in fuel or deposition of partially combusted particles on the hot inlet valve surfaces.
- Antioxidants / stability improvers which prevent the formation of gums during combustion.
- Conductivity improvers which reduce the accumulation of static charge in fuels, reducing the risk of explosion.
- Markers and dyes are also added to both fuel types which can be used to identify fuel type or for inventory control / theft deterrence.
- Demulsifiers which either prevent the formation of or break emulsions within the fuels.
- Additives that bind to metal ions in the fuel, to reduce the oxidation effect of these ions.
- Anti-foaming additives, preventing foaming during the fuelling process
- Reducing the crystallisation of diesel into waxes at low temperature, maintaining flow
- Anti-freezing additives that prevent the freezing of the water present in the fuel
- Increasing the cetane number, which improves ignition.
- Additives to improve the Diesel Particulate Filters catalyst regeneration.
- Additives to improve the flow of the diesel through pipes.
- Additives that react with hydrogen sulphide.

Almost all of these fuel additives are organic, with only a small inorganic component (e.g. an oxygen, sulphur or nitrogen acting as the functional group). The exceptions are provided in **Table 12** below.

Table 12 Inorganic fuel additives for DERV

Fuel additive	Purpose	Treatment rate (mg/kg fuel)
Fuel Borne Catalysts	Metal based compounds to improve regeneration of the Diesel Particulate Filters catalyst	5-30
Conductivity improvers	Polymeric sulphur or nitrogen compounds that increase the conductivity of fuel, preventing static charge build up and explosions.	1-40
Anti – foam	Silicon containing polymers that reduce the foaming ability of diesel	2-10

The additives above have a higher inorganic component, and in high enough quantities could impact the carbon content of fuel. However, as shown the treat rates are not significant (8 to 80 mg/kg = 0.0008 to 0.008%) and therefore it can be concluded that additives are not expected to impact the carbon content of diesel.

A University College London PhD research paper (Duboc, 2015)[27] reviewed the effect of fuel additives on diesel fuel delivery system and combustion performance. It noted that:

Additives are chemical compounds added in very small quantities (parts per million) to a fuel. For this reason, it is expected that all additives, as they break down during combustion, will have some effect on emissions. This effect is, however, insignificant for most additives (ATC, 2004) compared to the effect of combustion and fuel properties.

Overall, as for petrol it seems that additives are not a significant factor in diesel carbon content.

5.5.5 Comparison with the NAEI and uncertainties

DERV

When the DERV emission factor from the NAEI is converted into a percentage by mass, the carbon content of fossil diesel used in the NAEI in 2021 is 86.3% (**Table A.2** in Appendix A). This is 0.7 to 0.9 percentage points higher than the average carbon content of the fossil fraction of summer blends established from the sampling campaign, of 85.4% to 85.6% (85.52% is the overall un-weighted average).

Fully quantifying the uncertainty of the sampling campaign results has not been possible, as there are many sources of uncertainty as described in **section 4.4.3** which are difficult to estimate. **Indicative** confidence intervals of the mean carbon content in the fossil fraction from the sampling campaign given in **Table 13** below based on the sampling and measurement uncertainty respectively. The confidence interval represents the range in which the sample mean value will fall 95% of the time, if the sampling were to be re-done with the same sample size and design. See **section 4.5.4** and **Appendix D** for further information.

Table 13. Sampling and measurement uncertainty of the estimates of carbon content in the fossil fraction of DERV, expressed as 2 times the standard error of the mean of the samples.

	2 x Standard error of the mean (percentage points of carbon in fossil fraction)	Lower confidence bound (%m/m)	Upper confidence bound (%m/m)
Sampling uncertainty	±0.16	85.38	85.70
Measurement uncertainty	±0.86	84.68	86.40

The measurement uncertainty range is considerably larger than the sampling uncertainty range, so this can be taken as a conservative estimate of the uncertainty range of the sampling campaign results. This suggests a 95% confidence interval of 84.68% to 86.40% carbon in the fossil fraction when all samples are combined. The current NAEI figure of 86.3% lies just inside the upper bound of this uncertainty range for the summer blend estimates.

[27] Available at https://discovery.ucl.ac.uk/id/eprint/1455626/1/Baptiste_Duboc_-_Final_Thesis.pdf.REDACTED.pdf

As noted above, unaccounted for seasonal variation could mean that the current NAEI carbon content is closer to the true annual average carbon content of the non-biofuel fraction than to the summer blend value obtained in this study. However, the little data and expert opinion on seasonal variation obtained suggests that seasonal variation in the carbon content would not be significant.

Gas oil

When the gas oil emission factor from the NAEI is converted into a percentage by mass, the carbon content of diesel used in the NAEI in 2021 is 87.0% (**Table A.3** in Appendix A).

This value is identical to the typical value stated in the fuel specification sheets from various bulk fuel suppliers for the 2 grades of gas oil and dual-graded white diesel (EN 590).

The review of measured data from the ETS in 2022 (**Appendix C, Tables C.1 – C.3**) yielded only 1 example, from gas oil use in a power station. Although gas oil used in power stations may not be representative of other sectors, the implied carbon content of the measured emission factor was 87.12%, which is close to the NAEI value for other sectors.

Regarding differences in carbon content between DERV and gas oil, the information found on gas oil carbon content is not considered robust enough to make a reliable comparison. It is not clear how the typical carbon content values provided in fuel specification sheets were determined, or the degree of rounding applied.

5.6 Findings – Sulphur

5.6.1 Results of sampling campaign – Sulphur

The weighted average sulphur content by mass of the 50 DERV samples was **6.39 mg/kg.** Samples were weighted by fuel sales per country, as described in **Appendix D**.

Table 14 and **Figure 6** show the results of the sampling for sulphur in DERV. There was some variation in sulphur content across samples (between 3.3 and 9.3 mg/kg), but the weighted averages for regular vs. premium and supermarket versus non-supermarket DERV were very similar at 6.3-6.5 mg/kg.

Table 14 Overall summary results for sulphur content of diesel (weighted average, min and max mg/kg) from the sampling campaign.

Type of location	Weighted average sulphur content mg/kg (Min – max range)		
	Regular	Premium	All grades
Branded retailer	6.4 (4.2-8.9)	6.3 (4.8-8.5)	6.34
Supermarket	6.5 (3.3-9.3)	N/A	6.47
All retailer types	6.42	6.32	**6.39**

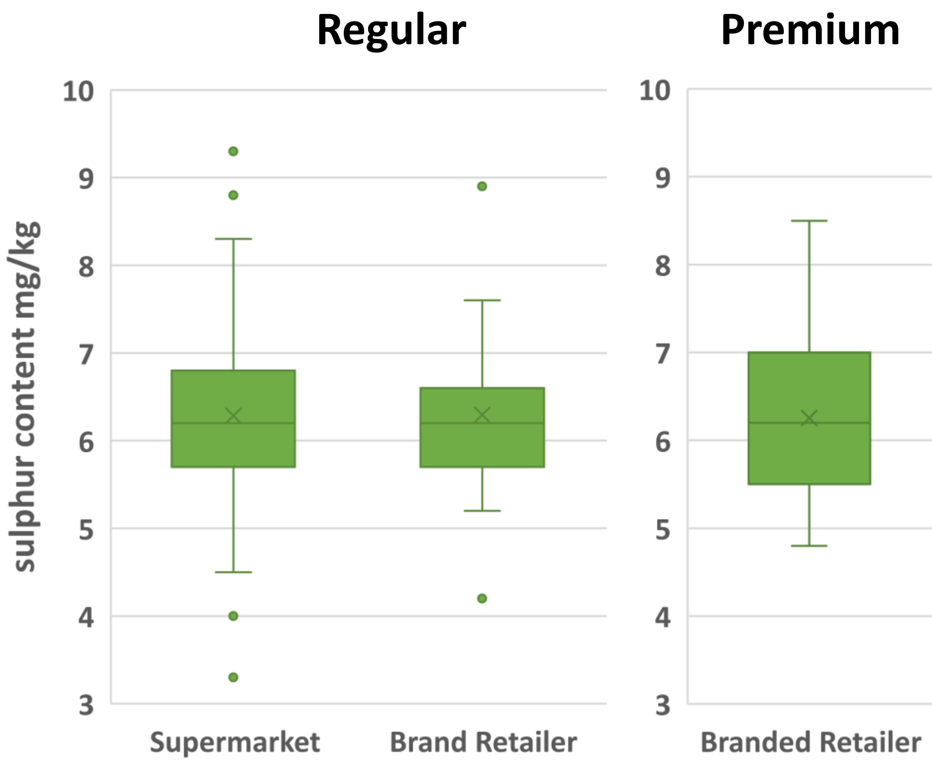

Figure 6 Distribution of sulphur content values obtained from the sampling campaign for DERV, broken down by fuel grade (regular and premium) and type of retailer (supermarket versus branded retailers).

Fuel Industry UK provided fuel quality data for 2021[19] and 2022[20] during the project including sulphur content, summarised in **Table 15** below. The table also include indicated typical sulphur content based on the fuel specification sheets from fuel suppliers.

Table 15. Typical sulphur content of diesel and gas oil in 2021 and 2022 from UK refineries and fuel suppliers affiliated with Fuel Industry UK , and from fuel suppliers.

Fuel type	Fuel Industry UK data Sulphur (mg/kg)		Fuel supplier specification sheets “typical” value
	2021	2022	mg/kg
DERV	7.19	Summer: 7.4; Winter: 7.3	
Low-sulphur gas oil (BS 2869 class A2 and dyed EN 590), 10 ppm max	6.99	6.2	<15
High-sulphur gas oil (BS 2869 class D), 1000 ppm max	154.4	715.5	<980

Differences between DERV and gas oil

The data collated during this work shows that there is little difference in sulphur content between DERV and the two grades of low-sulphur gas oil (dyed EN 590 and class A2 gas oil BS 2869), but that the sulphur content of class D gas oil is significantly higher.

5.6.2 Comparison with the NAEI and uncertainties

When NAEI emission factors are expressed as a % sulphur content in fuel, the values used for emissions in 2021 are 7.19 mg/kg for DERV, 5.95 mg/kg for gas oil used in mobile applications (excluding marine gas oil) and 80.9 mg/kg for use in stationary applications (excluding large industrial installations). Fuel Industry UK data indicates that class A2 gas oil / dyed EN 590 diesel predominate in mobile applications, whereas class D gas oil is used in stationary applications. The NAEI sulphur content values are, in this context, a good match for the data provided by Fuel Industry UK. However, a large difference in sulphur content data for 2021 and 2022 is apparent for high-sulphur gas oil (154.4 vs. 715.5 mg/kg), which may relate to changes in definitions of fuels.

The DERV sulphur content results from the sampling programme in 2023 are slightly lower (6.39 versus 7.19 mg/kg) than the sulphur content for DERV used in the NAEI for 2021, but the figure for DERV obtained from Fuels Industry UK matches the NAEI figure exactly because Fuels Industry UK data is the source of the NAEI emission factor.

Indicative estimates of the confidence intervals around the mean DERV sulphur content, based on sampling and measurement uncertainty respectively, are presented below in **Table 16.** The confidence interval represents the range in which the sample mean value will fall 95% of the time, if the sampling were to be re-done with the same sample size and design. **Appendix D** provides further details on how these were calculated.

Table 16. Sampling and measurement uncertainty of the estimates of sulphur content of DERV, expressed as 2 times the standard error of the mean of the samples.

	2 x Standard error of the mean (mg S/kg fuel)	Lower confidence bound	Upper confidence bound
Sampling uncertainty	±0.35	6.04	6.74
Measurement uncertainty	±0.17	6.22	6.56

For sulphur content, the larger of the two uncertainty ranges is the sampling uncertainty, and the measurement uncertainty likely contributes to this (assuming it is random), so the sampling uncertainty range can be taken as the indicative confidence interval around the mean.

The NAEI estimate of 7.19 mg/kg falls outside the upper limit of the uncertainty range of the overall mean (6.63 mg/kg), although i) the data underpinning the two values relate to different years (2021 and 2023 respectively) and ii) there are other sources of unquantified uncertainty around the sampling results, not included in these estimates, as described in **section 4.5.4**.

5.7 Recommendations and implications for the inventory

The proposed changes to the NAEI carbon emission factors and sulphur emission factors for DERV and gas oil are summarised in **Table 17**. Details of any additional recommendations are set out below.

Table 17 DERV and gas oil carbon emission factors and sulphur emission factors proposed changes

	DERV		Gas Oil	
	Carbon (% mass or energy based-CEF)	Sulphur content (% mass or energy based CEF)	Carbon (% mass or energy based-CEF)	Sulphur content (% mass or energy based CEF)
Current NAEI value (2021)	86.3% or 0.02005 kt/TJ	0.334 g/GJ or 7.19 mg/kg	87.00 – 87.44 % or 0.02044 kt/TJ	0.28 – 3.80 g/GJ or 5.95 - 80.9 mg/kg
Recommended value (2021)	85.54% or 0.01988 kt/TJ	No change proposed.	No change proposed.	No change proposed.
% difference recommended vs. current	-0.88%	No change.	No change.	No change.
Impact on 2021 emissions at national level (kt)	-611.75kt	No change.	No change.	No change.
Impact as % of 2021 inventory total	-0.14%	No change.	No change.	No change.

*Recommended energy-based CEF is calculated using the NCV used in the NAEI for 2021, because NCV was not measured independently as part of the sampling study.

5.7.1 Carbon

For **DERV**, based on the results of the sampling campaign it is recommended that a carbon content value for the fossil fraction of 85.54% be used for inventory year 2023 and the following years, until further data is available / studies are undertaken. There are some caveats regarding the representativeness of the sample as an annual average for the UK as a whole, as discussed in **Section 4.4.3, 5.5.5** and **Appendix D**.

Some limited additional sampling of winter DERV blends could be justified to improve evidence around seasonality.

Regarding revisions to the historical time-series for DERV, similarly to petrol a decrease in carbon content of fossil DERV over time is suggested by the Dutch inventory, but given the lack of concrete time-series data found for the UK this is best left for the NAEI team to decide.

For **gas oil**, based on the limited information found, it has been determined that the carbon emission factors used in the NAEI are still valid. However, given the lack of publicly available information regarding the carbon factors for gas oil a sampling campaign for gas oil could be undertaken. This was originally considered for this project, but the compressed timescale for the project did not allow a representative set of samples to be collected.

5.7.2 Sulphur

Based on the information collected in this project, it has been determined that sulphur content values for DERV and gas oil currently used in the inventory are still valid. For DERV, although the 2021 NAEI value of 7.19 mg/kg falls above the upper uncertainty interval of the analysed DERV samples from 2023, the difference in year of data collection may explain this. The NAEI value for 2021 aligns with data received from Fuel Industry UK, so is likely to be quite representative of average sulphur content in 2021.

For **gas oil** the 2021 NAEI figure is appropriate, but given the large difference in sulphure content reported by Fuels Industry UK for high-sulphur gas oil between 2021 and 2022, for the 2022 and future inventories it is recommended that the NAEI team review the definition of sub-types of gas oil used by Fuel Industry UK and how those align with the types allocated to different source categories in the NAEI.

6 LPG

6.1 Definition and Contribution to GHG Inventory

The 2017 review provided definitions of fuels, which have been reused in this report and updated as necessary.

Liquid Petroleum Gas (LPG) is a petroleum product, consisting primarily of propane and butane, used for heating, as feedstocks for the chemical industry, and as aerosol propellants. These are very volatile hydrocarbons which require pressurised containers to avoid evaporation. Propane and butane are usually sold separately, rather than as a mixture.

In 2021, LPG accounted for 1% of total GHG emissions generated from combustion of fuels, and 0.8% of total GHG emissions in the UK overall.

6.2 Existing Inventory

The CEFs for LPG used in the NAEI are derived from the following source:

- Data provided by UKPIA (now Fuel Industry UK) (1989)

Although comprising both propane and butane which are usually sold separately, the NAEI considers LPG as one fuel. However, the 1990-1999 UK NAEI Appendix 1 (AEA Technology, 2001) noted that:

A comparison of the current factors was carried out based on limited industry and supplier data […]. The comparison suggested that the factor used for LPG was anomalously high. The industry was using factors for propane and butane, the major constituents of LPG. Based on a review of these factors and those suggested by IPCC (1997), a new factor was estimated based on an assumed 80%/20% mixture of propane and butane. This is broadly the proportion of the two gases produced.[28]

Appendix A (**Table A.4**) sets out the CEFs for LPG across the 1990-2021 NAEI timeseries. The CEF is consistent across all sources (i.e., power stations, domestic boilers etc. etc.). Small adjustments to the CEFs have been made over time. This is as a result of recalculations based on the calorific value data received from DUKES. Once the NCV fluctuations have been accounted for, the emissions per mass of fuel remains the same across the timeseries.

The CEF for LPG used in the NAEI in 2021 is **0.01742 kt carbon/TJ** which is equivalent to **63.89 tCO_2/TJ**.

Unlike other fuels discussed in this report, the carbon content of LPG is the average of the carbon content of the individual propane and butane fuels (noting that these are likely not pure propane and butane), weighted by their proportional consumption. The current assumption of a fixed propane:butane ratio of 80%:20% (v/v) is therefore a key factor in determining the overall carbon content of LPG consumed.

[28] Available at: https://uk-air.defra.gov.uk/assets/documents/reports/empire/ghg/ukghgi_90-99_append_1-2.pdf

6.2.1 Sulphur emission factors

The sulphur EFs used in the NAEI are provided in **Table 18** below. This demonstrates that the EF has remained constant across the timeseries for domestic and stationary industrial applications, but has fallen (though already from a low starting point) for mobile industrial machinery.

Table 18. LPG SO_2 emission factors and apparent fuel sulphur content used in the NAEI

Measure	Sector	1990	1995	2000	2005	2010	2015	2021
SO_2 EF used in NAEI (g/GJ)	Domestic	0.300	0.300	0.300	0.300	0.300	0.300	0.300
	Industrial* stationary	0.670	0.670	0.670	0.670	0.670	0.670	0.670
	Industrial mobile	0.824	0.646	0.194	0.057	0.011	0.009	0.010
Apparent S content of fuel (mg/kg)	Domestic	6.900	6.900	6.900	6.900	6.900	6.900	6.900
	Industrial* stationary	15.4	15.4	15.4	15.4	15.4	15.4	15.4
	Industrial mobile	19.0	14.9	4.46	1.31	0.244	0.208	0.223

**Note for LPG, industrial includes only small combustion, as large combustion emissions are out of scope of this work.*

6.3 Previous Inventory Improvements and Reviews

The 2017 Review was not able to determine whether data or specifications were available to determine LPG carbon contents with a high confidence, and no new data were presented. It recommended that:

The one, key supplier of LPG for energy use and/or the UK LPG association (UK LPG) is contacted to understand:

- *How accurate it would be to use a stoichiometric analysis for propane and butane*
- *Whether there are specifications for LPG that mean that there is a narrow range of carbon contents possible*
- *Whether data are routinely collected on the content or properties of LPGs*

In response to this recommendation, Aether contacted UKLPG. This is discussed in **section 6.4** below.

Ricardo provided information about a review of the carbon emissions factors for LPG that was undertaken in 2019, however this report was unpublished and is not publicly available[29]. It is discussed further in the section on findings and implications for the inventory below.

6.4 Methodology

Aether engaged with industry stakeholders including Liquid Gas UK and Calor Gas to seek answers to the following questions:

- Do these companies test for and collect data on carbon content of LPG?

[29] Updating NAEI Carbon Emission Factors for LPG and Solid Fuels (Ricardo, March 2019) unpublished and prepared in Confidence.

- What fraction of the LPG they produce is biogenic?
- Are the mixing ratios between propane and butane fixed? and
- What fraction of the UK market share they represent.

In addition, existing data published by DUKES was reviewed and analysed. The National Statistics publication includes petroleum products commodity balance from 1998 to 2021[30]. DUKES was contacted directly to obtain further detail of the NCVs of propane and butane.

6.5 Findings - Carbon

There are two key British Standards which govern the specifications for LPG:

- BS 4250:2014 Specification for commercial propane and commercial butane
- BS EN 589 Automotive fuels – LPG – Requirements and test methods

Calor Gas noted that the mixing ratios for propane and butane where not fixed and vary by markets and thresholds defined in the local LPG specifications. In the UK, Butane or higher hydrocarbons cannot exceed 10% mol fraction.

The Ricardo research paper into LPG (Ricardo, 2019, unpublished) focusing largely on the residential and small-scale commercial sectors, reviewed data collected from LPG import shipments and storage terminal material in 2016 and 2017.

The supplier data shown in **Table 19** demonstrates that propane accounts for the vast majority of the market.

Table 19. Summary of supplier data for non-residential propane and butane market (extract from Ricardo, 2019, unpublished)

Type of supply	Propane (kTonnes, %)	Butane (kTonnes, %)
Bulk	452 (71.9%)	2 (0.3%)
Cylinder	160 (25.4%)	15 (2.3%)

"Suppliers also provided additional context to data including:

- *Market for heating is predominantly for propane to BS 4250.*
- *Propane sourced from either refineries or fossil fuel production, with fossil fuel generally having higher propane content.*
- *Bio-LPG (propane), a refined by-product of biodiesel production, has been a relatively recent input to UK LPG supplies. Currently it is treated by suppliers as another source of propane and blended with conventional product"*

The report noted that data indicates there is little seasonal variation in the composition of commercial propane.

Below are extracts from the Ricardo 2019 unpublished review showing the propane and butane carbon content and calorific value based on the samples collected and supplier data collated in that study. It showed that there are impurities in propane and butane, which makes simple stoichiometric calculation of the carbon factor assuming 100% purity slightly inaccurate, especially for butane.

[30] Available at: https://www.gov.uk/government/statistics/petroleum-chapter-3-digest-of-united-kingdom-energy-statistics-dukes Table 3.2

Ricardo also summarised the CEF for Propane and Butane, shown in **Table 20** below.

Table 20. Summary of carbon emission factors, propane and butane, from the Ricardo 2019 review

LPG type	Source	Carbon content	Lower Calorific Value	CO_2 Emission Factor	SD
		g/100g	kJ/100g	TCO_2/TJ (net)	
Propane	Samples (N=36)	81.74	4635.24	64.7	0.11
	Supplier data (N = 66)	81.72	4632.64	64.7*	not est.
Butane	Samples (N= 15)	82.59	4573.77	66.2	0.15

** Individual CO2 Emission Factors for supplier data not completed – figure derived from two mean values from Carbon content & NCV*

Table 21 presents calculations undertaken for this report of alternative carbon emission factors. These use the carbon content and calorific value results of the Ricardo 2019 unpublished review for propane and butane respectively, and combine these with the relative quantities of propane and butane consumed for energy use as reported in DUKES table 3.2[31] to calculate a weighted average CEF. For propane, based on the recommendation in the Ricardo 2019 report the results of the sample analysis rather than supplier data have been used, although the energy-based CEFs is the same in both cases so this choice does not make a material difference to the conclusions drawn. The extrapolation back to 2000 across the time series assumes that the Ricardo 2019 report figures have not changed significantly over time, which may not be accurate, but is shown here indicatively.

Table 21. Comparison of LPG emission factors since 2000, between the values used in the NAEI, and the weighted average factors by mass and energy calculated using data from the Ricardo 2019 unpublished review (sample data for propane) and proportion of propane and butane used for energy from DUKES table 3.2.

Year	By mass		By energy		
	% propane	Weighted average LPG carbon content (g/100g)	% propane	Weighted average LPG CEF (tCO_2/TJ)	NAEI LPG CEF (tCO_2/TJ)
2022	91.95%	81.81	92.05%	64.82	63.89
2021	92.17%	81.81	92.26%	64.82	63.89
2020	91.32%	81.81	91.43%	64.83	63.89
2015	92.93%	81.80	93.01%	64.80	63.89
2010	65.08%	82.04	65.38%	65.22	63.89
2005	87.13%	81.85	87.28%	64.89	63.89
2000	85.16%	81.87	85.33%	64.92	63.89

[31] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1174050/DUKES_3.2.xlsx

A review of the LPG CEF was also undertaken for the German GHG Inventory[18]. This study calculated the carbon content of butane and propane via molar weights, reviewing data from 1990. The review calculated weighted emission factors for LPG (weighted by the relative share of propane and butane in the fuel mix) of 64.0 to 66.6 t CO2/TJ depending on the year. We can conclude that the German factors range are very consistent with the factors presented in the Ricardo 2019 study, and these are both higher the default value given by the 2006 IPCC Guidelines of 63.1 t CO_2/TJ. for Tier 1

The analysis of ETS data yielded one example of measured CO_2 emissions from propane at a site classed as sector "Other industrial combustion", of 64.57 tCO_2/TJ, which is comparable with the results of the Ricardo 2019 review, though it is not clear how representative this value would be of consumption in other sectors.

6.5.1 Bio-LPG

For petrol and diesel, DUKES commodity balances provide activity data for the fossil portion of these fuels only, because reporting to the DUKES team occurs upstream in the supply chain from blending with biofuels.

From the literature review and stakeholder consultation, it is clear that some bio-LPG is used in the UK. Initially, the DUKES liquid fuel statistics team indicated that propane and butane final consumption figures in DUKES table 3.2 were likely to also refer to fossil sources only. However, further consultation with the NAEI team clarified that, in fact, bio-LPG is blended with fossil LPG within main storage tanks, and that **the commodity balance figures in DUKES are likely to represent a mixture of fossil LPG and bio-LPG**. The quantity of bio-propane destined for use in transport is reported by DfT as part of the renewable transport fuels obligation (RTFO) statistics[32], but data on the quantity of bio-propane or bio-butane supplied for domestic or commercial stationary applications or industrial mobile machinery is not currently available.

It is not thought that this mixing affects the conclusions on carbon emission factors emerging from the Ricardo 2019 report presented above, because the NAEI inventory team expect the chemical composition of bio-propane and bio-butane to be almost identical to the fossil equivalent. Therefore, the carbon emission factors for a blend of fossil and bio-LPG could reasonably be applied to pure fossil LPG.

Rather, the issue here is the uncertainty in the quantity of propane and butane reported in DUKES which are of fossil and biogenic origin, and therefore what proportion of CO_2 emissions from LPG should be included in the GHG inventory national total. This question could be a priority for future NAEI improvement work to address.

6.5.2 Comparison with the NAEI and uncertainties

The CEF currently used across the timeseries for LPG (63.89 tCO_2/TJ) is between 1.4% and 2% lower than the estimates obtained from propane and butane sampling in the Ricardo 2019 study (for the years shown in **Table 21**), when combined with data on the proportion of propane and butane in energy use (between 64.8 and 65.2 tCO_2/TJ). The NAEI figure is also between 0.2% and 4.1% lower than the minimum and maximum range of German factors cited, and 1.1% lower than the single ETS value.

[32] https://www.gov.uk/government/statistics/renewable-fuel-statistics-2022-final-report

The standard deviations of the CEFs in the Ricardo 2019 review were 0.11 and 0.15 tCO_2/TJ for propane and butane respectively. This would translate into an uncertainty range (2 x standard error) of 0.04 and 0.08 respectively with the quoted sample sizes[33]. However, there are other factors contributing to the uncertainty in the Ricardo 2019 numbers which are not accounted for, but the Ricardo 2019 review suggests an estimated overall uncertainty range of around 1%, which translates into an uncertainty range between 64.2 and 65.9 tCO_2/TJ. The current NAEI CEF is slightly below the bottom end of this range. When combined with uncertainty in the DUKES data on propane and butane consumption, this will increase the overall uncertainty of the emission factor slightly further, and the current NAEI CEF may fall just within the lower uncertainty bound.

A key finding from the data presented above is that the ratio of propane:butane in final energy use reported in DUKES table 3.2 is substantially higher than the 80%:20% split currently used in the NAEI, being typically over 90%:10% or greater. However, there is also uncertainty present in the DUKES statistics, which will add to the overall level of uncertainty of the weighted-average LPG CEF.

6.6 Findings - Sulphur

No quantitative data was available from the literature or stakeholders on the current sulphur content of LPG.

To meet the requirements of BS: 4250 the limit for total sulphur is 50 mg/kg.

The current SO_2 emission factors from the NAEI converted to sulphur content on a mass basis, are 6.9 mg/kg for domestic LPG, and 15.4 mg/kg and 0.22 mg/kg for commercial and industrial LPG in stationary and mobile applications respectively, which are well below the 50 mg/kg limit.

Discussions with Fuel Industry UK indicate that the commercial propane and butane specification is less prescriptive of sulphur content, and there could be a high sulphur content in road LPG. This agrees with the differentiated LPG SO_2 EFs used in the NAEI.

[33] Standard error of the mean, when error is random (which is the normal assumption), is defined as SD / sqrt(N), where N is the number of samples.

6.7 Recommendations and implications for the inventory

The proposed changes to the NAEI carbon emission factors and sulphur emission factors for LPG are summarised in **Table 22**. Details of any additional recommendations are set out below.

Table 22. LPG carbon emission factors and sulphur emission factors proposed changes

	Carbon (% mass or energy based-CEF)	Sulphur content (% mass or energy based CEF)
Current NAEI value (2021 for carbon, 2020 for sulphur)	0.01742 kt carbon/TJ 63.89 tCO_2/TJ	Domestic: 0.3 g/GJ or 6.9 mg/kg Industrial: 0.67 g/GJ or 15.4 mg/kg (stationary), 0.01 g/GJ or 0.22 mg/kg (mobile)
Recommended value (2021)	64.82 tCO2/TJ	No change proposed.
% difference recommended vs. current	+1.46%	No change.
Impact on 2021 emissions at national level (kt)	+48.3 kt	No change.
Impact as % of 2021 inventory total	0.01%	No change.

6.7.1 Carbon

It is recommended that for the latter part of the time series (at least), the NAEI makes use of the carbon emission factors for propane and butane included in the unpublished 2019 review, as they are higher than the currently used values in the NAEI. The uncertainty of the 2019 review estimates is not fully quantified, but would indicate the current NAEI values sit at or below the lower uncertainty bound. It is understood that implementing this change may require additional industry stakeholder engagement to secure agreement.

Due to the lack of a time series of data on LPG composition, further discussions are needed with the NAEI team on how to integrate these results for later years with previously obtained data for much earlier years, ensuring time-series consistency.

In addition, it is recommended that the NAEI moves away from assuming a fixed ratio of propane and butane in energy use, and instead makes use of available data on propane and butane consumption for energy uses to calculate a weighted average varying by year. Alternatively, the NAEI could move to representing emissions for propane and butane separately as two different fuels with differing CEFs, rather than combining these into a single LPG fuel type. Activity data, NCV, emission factors and emissions from the separate fuels could then be combined by summation and weighted-averaging for reporting numbers for LPG in the UNFCCC common reporting format.

Finally, it is recommended that in future NAEI improvement work, targeted engagement is undertaken with the DUKES statistics team, LPG suppliers and any other relevant stakeholders (such as HMRC), to better determine the fractions of bio-LPG and fossil LPG consumed.

6.7.2 Sulphur

There was insufficient data available on sulphur content of LPG to make recommendations regarding the NAEI sulphur emission factors.

7 Aviation Turbine Fuel

7.1 Definition and Contribution to GHG Inventory

The 2017 review provided definitions of fuels, which have been reused in this report and updated as necessary.

Aviation turbine fuel (ATF) is a middle distillate and highly refined kerosene, with similar properties to burning oil used for heating, except that the properties of ATF are rigorously controlled to ensure that it can safely be used for aviation. It is the primary aviation fuel.

ATF is the fuel name in the NAEI. The IPCC refers to this fuel as 'jet kerosene'. It is also referred to as 'jet fuel' within the literature and within this report.

In 2021, ATF accounted for 0.4% of total domestic GHG emissions generated from combustion of fuels, and 0.5% of total GHG emissions in the UK overall, although the cruising phase of international aviation (not included in the UK national total) emits a significantly greater quantity of GHGs.

7.2 Existing Inventory

The CEFs for Aviation Turbine Fuel (ATF) used in the NAEI are derived from the following source:

- Data provided by UKPIA (now Fuel Industry UK) (2004)

The Fuel Industry UK 2004 survey results were consistent with the data from Fuel Industry UK 1989 and therefore no changes were made to the CEF.

Appendix A (**Table A.5**) sets out the CEFs for ATF across the 1990-2021 NAEI timeseries. The CEF is consistent across different aircrafts. Small adjustments to the CEFs have been made over time. This is as a result of recalculations based on the calorific value data received from DUKES. Once the NCV fluctuations have been accounted for, the carbon emissions per mass of fuel remains the same across the timeseries, at **859 g carbon as CO_2/kg** (85.9% carbon by mass).

7.2.1 Sulphur emission factors

The table below shows the sulphur emission factors that are currently used in the NAEI.

Table 23. Aviation turbine fuel SO_2 emission factors and apparent fuel sulphur content used in the NAEI

Measure	1990	1995	2000	2005	2010	2015	2021
SO_2 EF used in NAEI (g/GJ)	13.7	18.2	16.4	18.7	19.1	36.3	9.91
Apparent S content of fuel (mg/kg)	300	400	360	410	420	798	218

According to the UK 1990-2021 Informative inventory report (IIR)[34] (p.181) The values used in the NAEI are based on data from Fuel Industry UK up to 2016 based on sampling data from the UK members, but Fuel Industry UK have not provided data since then. From consultation with Fuel Industry UK, these data are a weighted-average of the samples tested by Fuel Industry UK member companies.

7.3 Previous Inventory Improvements and Reviews

The 2017 Ricardo review did not focus on ATF, but concluded in the assessment of uncertainty by fuel that it was a low priority given the small contribution of domestic aviation to the UK's emissions.

7.4 Methodology

Aether contacted industry stakeholders to understand whether data on carbon and sulphur content of ATF are available. This included a series of email exchanges and online meetings.

The purpose of the stakeholder engagement was to understand whether carbon and sulphur content of ATF are tested for and monitored in industry. If so, it was necessary to determine whether these data could be used to support the CEF currently used in the NAEI. If no available data on carbon and sulphur content was available, then this would be identified as a gap in our understanding of this fuel type.

7.5 Findings - Carbon

Little direct information on carbon content of ATF was forthcoming from review of the literature or stakeholder engagement.

7.5.1 Standards

ATF is heavily regulated and governed by strict safety standards. There are two international, universally adopted standards:

- ASTM D1655: Standard Specification for Aviation Turbine Fuels (ASTM, 2022)[35]
- DEF STAN 91-091: Turbine Fuel, Kerosene Type, Jet A1; NATO Code: F-35; Joint Service Designation: AVTUR (Ministry of Defence, 2019)[36]

However, these are performance standards, rather than compositional standards, and do not specify carbon content. DEF Stan 91-091 acknowledges that:

"Jet fuel is a complex mixture of hydrocarbons that varies depending [on the] crude oil [properties] and the manufacturing process. Consequently, it is impossible to define the exact composition of jet fuel.

Jet fuel, except as otherwise specified in this Standard, shall consist predominantly of refined hydrocarbons derived from conventional sources including crude oil, natural gas liquid condensates, heavy oil, shale oil, and oil sands, and qualified additives as listed in Annex A."

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[34] https://uk-air.defra.gov.uk/reports/cat09/2303151609_UK_IIR_2023_Submission.pdf
[35] Available at https://www.astm.org/d1655-22a.html
[36] Available at http://inaca.or.id/wp-content/uploads/2019/11/Def-Stan-91-091-Issue-11-Oct-2019-Turbine-Fuel-Kerosene-Type-Jet-A-1-NATO-CodeF-35-Joint-Service-Designation-AVTUR.pdf

Annex A of DEF STAN 91-091 sets the approved qualified additives, including Anti-oxidant, Metal Deactivator Additive, Fuel System Icing Inhibitor (FSII), and Leak Detection Additive.

The composition of ATF typically contains a range of different molecules from the n-alkanes, iso-alkanes, cyclo-alkanes, and aromatics groups. Alkenes are not normally present, except under conditions of severe cracking. Within the aviation fuel standards, the aromatic group of molecules is the only group to have specifically identified control limits (max 25% v/v, of which max 3% v/v naphthalene).

While other chemical groups are not necessarily restricted, the fuel must meet the standards for other properties such as freezing point, smoke point, flash point etc. While minimum safety standards must be met, each producer will use different refineries, resulting in a wide variation of chemical composition. The fuel produced must be endorsed by the Original Equipment Manufacturer (OEM) for aircraft components to be added to a list of approved fuels that are suitable for use in equipment. Discussions with Q8 Aviation indicated that carbon atoms per jet fuel molecule is typically within the range of C8 and C18, depending on the crude oil properties and the manufacturing method.

As defined by these standards, testing for carbon content is not mandatory. However, the standards define the minimum net calorific value as 42.80 MJ/kg.

The Energy Institute has prepared research reports[37] on the quality of aviation fuel (Jet A-1) available in the United Kingdom, based on data supplied by all aviation fuel suppliers operating in the UK. These do not include information on carbon content, but the introduction (p.8) of the report for 2016/17 highlights that an increasing proportion of ATF has been imported to the UK over time, and now makes up a large fraction of the total. This may have implications for the validity of the continued use of Fuel Industry UK data from 2004, the scope of which is restricted to outputs of UK refineries and fuel imported by member companies.

7.5.2 Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)

The International Civil Aviation Organisation (ICAO) is the regulatory body for the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). The ICAO CORSIA CO_2 Estimation and Reporting Tool (CERT) can be used by an aeroplane operator to support the monitoring and reporting of their CO_2 emissions. It has set the following fuel conversion factors[38]:

- 3.16 kg CO_2/kg of fuel for Jet-A and Jet-A1 fuel (equivalent to 862 gC/kg fuel); and
- 3.10 kg CO_2/kg fuel for AvGas or Jet-B fuel (equivalent to 845 gC/kg fuel).

These figures were derived from work of the IPCC, information from petroleum quality surveys, information from national GHG inventories, other emissions trading schemes, worldwide and regional values for the CO_2 fuel conversion factor, as well as methods

[37] Available at https://publishing.energyinst.org/topics/aviation/aviation-fuel-quality/the-quality-of-aviation-fuel-available-in-the-united-kingdom-annual-survey-2016-17

[38] Available at https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA_FAQs_Dec2022.pdf

that are based on measuring hydrogen and sulphur contents to calculate carbon content. However, this background data has not been available to review.

The value of 862 gC/kg fuel of carbon is slightly higher than the 859 gC/kg fuel currently used in the NAEI, but this is an international figure so does not imply that the UK value is low. The NAEI uses the same CEF for ATF, irrespective of the different fuel types or sources.

7.6 Findings - Sulphur

Unlike carbon, sulphur is frequently tested for in ATF, with the upper limit of 3,000 ppm set by aviation safety standards (outlined above). The sulphur in the fuel is largely converted to sulphur dioxide gas (SO_2), emitted in the exhaust and approximately 2% is emitted directly as sulphuric acid.

Table 24 presents the results of the Energy Institute ATF surveys, from 2009 to 2017, of batches of ATF released by oil companies and suppliers for use in the UK. The latest 2028/19 report is currently being prepared and was not available for review. Due to the variation in volume of each fuel batch, the Energy Institute reports provides the mean values expressed as weighted means according to the relative batch fuel volume associated with the results from each fuel batch. There is substantial variation across samples, showing a modal value between 0 and 400 mg/kg depending on the year. In some years, the distribution is bimodal, with a second, smaller peak at 1,200 – 1,600 mg/kg.

The 2021 mean sulphur content was provided by Fuel Industry UK from an aggregated data set, representing the weighted-mean of samples tested by Fuel Industry UK members[Error! Bookmark not defined.].

Table 24. Total sulphur content, mg/kg (converted from % mass) (Energy Institute, 2009-2017, Fuel Industry UK 2023[19,20]). Dashes indicate where data are not available.

Year	Sample Size	Min, mg/kg	Max, mg/kg	Mean, mg/kg	NAEI, mg/kg
2009	608	10	2480	520	410
2010	491	0	2900	470	420
2011	765	10	2100	470	440
2012	1,204	10	2530	550	632
2013	1,259	2	2000	480	591
2014	1,087	5	2200	570	751
2015	1,488	10	2170	510	798
2016	1,232	0	2600	500	798
2017	1,116	0	2070	440	798
2018	-	-	-		798
2019	-	-	-		798
2020	-	-	-		798
2021*	-	-		217	218
2022*	477	0	2054	227	-

**provided by Fuel Industry UK[19,20]*

In 2021 the NAEI SO_2 EF is based on the latest Fuels Industry UK figure, so there is no discrepancy between the NAEI and other data sources available for 2021. However, for the years 2012 – 2017 the NAEI values are much higher than the Energy Institute values, and the latter show a general decrease whilst the NAEI value generally increases then is held constant at 798 mg/kg (whilst no data was available from Fuels Industry UK). This results in a step-change in EF between 2020 and 2021, which is not based on actual data. Unfortunately, no data is available between 2017 and 2021 from the Energy Institute with which to make a comparison with the NAEI values and 2021 Fuels Industry UK numbers. As mentioned in **section 7.2.1**, the NAEI values up to 2016 are derived from data supplied by Fuel Industry UK each year, which represents fuel output from UK refineries and imported by member companies. It is not clear from the Energy Institute report if the survey achieves complete coverage of ATF supplied to the UK, but based on the list of contributing companies the market coverage appears to be more complete than the Fuel Industry UK figures. This may be one reason for the discrepancy in values seen in the table above for 2012-2017.

7.7 Recommendations and implications for the inventory

The proposed changes to the NAEI carbon emission factors and sulphur emission factors for ATF are summarised in **Table 25** ATF carbon emission factors and sulphur emission factors proposed changes. Details of any additional recommendations are set out below.

Table 25 ATF carbon emission factors and sulphur emission factors proposed changes

	Carbon (% mass or energy based-CEF)	Sulphur content (% mass or energy based CEF)
Current NAEI value (2021)	85.9%	9.91 g/GJ 218 mg/kg
Recommended value (2021)	No change proposed.	No change proposed to the 2021 value, though some changes recommended to the historical time series may be advisable.
% difference recommended vs. current	No change.	No change.
Impact on 2021 emissions at national level (kt)	No change.	No change.
Impact as % of 2021 inventory total	No change.	No change.

7.7.1 Carbon

On the basis of the information found, there is no reason to recommend changing the CEF of ATF used in the NAEI.

7.7.2 Sulphur

There is a clear gap in real sulphur content data for years 2016 to 2020 underlying the NAEI SO_2 EFs for ATF, which causes an inconsistency in the time series of EFs used in the NAEI. It is recommended that revisions are made to the historical timeseries between 2016 and 2020 (at least) to improve time series consistency, for example by engaging further with Fuels Industry UK to attempt to attain data for 2016-2020, or applying splicing techniques.

In addition, given the discrepancies observed in the sulphur content data from Fuels Industry UK and the Energy Institute for the years 2012 to 2017 and the possibility that Fuels Industry UK figures are reflecting a decreasing proportion of the UK fuel supply over time, it is recommended that the NAEI team:

- Make use of future Energy Institute publications and/or set up regular data supply agreements with the Energy Institute to provide an alternative source of data on ATF sulphur content; and
- Continue to monitor differences between Energy Institute and Fuels Industry UK ATF sulphur content data, and regularly review which source to use for the NAEI SO_2 EF.

8 Solid Fuels

8.1 Definition and Contribution to GHG Inventory

The 2017 Review provided definitions of fuels, which have been reused in this report and updated as necessary.

8.1.1 Coal

Coal is usually separated into various subcategories, such as lignite, sub-bituminous coal, bituminous coal and anthracite – with the carbon content and calorific value increasing from lignite through to anthracite. Coal in the UK is used in some larger industrial applications such as primary steel making and cement production, but also in the domestic sector to heat homes. The 2017 Review noted that:

Lignite is not extracted or known to be used to any significant extent in the UK and it is expected that coal for domestic and industrial customers would be bituminous or anthracitic. However, these are all very broad categories and the carbon contents of coals cover a very wide range. For example, one system[39] suggests the following figures for carbon content, on a dry, mineral matter-free basis, of bituminous coals alone:

- *Low volatile bituminous 78-86%*
- *Medium volatile bituminous 69-78%*
- *High volatile bituminous <69%*

*UK energy statistics provide separate figures for consumption of anthracite and for steam coal and DUKES explains that these are classifications used by UK coal producers and coal importers. DUKES also states that steam coal tends to "*have calorific values at the lower end of the range*", while anthracite "*has a high heat content*". However, DUKES does not provide any detailed definition of the two types of coal.*

8.1.2 Petroleum coke

Petroleum coke ("petcoke") is a solid by-product from a refinery process known as coking. Coking is an intense form of thermal cracking, which is used to convert residual oils into more valuable transport fuels, but the process also produces the solid residue which is sold as petroleum coke.

There are two grades of petcoke often distinguished: calcined petcoke is used in industrial processes and has a very high C content (>90%); and non-calcined petcoke which is burned as fuel and has a lower carbon content. According to engagement with the coal merchants federation (CMF) undertaken for the Ricardo 2017 Review, most non-calcined petcoke in the UK is used to make MSF, rather than burned pure.

In 2021, pet coke accounted for 1.3% of GHG emissions generated from combustion of fuels, and 1.0% of emissions in the UK overall.

[39] https://uk-air.defra.gov.uk/assets/documents/reports/cat07/1711280843_Carbon_Emission_Factors_Update_v01_04.pdf

8.1.3 Manufactured solid fuels (MSF)

In addition to coal and anthracite, the residential sector uses manufactured solid fuels (MSF), particularly in smoke control areas. The ban on domestic use of house coal from May 2023 is another driver for use of MSF. The Coal Merchant's Federation consider that manufactured solid fuels are the dominant fuels in the residential sector. They are commonly made out of a mixture of anthracite and bituminous coal fines, petcoke, sometimes biomass, and a binding material which may be organic. The ingredient proportions vary widely between products. The rough composition of approved fuels (quantities are only given in ranges) can be found on the Defra website[40].

Solid smokeless fuel (SSF) is the name given in the NAEI to MSF (which is the term used in DUKES).

Table 26. Solid fuel combustion contributions to UK NAEI emission in 2021

Fuel/ Source	GHG emissions from fuel combustion	GHG emissions of UK total
Coal	3.2%	2.4%
Anthracite	0.2%	0.1%
Petroleum Coke	1.3%	1.0%
Coke	0.3%	0.2%
Coke production	<0.001%	<0.001%
SSF	0.2%	0.1%
SSF production	<0.001%	<0.001%

8.2 Existing Inventory

8.2.1 Carbon content

There are currently ten different CEFs for coal, differentiated by the following sources (listed from lowest CEF to highest CEF in the 1990-2021 NAEI):

- Solid smokeless fuel production
- Autogeneration
- Agriculture - stationary combustion
- Collieries
- Domestic combustion
- Power stations
- Lime production
- Cement production
- Various other industrial combustion (iron and steel, chemicals etc.)
- Rail

Emissions from solid fuel use in large industrial installations such as power stations, cement production, lime production and steelworks are reported directly by

[40] For example, https://smokecontrol.defra.gov.uk/fuels.php?country=england

installations on a site-by-site basis under the Emissions Trading Scheme (ETS). These reported emissions are validated by the NAEI team, then included directly in the NAEI.

For solid fuel users not covered by ETS reporting (domestic users, and small industrial, agricultural or transport users), CEFs are applied, which have higher uncertainty than the ETS estimates.

For coal, the 2017 Ricardo Review demonstrated the very high positive correlation between carbon content and calorific value. For this reason, the CEFs in energy terms (i.e. ktC/TJ) have been kept constant for coal and anthracite over time, as any changes in carbon content per tonne of fuel over time (e.g. due to a different source location) would be matched by a similar proportional change in calorific value. However, the exact relationship between carbon content and calorific value may vary by the source of the coal, which is not taken into account in the current CEFs.

Table 27 presents the fuels/ sources where CEFs have had consistent carbon factors since 1990. **Appendix A** presents the CEFs for the other solid fuel types and source sectors where the CEF has varied over time (**Tables A.6** and **A.7**).

Table 27. Solid fuel carbon factors that are consistent across 1990-2021 NAEI timeseries

Fuel/ Source	2023 GHG Inventory (kt/TJ)
Coal - Agriculture	0.02462
Coal - Collieries	0.02489
Coal - Domestic Boiler	0.02509
Coal - Other Industrial	0.02564
Coal - Rail	0.02621
Anthracite	0.02691
Pet coke - Domestic	0.02622
Pet coke - Refineries	0.02738

8.2.2 Sulphur content

Table 28 presents the sulphur emission factors currently used in the inventory. Note that “industry” in this context excludes power stations and collieries. The sulphur content values used for most industrial and public sector coal types per unit mass are equal, but the SO_2 EF varies due to different net calorific values estimated for different sectors.

Table 28 Solid fuel SO_2 emission factors and apparent fuel sulphur content used in the NAEI

Measure	Fuel	Sector	1990	1995	2000	2005	2010	2015	2021
SO_2 EF used in NAEI (g/GJ)	Anthracite	Domestic	501	733	654	713	643	645	621
	Coal	Domestic	700	819	709	785	747	736	708
		Industry and public sector	1053	835	794	801	763	778	768
	Petcoke	Domestic	4186	4186	4181	4186	4186	4186	4186
	SSF	Domestic fireplace	500	500	500	500	500	500	500
		Domestic stove	900	900	900	900	900	900	900
Apparent S content of fuel (%)	Anthracite	Domestic	0.80	1.18	1.04	1.14	1.06	1.05	1.01
	Coal	Domestic	1.00	1.18	1.04	1.14	1.06	1.05	1.01
		Industry and public sector	1.37	1.15	1.10	1.11	1.05	1.06	1.04
	Petcoke	Domestic	7.11	7.11	7.11	7.11	7.11	7.11	7.11
	SSF	Domestic fireplace	0.72	0.72	0.73	0.77	0.77	0.78	0.78
		Domestic stove	1.29	1.29	1.32	1.39	1.39	1.40	1.40

8.3 Previous Inventory Improvements and Reviews

In the 2004 review, a timeseries (1990-2003) was obtained based on E.ON (formerly Powergen) operated sites but was considered representative of the UK as a whole. A working paper was obtained from Energy UK (formerly the Association of Electricity Producers) containing their recommended carbon content of fuel and oxidation factor. The two datasets were consolidated to form a new CEF, which took into account the increase in the UK's use of imported coals, as well as the proportion of un-oxidised carbon that remains in the ash after combustion.

During the Ricardo 2017 Review, the NAEI team engaged extensively with the Coal Merchants Federation (CMF). This engagement suggested that solid fuel producers and suppliers routinely sample fuel characteristics and could provide data on carbon content and calorific value to inform the NAEI. On the basis of this, the review recommended that data be collated from the producers and suppliers.

8.4 Methodology

The objective for solid fuels in this project was to obtain information on the carbon content, sulphur content and calorific value of solid fuels used in non-ETS sectors, in order to compare against the currently used NAEI carbon and sulphur emission factors.

Three different approaches were initially considered:

1. Engagement with solid fuel suppliers and UK producers to request data from routine sample testing;

2. Use of reported data from ETS installations where emissions and/or fuel characteristics are measured (so-called Tier 3 methods are used) to estimate the

CEF, which could be extrapolated (in certain circumstances) to the same fuel type used in non-ETS sectors.

3. Estimate the carbon content and calorific value of solid fuels imported into the UK based on their provenance. This would make use of HMRC data on the quantity of fuel imported to the UK from different destinations, combined with information on the CEF or carbon content and calorific values of the fuels from their source location, to estimate a weighted average of the CEF / carbon content and calorific value of total imports.

The third approach was in the end not pursued. This approach had been trialled and evaluated in the Ricardo 2017 review for coal, using information in the NIRs of the countries from which the UK imports coal as the basis for the CEF of each source of coal. However, the conclusion of this evaluation was that the uncertainty in the results of this calculation would be very high. This is due to the variability of coal produced in many of the countries from which coal was imported, and the weakness of the assumption that the CEF stated in a country's NIR for consumption in that country would be representative of the CEF for exports to the UK. Based on this evaluation, for this project it was deemed that following this approach would be a disproportionate amount of effort for the uncertain conclusion it would bring.

The main approach undertaken was stakeholder engagement. Aether contacted a range of industry stakeholders to determine whether they hold any data on carbon or sulphur content of solid fuels, and if so, whether this information was available to share. The stakeholders included the UK Coal Authority, CPL, the Defra Air Quality and Industrial Emissions team and M&G Solid Fuels, although M&G Solid Fuels were not able to respond. Aether also consulted with the DUKES solid fuel statistics team, to understand what data producers and suppliers share with them already.

ETS installations reporting emissions from solid fuels using a Tier 3 approach were identified, and the CEF and calorific value extracted (in an aggregated form).

8.5 Findings - Carbon

The stakeholder engagement process yielded only limited data on solid fuel carbon content.

The DUKES solid fuel statistics team confirmed that carbon content information is not shared with them as part of their routine data collection. Calorific values, however, are shared, and this information in DUKES is already used by the NAEI team when preparing the NAEI.

The Coal Authority likewise confirmed that it holds no data on the carbon content or calorific value of coal.

Discussions with CPL – one of the largest suppliers of solid fuels to the domestic market in the UK - indicated that they do not undertake testing of carbon content in the coal or MSF that they produce and supply, so are not able to provide any data. However, CPL did provide indicative ranges for their MSF products as follows:

- Carbon content: 75-80%
- Calorific value: 32-35 MJ/kg

CPL also commented that – apart from an increase in biomass-containing products – there have been no particular shifts in the types of MSF and other fuels consumed in the domestic sector, and that fuel choice is largely governed by the appliances consumers own.

The only directly measured data for the domestic sector obtained on carbon content were provided by Defra, based on data collected as part of the Emission Factors for Domestic Solid Fuels (EFDSF) testing programme[41]. The results of the testing are shown in **Table 29** below. CO_2 and SO_2 emission factors have been calculated for this report using the net calorific value, carbon and sulphur content information from Defra, to enable comparison with the NAEI factors.

Table 29. Results of domestic solid fuel analysis on selected typical fuel samples, undertaken by Defra to as part of the EFDSF testing programme. All parameters are reported on an "as received" basis – i.e. at the reported moisture and ash content.

Component	Units	MSF1	MSF2	Coal	Anthracite
NCV	MJ/kg	24.995	28.007	26.273	32.591
Moisture	% m/m	20.2	7	10.3	1.9
Ash	% m/m	3.8	4.6	1.3	3.6
Carbon	% m/m	63.9	73.4	68.1	88.1
Hydrogen	% m/m	3.13	3.93	4.71	3.62
Nitrogen	% m/m	1.05	1.16	1.11	1.03
Sulphur	% m/m	1.36	2.35	0.18	0.75
CO_2 as C EF	tonne/GJ	0.02557	0.02621	0.02592	0.02703
SO_2 EF	g/GJ	1,088	1,678	137	460

MSF1 is compliant with the Air Quality Domestic Solid Fuel Standards (England) Regulations (AQDSFS). MSF2 is a high sulphur fuel which is no longer sold in England as it is not compliant with AQDSFS (and is no longer available in UK).

The samples were analysed as part of the EFDSF test programme. Sample preparation and analysis was undertaken by a UKAS-accredited laboratory to ISO/EN Standards, but the samples represent small batches of fuels as used in the EFDSF test programme, not samples representative of current or historic annual UK average fuel usage.

8.5.1 ETS data

Table 30 below shows the aggregated data available on CEFs (both in energy terms and converted to mass terms) from ETS installations where emissions are measured, for relevant solid fuels.

[41] Defra, 2023, personal communication. Note that these data have not yet been published and have not been reviewed by Defra, the project steering group or the air quality inventory steering group.

Table 30. Extract of ETS data for solid fuels from installations using Tier 3 measurement approaches, aggregated by fuel type and sector.

Sector	Fuel	ktC/TJ			tC/tonne fuel*		
		Mean	Min	Max	Mean	Min	Max
Food & drink, tobacco (combustion)	Coal	0.0256	0.0254	0.0257	0.686	0.655	0.715
Lime production - non decarbonising	Coal	0.0261	0.0261	0.0261	0.638	0.638	0.638
Other industrial combustion	Coal	0.0257	0.0253	0.0266			
Lime production - non decarbonising	Anthracite	0.0262	0.0255	0.0268	0.789	0.777	0.804

*Included because if 100% carbon oxidation is assumed, this is equal to the carbon content of the fuel.

8.5.2 Biomass in MSF

From consultation with CPL and reviewing the ingredients lists of selected products on the Defra website[45], it is clear that some MSF products include biomass, e.g. Homefire "Ecoal" from CPL contains 5-20% biomass and 0-10% biomass char. CPL indicated that more biomass-containing MSF is now sold than previously. Moreover, many MSF products contain an organic binder, often molasses. CPL indicated that where molasses is used as a binder, it accounts for about 10% of cured (final) weight of the MSF. The composition of molasses varies, but according to one paper[42] is c. 37% carbon. If this information from CPL is typical, this would mean that c.3.7% of the final weight of molasses containing MSF is biogenic, even when no other biomass is specifically added.

The DUKES solid fuel statistics team stated that the data reported by MSF suppliers does not currently separate fossil and biomass content, so DUKES statistics on MSF consumption will include both of these elements. It is not clear from the UK NIR if this biomass content is accounted for currently in the UK inventory, or whether the CO_2 emissions from MSF are assumed currently to all be of fossil origin.

8.5.3 Comparison with the NAEI

No data was available for some of the solid fuels in scope to compare with the NAEI, namely petroleum coke and other coke.

Anthracite

The NAEI CEF for anthracite is 0.02691 ktC/TJ. This is less than 0.5% lower than the value obtained by Defra in the EFDSF testing programme of 0.02703. It is also only around 3% higher than the mean CEF from anthracite used in lime production from the ETS data, despite it not being clear how representative the anthracite used in lime production would be for anthracite used in the domestic sector. Therefore, these comparisons seem very consistent.

42 https://www.researchgate.net/publication/227056897_Comparative_studies_on_citric_acid_production_by_Aspergillus_niger_and_Candida_lipolytica_using_molasses_and_glucose

Coal

The NAEI CEF for coal varies between 0.02462 and 0.02621 ktC/TJ across sectors, based on the variation in types of coal used in those sectors. It is static across the time series. In the domestic sector the value is 0.02509 ktC/TJ, which is 3.2% lower than the value obtained by Defra in the EFDSF testing programme of 0.02592. It is also between 1.9% and 4% lower than the mean values from ETS data for various industries. As indicated for anthracite however, domestic coal may come from different sources than coal used in industry so have a different composition.

MSF

The NAEI CEF for MSF in 2021 was 0.02544 ktC/TJ across all sectors but varies across the time series according to calorific value, as the carbon emissions per mass are held constant at 790 ktC/Mt (~79% carbon content in the fuel). This is 0.5% and 2.9% lower than the values obtained by Defra for “MSF1” and “MSF2” in the EFDSF testing programme. The implied carbon content of MSF in the NAEI of 79% also aligns well with the 75-80% figure cited by CPL.

Additional information was not available on trends in carbon content over time for any of the fuels, to make comparisons with the NAEI over the time series.

8.6 Findings - Sulphur

Table 29 above includes the results of sulphur content analysis from the Defra EFDSF testing programme. No other data on sulphur content was yielded by stakeholder engagement, other than an indication from CPL that solid fuels sold in the home heating market have a sulphur content of 2% or less on a mass basis.

8.6.1 Comparison with the NAEI

Anthracite

The apparent sulphur content of anthracite based on the SO_2 EF in the NAEI varies over timeseries, between 0.8 and 1.2% by mass, and was 1.01% in 2021. This is slightly higher than the 0.75% sulphur by mass found in the Defra EFDSF testing programme, but not substantially so.

Coal

The apparent sulphur content of coal for domestic use based on the SO_2 EF in the NAEI varies over timeseries, between 1.0 and 1.2% by mass, and was 1.01% in 2021. This is considerably higher than the 0.18% sulphur by mass found in the Defra EFDSF testing programme.

No data was available to compare to the NAEI sulphur emission factor for industry and public sector uses.

MSF

The apparent sulphur content of MSF for domestic use based on the SO_2 EF in the NAEI is 0.72 – 0.78% across the timeseries for open fireplaces, and 1.29-1.40% for closed stoves and boilers. The value for stoves and boilers aligns well with the values obtained for “MSF1” in the Defra EFDSF testing programme of 1.36%. The value obtained for “MSF2” of 2.35% sulphur now applies to a high-sulphur MSF that is no longer legal for domestic use in England and no longer manufactured, so is not a relevant comparison.

However, as previously mentioned, the Defra EFDSF data does not provide a representative average value for the UK; they are individual sample results for typical fuels. Therefore, in these comparisons the Defra values should not be viewed as the "true" number, and discrepancies highlight the need for further work.

8.7 Recommendations and implications for the inventory

The proposed changes to the NAEI carbon emission factors and sulphur emission factors for solid fuels are summarised in **Table 31** Solid fuel carbon emission factors and sulphur emission factors proposed changes. Details of any additional recommendations are set out below.

Table 31 Solid fuel carbon emission factors and sulphur emission factors proposed changes

	Carbon (% mass or energy based-CEF)	Sulphur content (% mass or energy based CEF)
Current NAEI value (2021)	Ranging from 0.024 - 0.03 kt/TJ	Ranging from 500 – 4186 g/GJ
Recommended value (2021)	No change proposed.	No change proposed.
% difference recommended vs. current	No change.	No change.
Impact on 2021 emissions at national level (kt)	No change.	No change.
Impact as % of 2021 inventory total	No change.	No change.

8.7.1 Carbon

Based on the limited information available, in light of the inherent variability of solid fuels, the carbon content values currently used in the NAEI are relatively consistent with other data sources. Given the uncertainty associated with those other data sources, no change is recommended for the CEFs for solid fuels in the NAEI on the basis of this work.

However, it was also noted that the stakeholder engagement approach recommended by the Ricardo 2017 Review may not be a reliable source of data on carbon content, as that does not seem to be routinely measured by fuel suppliers. Therefore, it is recommended that consideration is given to a sampling campaign, to complement any data available from producers and suppliers to provide a representative overall picture of UK solid fuel consumption.

An additional recommendation that can be made on the basis of this work, is that the activity data used for MSF consumption should be reviewed, to ascertain whether biomass contained in MSF is currently being erroneously counted as fossil carbon in the NAEI. If that is the case, it is recommended that methods are considered to separate out the fossil and biogenic components of MSF when collecting activity data. Relevant data from MSF suppliers would include detailed data on sales by specific product, combined with accurate information on the composition of each product.

8.7.2 Sulphur

Although some discrepancy was found in sulphur content used in the NAEI compared with those found in the Defra EFDSF testing programme[41] for domestic coal, the uncertainty associated with the latter means that no firm recommendations can be made to alter SO_2 EFs in the NAEI.

Rather, it is recommended that additional stakeholder engagement and potentially fuel testing is considered to provide more robust estimates of typical UK fuel sulphur contents.

9 Summary of conclusions and recommendations

This section summarises the recommendations presented for each of the fuels for both carbon and sulphur emission factors. More detailed information is found in each of the individual fuel chapters (4-8).

Petrol

Carbon:

- For petrol it is recommended that a carbon content value of 86.17% be used for inventory year 2023 and the following years, until further data is available / studies are undertaken.
- Some limited additional sampling of winter petrol blends could be justified to improve evidence around seasonality.
- An over-arching recommendation for both petrol and diesel sampling in future would be to include NCV measurement as part of the lab analysis undertaken, to allow sample-by-sample estimation of the energy-based CEF, rather than linking to DUKES NCV data from a completely separate set of samples.

Sulphur:

- Based on the information gathered during this project, it has been determined that that the NAEI sulphur emission factors currently used in the inventory are still valid.

Diesel and Gas Oil

Carbon:

- For the fossil fraction of DERV, it is recommended that a carbon content value of 85.54% be used for inventory year 2023 and the following years, until further data is available / studies are undertaken.
- Some limited additional sampling of winter DERV blends could be justified to improve evidence around seasonality.
- For gas oil, based on the limited information found, it has been determined that the carbon emission factors used in the NAEI are still valid.
- However, given the lack of publicly available information regarding the carbon factors for gas oil a sampling campaign for gas oil could be undertaken. This was originally considered for this project, the compressed timescale for the project did not allow a representative set of samples to be collected.

Sulphur:

- Based on the information collected in this project, it has been determined that sulphur emission factors for DERV and gas oil currently used in the inventory are still valid.
- For gas oil, for the 2022 and future inventories it is recommended that the NAEI team review the definition of sub-types of gas oil used by Fuel Industry UK and how those align with the types allocated to different source categories in the NAEI.

LPG

Carbon:

- It is recommended that for the latter part of the time series (at least), the NAEI makes use of the carbon emission factors for propane and butane presented in the 2019 review, as they clearly differ from the currently used values in the NAEI.
- It is not clear whether these values can be extrapolated back across the time series however, so further discussions are needed with the NAEI team on that aspect.
- In addition, it is recommended that the NAEI moves away from assuming a fixed ratio of propane and butane in energy use, and instead makes use of available data on propane and butane consumption for energy uses to calculate a weighted average varying by year. Alternatively, the inventory could move to representing emissions for propane and butane separately as two different fuels with differing CEFs, rather than combining these into a single LPG fuel type.
- Finally, it is recommended that in future NAEI improvement work, targeted engagement is undertaken with the DUKES statistics team, LPG suppliers and any other relevant stakeholders (such as HMRC), to better determine the fractions of bio-LPG and fossil LPG consumed.

Sulphur:

- There was insufficient data available on sulphur content of LPG to make recommendations regarding the NAEI sulphur emission factors.

Aviation Turbine Fuel

Carbon:

- Not enough information was found to make a firm recommendation regarding the CEF of ATF used in the NAEI.

Sulphur:

- It is recommended that revisions are made to the historical timeseries between 2016 and 2020 (at least) to improve time series consistency, for example by engaging further with Fuels Industry UK to attempt to attain data for 2016-2020, or applying splicing techniques.

- In addition, given the discrepancies observed in the sulphur content data from Fuels Industry UK and the Energy Institute for the years 2012 to 2017 and the possibility that Fuels Industry UK figures are reflecting a decreasing proportion of the UK fuel supply over time, it is recommended that the NAEI team:
    - Make use of future Energy Institute publications and/or set up regular data supply agreements with the Energy Institute to provide an alternative source of data on ATF sulphur content; and
    - Continue to monitor differences between Energy Institute and Fuels Industry UK ATF sulphur content data, and regularly review which source to use for the NAEI SO_2 EF.

Solid Fuels

Carbon:

- There was little substantial data found for solid fuels, from which to make clear recommendations. For the comparisons that were possible, given the inherent variability of solid fuels, the NAEI values were relatively consistent with other data sources. Given the uncertainty associated with those other data sources representativeness of the UK as a whole, no change is recommended for the CEFs for solid fuels in the NAEI on the basis of this work.
- However, it was also noted that the stakeholder engagement approach recommended in the Ricardo 2017 Review Report may not yield data on carbon content, as that does not seem to be routinely measured by fuel suppliers. Data provision was also hampered by a lack of response from some stakeholders. Therefore, it is recommended that consideration is given to a sampling campaign to complement data available from producers and suppliers.
- The strongest recommendation that can be made on the basis of this work, is that the activity data used for MSF consumption needs to be reviewed, to ascertain whether biomass contained in MSF is currently being erroneously counted as fossil carbon in the NAEI. If that is the case, it is recommended that methods are considered to separate out the fossil and biogenic components of MSF.

Sulphur:

- Although some discrepancy was found in sulphur content used in the NAEI compared with those found in the Defra EFDSF testing programme for coal and MSF, the uncertainty associated with the latter means that no firm recommendations can be made to alter SO_2 EFs in the NAEI.
- Rather, it is recommended that additional stakeholder engagement and potentially fuel testing is considered to provide more robust estimates of typical UK fuel sulphur contents.

Cross-cutting recommendation on data supply by industry

It is clear that there is a general lack of recent, easily accessible data on the carbon content of liquid and solid fuels available from industry stakeholders. Dedicated sampling campaigns (such as those undertaken for petrol and DERV in this project) are costly and need to be regularly repeated, so it is worth considering further whether opportunities currently exist – or could potentially exist in future – to harness fuel composition data already collected by stakeholders.

As mentioned for several fuels in the sections above, carbon content *per se* is not specifically tested for by fuel producers, blenders or suppliers, because it does not form part of fuel specifications. Nevertheless, it is possible that in some cases, carbon content of fuels could be calculated or measured with relatively little additional effort by those currently conducting analyses which are necessary to demonstrate conformance with specifications, or to provide input into fuel safety data sheets, for example. To determine carbon content of petrol sampled in this study, a compositional analysis technique was used which measures the distribution of different hydrocarbons in the fuel, then converted to carbon content based on knowledge of their molecular formulae. If similar compositional analysis is done in order to assess, for example, total polyaromatic hydrocarbon content, then the results could also be harnessed to report carbon content. Concerning data on blended fuels, assessment of biofuel content of blended fuels is commonplace, so in tandem with total carbon content data this could underpin similar calculations to those undertaken on forecourt-sampled petrol and DERV in this study.

In this study, conversations with stakeholders did not provide a clear indication on whether suitable data as described above is regularly and widely collected.

Therefore a final recommendation is for DESNZ and the NAEI to engage in further dialogue with fuel suppliers to understand:

- which laboratory analytical techniques are commonly applied to fuel samples and at which stage in the fuel supply chain;
- whether any of the laboratory analytical techniques applied could – in principle – yield estimates of fuel carbon content;
- if no techniques currently applied can yield carbon content information, what the additional costs would be to the stakeholders of changing the analytical techniques and/or specifically testing for carbon content.

If the outcome of such further dialogue is promising, this could lead to much more efficient and frequent updates to carbon emission factors in future.

Appendix A 1990-2021 NAEI CEF Timeseries

Table A.1: 1990-2021 NAEI Petrol CEF and change over time

Year	2023 GHG Inventory CEF	
	g C as CO_2/kg fuel	kt/TJ
1990	855	0.01914
1991	855	0.01913
1992	855	0.01913
1993	855	0.01913
1994	855	0.01913
1995	855	0.01913
1996	855	0.01915
1997	855	0.01915
1998	855	0.01915
1999	855	0.01911
2000	855	0.01915
2001	855	0.01911
2002	855	0.01911
2003	855	0.01911
2004	855	0.01911
2005	855	0.01913
2006	855	0.01912
2007	855	0.01911
2008	855	0.01911
2009	855	0.01911
2010	855	0.01911
2011	855	0.01911
2012	855	0.01909
2013	855	0.01909
2014	855	0.01909
2015	855	0.01909
2016	855	0.01909
2017	855	0.01911
2018	855	0.01913
2019	855	0.01915
2020	855	0.01915
2021	855	0.01916

Table A.2: 1990-2021 NAEI DERV CEF and change over time

Year	2023 GHG Inventory CEF	
	g C as CO_2/kg fuel	kt/TJ
1990	864	0.02005
1991	864	0.02016
1992	864	0.02016
1993	864	0.02016
1994	864	0.02016
1995	864	0.02016
1996	864	0.02016
1997	864	0.02016
1998	864	0.02011
1999	863	0.02005
2000	863	0.01993
2001	863	0.01993
2002	863	0.01993
2003	863	0.01993
2004	863	0.01993
2005	863	0.02006
2006	863	0.02007
2007	863	0.02012
2008	863	0.02012
2009	863	0.02010
2010	863	0.02011
2011	863	0.02010
2012	863	0.02010
2013	863	0.02011
2014	863	0.02011
2015	863	0.02010
2016	863	0.02010
2017	863	0.02010
2018	863	0.02010
2019	863	0.02014
2020	863	0.02013
2021	863	0.02005

Table A.3: 1990-2021 NAEI Gas Oil CEF and change over time

Year	1990-2021 NAEI CEF: Gas oil – oil and gas		1990-2021 NAEI CEF: Gas oil – shipping and marine vessels		1990-2021 NAEI CEF: Gas oil – all other sources	
	g C as CO_2/kg fuel	kt/TJ	g C as CO_2/kg fuel	kt/TJ	g C as CO_2/kg fuel	kt/TJ
1990	872.7	0.02043	874.4	0.02047	869.0	0.02034
1991	872.7	0.02045	874.4	0.02049	869.0	0.02036
1992	872.7	0.02045	874.4	0.02049	869.0	0.02036
1993	872.7	0.02045	874.4	0.02049	869.0	0.02036
1994	872.7	0.02045	874.4	0.02049	869.0	0.02036
1995	872.7	0.02045	874.4	0.02049	869.0	0.02036
1996	872.7	0.02045	874.4	0.02049	869.0	0.02036
1997	872.7	0.02045	874.4	0.02049	870.0	0.02039
1998	872.7	0.02041	874.4	0.02044	870.0	0.02034
1999	872.7	0.02036	874.4	0.02040	870.0	0.02030
2000	872.7	0.02036	874.4	0.02040	870.0	0.02030
2001	872.7	0.02036	874.4	0.02040	870.0	0.02030
2002	872.7	0.02036	874.4	0.02040	870.0	0.02030
2003	874.1	0.02039	874.4	0.02040	870.0	0.02030
2004	873.9	0.02039	874.4	0.02040	870.0	0.02029
2005	871.5	0.02044	874.4	0.02051	870.0	0.02041
2006	875.1	0.02054	874.4	0.02052	870.0	0.02042
2007	872.1	0.02050	874.4	0.02056	870.0	0.02045
2008	871.0	0.02046	874.4	0.02054	870.0	0.02044
2009	871.6	0.02048	874.4	0.02054	870.0	0.02044
2010	871.3	0.02047	874.4	0.02054	870.0	0.02044
2011	871.5	0.02047	874.4	0.02054	870.0	0.02044
2012	870.8	0.02046	874.4	0.02054	870.0	0.02044
2013	865.9	0.02034	874.4	0.02054	870.0	0.02044
2014	869.6	0.02043	874.4	0.02054	870.0	0.02044
2015	869.6	0.02043	874.4	0.02054	870.0	0.02044
2016	869.9	0.02044	874.4	0.02054	870.0	0.02044
2017	870.0	0.02044	874.4	0.02054	870.0	0.02044
2018	870.0	0.02044	874.4	0.02054	870.0	0.02044
2019	870.0	0.02044	874.4	0.02054	870.0	0.02044
2020	870.0	0.02044	874.4	0.02054	870.0	0.02044
2021	870.0	0.02044	874.4	0.02054	870.0	0.02044

Table A.4: 1990-2021 NAEI LPG CEF and change over time

Year	1990-2021 NAEI CEF (kt/TJ)
1990	0.01738
1991	0.01738
1992	0.01738
1993	0.01738
1994	0.01738
1995	0.01738
1996	0.01738
1997	0.01738
1998	0.01739
1999	0.01738
2000	0.01733
2001	0.01744
2002	0.01745
2003	0.01742
2004	0.01747
2005	0.01744
2006	0.01743
2007	0.01743
2008	0.01742
2009	0.01738
2010	0.01739
2011	0.01739
2012	0.01742
2013	0.01742
2014	0.01742
2015	0.01742
2016	0.01742
2017	0.01742
2018	0.01742
2019	0.01742
2020	0.01742
2021	0.01742

Table A.5: 1990-2021 NAEI aviation turbine fuel CEF and change over time

Year	1990-2021 NAEI CEF	
	g C as CO_2/kg fuel	kt/TJ
1990	859	0.01957
1991	859	0.01957
1992	859	0.01957
1993	859	0.01957
1994	859	0.01957
1995	859	0.01957
1996	859	0.01957
1997	859	0.01957
1998	859	0.01957
1999	859	0.01957
2000	859	0.01957
2001	859	0.01957
2002	859	0.01957
2003	859	0.01957
2004	859	0.01955
2005	859	0.01956
2006	859	0.01957
2007	859	0.01958
2008	859	0.01958
2009	859	0.01957
2010	859	0.01958
2011	859	0.01956
2012	859	0.01956
2013	859	0.01955
2014	859	0.01954
2015	859	0.01955
2016	859	0.01956
2017	859	0.01956
2018	859	0.01957
2019	859	0.01957
2020	859	0.01956
2021	859	0.01956

Table A.6: 1990-2021 NAEI coal and coal products (excluding petcoke) CEF and change over time

Year	SSF production		SSF		Autogenerators		Power Stations		Lime production		Cement Production		Coke	
	g C as CO2/kg fuel	kt/TJ	g C as CO2/kg fuel	kt/TJ	g C as CO2/kg fuel	kt/TJ	g C as CO2/kg fuel	kt/TJ	g C as CO2/kg fuel	kt/TJ	g C as CO2/kg fuel	kt/TJ	g C as CO2/kg fuel	kt/TJ
1990	276.2	0.009972	790.0	0.02754	595.0	0.02480	605.1	0.02487	677.0	0.02527	709.1	0.02759	827.1	0.02776
1991	228.5	0.008180	790.0	0.02754	595.0	0.02480	611.9	0.02515	677.0	0.02527	709.1	0.02759	828.4	0.02780
1992	224.0	0.007992	790.0	0.02754	595.0	0.02480	609.2	0.02504	677.0	0.02527	709.1	0.02759	831.3	0.02790
1993	196.0	0.006995	790.0	0.02754	595.0	0.02480	609.2	0.02504	663.8	0.02527	709.1	0.02759	823.3	0.02763
1994	172.6	0.006178	790.0	0.02754	595.0	0.02480	607.7	0.02498	663.8	0.02527	709.1	0.02759	825.6	0.02771
1995	192.7	0.006783	790.0	0.02754	595.0	0.02480	598.6	0.02461	650.6	0.02527	709.1	0.02759	827.3	0.02776
1996	147.2	0.005164	790.0	0.02754	595.0	0.02480	610.6	0.02510	658.2	0.02527	709.1	0.02759	821.6	0.02757
1997	189.7	0.006569	790.0	0.02733	595.0	0.02480	618.8	0.02543	649.2	0.02527	709.1	0.02759	829.9	0.02785
1998	106.3	0.003670	790.0	0.02709	595.0	0.02480	624.9	0.02569	639.3	0.02527	709.1	0.02759	834.8	0.02801
1999	79.72	0.002788	790.0	0.02690	595.0	0.02480	620.8	0.02552	641.1	0.02527	709.1	0.02759	859.4	0.02884
2000	72.01	0.002502	790.0	0.02697	595.0	0.02480	619.0	0.02544	648.2	0.02527	709.1	0.02759	843.3	0.02830
2001	90.28	0.003139	790.0	0.02717	595.0	0.02480	626.8	0.02576	648.2	0.02527	709.1	0.02759	817.2	0.02742
2002	86.48	0.002983	790.0	0.02694	595.0	0.02480	631.3	0.02595	648.2	0.02527	709.1	0.02759	800.8	0.02687
2003	82.10	0.002785	790.0	0.02672	595.0	0.02480	627.2	0.02578	669.7	0.02527	663.1	0.02580	781.4	0.02622
2004	95.47	0.003300	790.0	0.02619	595.0	0.02480	627.2	0.02578	669.7	0.02527	662.5	0.02578	798.7	0.02680
2005	100.0	0.003561	790.0	0.02557	594.3	0.02480	615.3	0.02527	663.3	0.02527	672.9	0.02618	806.5	0.02706
2006	119.6	0.004267	790.0	0.02556	596.3	0.02492	615.0	0.02529	663.6	0.02527	660.2	0.02568	807.1	0.02708
2007	186.9	0.006683	790.0	0.02555	594.5	0.02467	614.7	0.02528	663.6	0.02527	647.1	0.02518	836.8	0.02808
2008	207.5	0.007157	790.0	0.02553	581.3	0.02412	612.4	0.02508	701.4	0.02671	664.0	0.02583	834.0	0.02799
2009	182.1	0.006652	790.0	0.02552	600.6	0.02451	607.4	0.02506	698.9	0.02661	659.5	0.02570	829.0	0.02782
2010	158.7	0.005526	790.0	0.02550	599.9	0.02449	609.2	0.02506	634.4	0.02416	637.5	0.02492	822.8	0.02761

Year	SSF production		SSF		Autogenerators		Power Stations		Lime production		Cement Production		Coke	
	g C as CO2/kg fuel	kt/TJ	g C as CO2/ kg fuel	kt/TJ	g C as CO2/k g fuel	kt/TJ	g C as CO2/k g fuel	kt/TJ	g C as CO2/kg fuel	kt/TJ	g C as CO2/kg fuel	kt/TJ	g C as CO2/kg fuel	kt/TJ
2011	215.4	0.007980	790.0	0.02551	594.9	0.02458	609.2	0.02507	703.9	0.02680	646.6	0.02536	805.7	0.02704
2012	124.2	0.004599	790.0	0.02549	598.3	0.02446	612.0	0.02511	725.6	0.02757	660.6	0.02567	814.7	0.02734
2013	165.2	0.006111	790.0	0.02546	598.3	0.02379	612.7	0.02509	689.1	0.02612	694.5	0.02584	837.2	0.02810
2014	266.0	0.009824	790.0	0.02546	598.3	0.02436	612.3	0.02508	680.2	0.02567	673.2	0.02572	849.8	0.02852
2015	300.4	0.011107	790.0	0.02544	598.3	0.02458	608.6	0.02514	693.1	0.02615	672.2	0.02576	818.4	0.02746
2016	275.4	0.010223	790.0	0.02544	598.3	0.02458	615.6	0.02547	688.8	0.02599	683.6	0.02561	815.3	0.02736
2017	323.6	0.012009	790.0	0.02544	598.3	0.02458	613.9	0.02540	677.1	0.02584	684.0	0.02572	827.7	0.02778
2018	307.2	0.011400	790.0	0.02544	598.3	0.02458	602.7	0.02510	683.7	0.02609	663.5	0.02554	850.8	0.02855
2019	186.0	0.006905	790.0	0.02544	598.3	0.02458	610.7	0.02538	655.3	0.02501	663.8	0.02541	845.0	0.02836
2020	205.4	0.007625	790.0	0.02544	598.3	0.02458	615.6	0.02547	684.3	0.02612	664.1	0.02552	864.9	0.02902
2021	228.4	0.008477	790.0	0.02544	598.3	0.02458	596.6	0.02517	665.4	0.02540	656.9	0.02544	854.5	0.02868

Table A.7: 1990-2021 NAEI petcoke CEF and change over time

Year	SSF production		Cement		Power Stations		Other industrial	
	g C as CO2/kg fuel	kt/TJ	g C as CO2/kg fuel	kt/TJ	g C as CO2/kg fuel	kt/TJ	g C as CO2/kg fuel	kt/TJ
1990	276.2	0.008131	813.0	0.02627	846.0	0.02840	816.2	0.02402
1991	228.5	0.006725	813.0	0.02627	846.0	0.02840	816.2	0.02402
1992	224.0	0.006593	813.0	0.02627	846.0	0.02840	816.2	0.02402
1993	196.0	0.005770	813.0	0.02627	846.0	0.02840	816.2	0.02402
1994	172.6	0.005080	813.0	0.02627	846.0	0.02840	816.2	0.02402
1995	192.7	0.005671	813.0	0.02627	846.0	0.02840	816.2	0.02402
1996	147.2	0.004333	813.0	0.02627	846.0	0.02840	816.2	0.02402
1997	189.7	0.005584	813.0	0.02627	846.0	0.02840	816.2	0.02402
1998	106.3	0.003130	813.0	0.02627	846.0	0.02840	816.2	0.02402
1999	79.7	0.002347	813.0	0.02627	846.0	0.02840	816.2	0.02402
2000	72.0	0.002117	813.0	0.02627	846.0	0.02840	816.2	0.02400
2001	90.3	0.002655	813.0	0.02627	846.0	0.02840	816.2	0.02400
2002	86.5	0.002543	813.0	0.02627	846.0	0.02840	816.2	0.02400
2003	82.1	0.002414	813.0	0.02627	846.0	0.02840	816.2	0.02400
2004	95.5	0.002810	813.0	0.02627	846.0	0.02840	816.2	0.02402
2005	100.0	0.002943	813.0	0.02627	846.0	0.02840	816.2	0.02402
2006	119.6	0.003521	813.0	0.02627	861.6	0.02882	816.2	0.02402
2007	186.9	0.005502	811.3	0.02621	853.0	0.02806	816.2	0.02402
2008	207.5	0.006108	819.1	0.02647	855.6	0.02870	793.2	0.02335
2009	182.1	0.005360	807.3	0.02569	862.6	0.02927	818.2	0.02409
2010	158.7	0.004670	790.5	0.02564	866.9	0.02954	834.9	0.02458
2011	215.4	0.006341	785.4	0.02549	866.9	0.03008	825.7	0.02431
2012	124.2	0.003655	771.2	0.02555	866.9	0.02930	808.8	0.02381

Year	SSF production		Cement		Power Stations		Other industrial	
	g C as CO2/kg fuel	kt/TJ	g C as CO2/kg fuel	kt/TJ	g C as CO2/kg fuel	kt/TJ	g C as CO2/kg fuel	kt/TJ
2013	165.2	0.004864	810.4	0.02573	866.9	0.03032	809.5	0.02383
2014	266.0	0.007829	793.4	0.02562	866.9	0.03032	847.1	0.02493
2015	300.4	0.008841	824.6	0.02545	867.0	0.03033	848.5	0.02498
2016	275.4	0.008107	822.8	0.02535	867.0	0.03033	869.6	0.02560
2017	323.6	0.009524	823.1	0.02535	867.0	0.03033	855.4	0.02518
2018	307.2	0.009041	798.1	0.02553	867.0	0.03033	836.7	0.02463
2019	186.0	0.005476	782.0	0.02475	867.0	0.03033	825.0	0.02428
2020	205.4	0.006048	770.5	0.02474	867.0	0.03033	838.5	0.02468
2021	228.4	0.006723	747.9	0.02396	867.0	0.03033	841.6	0.02477

Appendix B Fuel CEF used in International Inventories

A literature review was conducted to determine the carbon content of fuels used in international emissions inventories, for comparison against those currently used in the NAEI. A selection of inventory reports from northwest Europe (climatically similar to the UK) were searched for relevant information. The only two inventory reports studied which presented emission factors in a comparable manner to the NAEI, separating the fossil and biogenic portion of the fuel, were from Germany and the Netherlands.

B.1 Germany

The study, *CO_2 Emission Factors for Fossil Fuels*[18], provides data on the carbon content of various grades of gasoline used in Germany's GHG inventory. Table 6 from that report (p. 33) presents CEFs for the fossil portion of the fuel mixtures only, which are comparable to the definition of factors as used in the NAEI. These are based on three different studies from 1994, 2002 and 2022 (based on 2020 data). For the 1994 and 2002 studies gasoline was entirely fossil and taken from refineries, whereas in the 2022 study samples were taken from filling stations (in 2020), and the CEF for the fossil portion was calculated after determination of the biogenic compounds in the fuel (similar to the approach taken in this study). It is not clear whether the samples from filling stations were taken in summer, winter, or over the course of the year. The range of CEFs are summarised in **Table B.1**.

Table B.1 Data from three German studies on the carbon emission factors of the fossil fraction of gasoline. Adapted from the results presented in table 6 of "CO_2 Emission Factors for Fossil Fuels"[43] by converting from CO_2 emission factors to % carbon to compare with the results in this report.

Study	% Carbon in fossil portion of gasoline (m/m)	
	Super (mid-grade/plus)*	Super Plus (premium)**
PetroLab, 2022	86.48	85.55
DGMK, 2002	86.86	85.66
DGMK, 1994	86.95	86.07

*Equivalent to the "Regular" grade of petrol using the terminology of this report

*** Equivalent to the "Premium" grade of petrol using the terminology of this report*

Table 23 of the German report provides a weighted-average emissions factor for 2020 of 3.169 t CO_2 / t based on sales volumes of the two grades of gasoline, which converted to a carbon percentage is 86.43%.

B.2 The Netherlands

The Dutch NIR annexes [17] provides a timeseries of emission factors used for the fossil portions of petrol and diesel. The **table B.2** below is adapted from Geilenkirchen et al. (2023) Methods for calculating the emissions of transport in NL_tables_def.xlsx, table 2.7.

Table B.2 Timeseries of emission factors used for the fossil portions of petrol and diesel in the Dutch inventory[17]

Year	Fossil petrol		Fossil diesel	
	gCO2/kg fuel	gC/kg fuel	gCO2/kg fuel	gC/kg fuel
1990	3174	865.658	3169	864.3
2000	3168	864.076	3168	863.959
2005	3168	864.076	3168	863.959
2010	3142	856.778	3154	860.073
2015	3139	856.164	3131	854.016
2020	3128	853.138	3129	853.25
2021	3128	853.079	3131	853.976

The study, *Dutch market fuel consumption for GHG emissions*[43], outlines the typical carbon content of market fuels consumed in the Netherlands and reported in its GHG inventory. The ranges for various fuels are summarised in **Table B.3 and B.4**

Table B.3 Netherlands JRC/Concawe typical values for market fuels

Fuel	Year	Density	LHV	Carbon	CO_2 emissions		
		kg/m³	MJ/kg	%m	kg/kg	g/MJ	g/l
Gasoline	2002	750	42.9	87.0	3.19	74.35	2393
	2010	745	43.2	86.5	3.17	73.38	2362
Ethanol		794	26.8	52.2	1.91	71.38	1517
Diesel	2002	835	43.0	86.2	3.16	73.54	2639
	2010	832	43.1	86.1	3.16	73.25	2629

Table B.4 Netherlands NIR Fuel List (Jan 2023)

Fuel	Unit	Net Calorific Value (MJ/kg)				CO_2 EF (kg/GJ)			
		2021	2022	2023	Ref	2021	2022	2023	Ref
Gasoline	kg	43.3	43.3	43.3	CS	72.2	72.2	72.2	CS
Jet Kerosene	kg	43.5	43.5	43.5	CS	71.5	71.5	71.5	IPCC
Other kerosene	kg	43.1	43.1	43.1	CS	71.9	71.9	71.9	IPCC
Gas/Diesel oil	kg	43.2	43.2	43.2	CS	72.5	72.5	72.5	CS
LPG	kg	45.2	45.2	45.2	CS	66.7	66.7	66.7	CS

Source: Annex 5, Netherlands NIR 2023

[43] Ligterink, N.E, 2016: https://www.umweltbundesamt.de/en/publikationen/co2-emission-factors-for-fossil-fuels-0

Appendix C EU-ETS data

The database of reported site-level ETS emissions in 2022 was filtered to extract data for Tier 3 (measured) emission factors of the year 2022. Emission factors related to the following range of fuels: anthracite, coal, fuel oil (heavy/medium/low), and petroleum coke. The mass-based emission factor (EF) was calculated based on the original EF and net calorific value (NCV) to convert to the unit of 'tCO2/tonne' for standardisation. These data were then aggregated at the level of source sector (Source Name) and fuel type.

Table C.1 Summary of mass-based emission factors, aggregated from 2022 ETS data

Source Name	Fuel type	Average of EF	Min of EF	Max of EF	EF_Units
Food & drink, tobacco (combustion)	Coal	2.515079334	2.400079151	2.621790719	tCO2/tonne
Lime production - non decarbonising	Anthracite	2.893564334	2.847357953	2.947669573	tCO2/tonne
Lime production - non decarbonising	Coal	2.337675479	2.337675479	2.337675479	tCO2/tonne
Other industrial combustion	Light Heating Oil	3.139349542	3.139349542	3.139349542	tCO2/tonne
Other industrial combustion	Coal	2.152214043	0	2.810862105	tCO2/tonne
Other industrial combustion	Fuel Oil	0	0	0	tCO2/tonne
Other industrial combustion	Propane	1.565850919	0.138722071	2.992979767	tCO2/tonne
Other industrial combustion	Petroleum Coke	0.510243146	0	2.92261004	tCO2/tonne
Power stations	Coal	0.592680377	0	2.254034579	tCO2/tonne
Power stations	Fuel Oil	0.12651592	0.12651592	0.12651592	tCO2/tonne
Power stations	Heavy Fuel Oil	2.181960835	0.131004747	3.217988348	tCO2/tonne
Power stations	Medium Fuel Oil	3.190613387	3.190613387	3.190613387	tCO2/tonne
Power stations	Gas/Diesel Oil	3.194418438	3.194418438	3.194418438	tCO2/tonne
Power stations	Petroleum Coke	0	0	0	tCO2/tonne
Refineries - combustion	Fuel Oil	0.131787975	0.131491146	0.132376003	tCO2/tonne

Table C.2 Summary on net calorific value (NCV), aggregated from 2022 ETS data

Source Name	Fuel type	Average of NCV	Min of NCV	Max of NCV	NCV_Units
Food & drink, tobacco (combustion)	Coal	26.81132152	25.52278323	28.17436	GJ/Tonne
Gas terminal: fuel combustion	LP Fuel Gas	47.24105487	47.24105487	47.24105487	GJ/Tonne
Lime production - non decarbonising	Anthracite	30.17136269	29.80103253	30.49749437	GJ/Tonne
Lime production - non decarbonising	Coal	24.38120086	24.38120086	24.38120086	GJ/Tonne
Other industrial combustion	Light Heating Oil	42.973	42.973	42.973	GJ/Tonne
Other industrial combustion	Coal	22.81094589	0	30.25214958	GJ/Tonne
Other industrial combustion	Fuel Oil	0	0	0	GJ/Tonne
Other industrial combustion	Propane	46.34343652	46.338	46.34887304	GJ/Tonne
Other industrial combustion	Petroleum Coke	5.654524952	0	31.25736491	GJ/Tonne
Power stations	Coal	18.49317696	0	24.84292756	GJ/Tonne
Power stations	Fuel Oil	40	40	40	GJ/Tonne
Power stations	Heavy Fuel Oil	40.66618741	40.60720654	40.719	GJ/Tonne
Power stations	Medium Fuel Oil	40.387	40.387	40.387	GJ/Tonne
Power stations	Gas/Diesel Oil	42.453	42.453	42.453	GJ/Tonne
Power stations	Petroleum Coke	0	0	0	GJ/Tonne
Refineries - combustion	Fuel Oil	41.42815857	41.3	41.4931231	GJ/Tonne

Table C.3 Summary of the original energy-based emission factors, aggregated from 2022 ETS data

Source Name	Fuel type	Average of EF	Min of EF	Max of EF	EF_Units
Food & drink, tobacco (combustion)	Coal	93.81911981	93.05591038	94.09191794	tCO2/TJ
Gas terminal: fuel combustion	LP Fuel Gas	56.57966272	56.57966272	56.57966272	tCO2/TJ
Lime production - non decarbonising	Anthracite	95.92425322	93.36366845	98.30098012	tCO2/TJ
Lime production - non decarbonising	Coal	95.88024364	95.88024364	95.88024364	tCO2/TJ
Other industrial combustion	Light Heating Oil	73.054	73.054	73.054	tCO2/TJ
Other industrial combustion	Coal	94.38687857	92.91445878	97.42191013	tCO2/TJ
Other industrial combustion	Coal	0	0	0	tCO2/Tonne
Other industrial combustion	Fuel Oil	0	0	0	tCO2/TJ
Other industrial combustion	Propane	64.57502784	64.57502784	64.57502784	tCO2/TJ
Other industrial combustion	Propane	2.9937	2.9937	2.9937	tCO2/Tonne
Other industrial combustion	Petroleum Coke	16.40357007	0	93.50148512	tCO2/TJ
Power stations	Coal	46.34768856	0	92.69537712	tCO2/TJ
Power stations	Coal	2.34990754	2.33711258	2.3627025	tCO2/Tonne
Power stations	Fuel Oil	3.162898	3.162898	3.162898	tCO2/Tonne
Power stations	Heavy Fuel Oil	78.81539632	78.511	79.11979264	tCO2/TJ
Power stations	Heavy Fuel Oil	3.22614526	3.22614526	3.22614526	tCO2/Tonne
Power stations	Medium Fuel Oil	79.001	79.001	79.001	tCO2/TJ
Power stations	Gas/Diesel Oil	75.246	75.246	75.246	tCO2/TJ
Power stations	Petroleum Coke	0	0	0	tCO2/TJ
Refineries - combustion	Fuel Oil	3.2052301	3.2052301	3.2052301	tCO2/TJ

Appendix D Detailed sampling and lab analysis methodology

Sampling strategy

The 2017 Review recommended that samples of the different components of petrol and diesel be taken from refineries, importers, wholesalers or other terminals, prior to blending. If there are differences in the carbon content of fuel produced by these different actors, in order to generate a representative UK average carbon content, statistically it would be most straightforward to approach these actors directly to request fuel samples, and then combine this with data on sales volumes to generate a weighted-average. The decision to sample from forecourts in this project rather than upstream actors was taken for several reasons:

- The difficulty of obtaining sensitive information from refineries, importers and wholesalers directly;
- The importance of understanding the composition of fuel at the point of sale; and
- Practical issues with obtaining samples from upstream suppliers, requiring considerable administrative effort with the risk of a failure to obtain samples. Forecourt sampling gave a greater degree of certainty and speed of sample collection given the short timescales of the project.

Ideally, the sampling campaign would have encompassed both summer and winter blends of petrol and diesel in case there are significant differences in carbon content between them. However, the time constraints of this project and limit on number of samples (50 samples maximum each of petrol and diesel) did not allow for sampling across the course of the year, so only summer blends were sampled. Seasonal variation was instead investigated through literature review and stakeholder engagement.

When conducting forecourt sampling, ensuring that the sampling campaign produces a representative UK average for defining new NAEI carbon emission factors is not feasible without access to detailed data on fuel sales volumes for the fuel batch applicable to each sample, year-round sampling and a larger number of samples. These conditions could not be met. Rather, given the limits to data availability and sample numbers, the aim of the sampling campaign was to obtain samples encompassing different potential sources of variation in carbon content. From this set of samples, the degree of variation due to different factors can be assessed, and an indicative average calculated for comparison against the current NAEI emission factors. Whilst the uncertainty of the specific indicative average value calculated from the samples will be high, it will nonetheless be sufficient to indicate whether the current NAEI emission factors are still valid or need to be revised.

There are several potential sources of variation in carbon content which were taken into account in the sampling design:

- **Different grades of fuel**: the standard unleaded petrol is now E10, but many petrol stations (most of the oil company branded sites, and some supermarkets) also sell premium petrol with a higher octane rating. In addition to standard diesel, many of the oil company branded sites also sell a premium diesel variety, though supermarkets only sell standard diesel. Standard and premium fuels may differ in carbon content due to different additives.

- **Different retailer types**: Supermarkets and oil company branded sites in the same area may differ in where they source fuel depending on supply contracts, as well as offering different grades of fuel. Different supermarkets and different oil company brands may also differ from one another.
- **Geographic variation**: It is likely that fuels differ somewhat in carbon content according to the terminal (refinery or import location), based on the 2017 Ricardo review. In addition, some supermarkets and oil company branded sites occur at different frequencies in different parts of the country, so if products vary by brand then this would also add to geographic variation. Therefore, it is important for sampling to take place across different parts of the country.

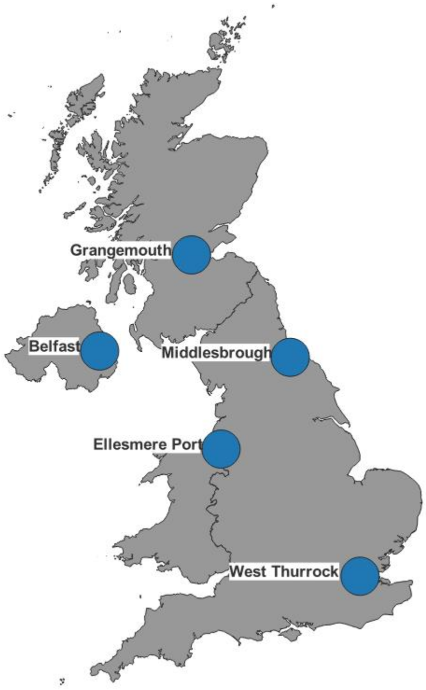
The aim of the sampling campaign was therefore to achieve a balanced combination of samples from different regions of the UK, different retailers and different fuel grades (regular vs. premium). To ensure this balanced combination of samples was achieved, the 50 samples each of petrol and diesel were allocated purposefully rather than randomly, as described below.

Choice of sampling locations

Sampling was undertaken by SGS[44] during June and July 2023. In order to provide as representative as possible profile of fuels in the UK, sampling was undertaken across a wide geographical range covering fuel filling stations within a 30km radius of Middlesbrough, Grangemouth, West Thurrock, Ellesmere Port and Belfast (termed "areas" hereafter). These locations correspond to SGS regional laboratories or offices in the UK, with more in England chosen than elsewhere due to the higher fuel consumption in England; this approach was chosen to minimise staff mileage costs incurred by the sampling campaign, so that the number of samples could be maximised within the available overall budget.

A rough indication of the areas covered by sampling is shown in **Map D1** below.

[44] SGS has ISO 17025 accreditation in ASTM D5453 (sulphur content) and ASTM D6733 (carbon content of gasoline). https://www.sgs.com/



Map D1 Location of fuel sampling areas around the UK. Each circle represents a 30km radius around one of the 5 SGS locations.

In each area, samples were purposefully taken from each of the four major supermarket chains and major oil company branded fuel stations[45] (where present), covering both regular and premium fuel grades. “Regular” petrol refers to E10 (up to 10% ethanol) 95 RON unleaded, and “Premium” to petrol products with higher RON numbers (97-99) and often lower ethanol content. For diesel, the difference between regular and premium products relate mainly to additives used to reduce engine wear or remove residues. Some supermarket filling station branches offer premium petrol, but most supermarkets do not offer premium diesel options.

To minimise the effect of fuel compositional changes due to fuel sitting in tanks or hoses for extended periods prior to samples being drawn, only well-frequented filling stations were visited.

For any one area, the sampling and analysis budget did not allow for a sample of both normal and premium unleaded from all of supermarkets and branded filling stations visited at which two options are on offer. However, a different supermarket and branded filling station was chosen in each region for a sample of premium unleaded (and diesel for branded), so that over all five regions at least one premium option was sampled from all the major suppliers. This flexibility to vary which fuels were sampled by area was considered sensible in case there is more difference between brands / different supermarket chains than there is for the same brand across different areas.

The distribution of fuel samples obtained across these is illustrated in **Table D1** below.

[45] Supermarkets: Asda, Morrisons, Tesco and Sainsbury’s; Oil company brands: EMO, ESSO, BP, Shell, Maxol, Texaco

Table D1 Number of petrol samples per area, by fuel grade (regular/premium) and supermarket versus branded sites.

Area	Brand Retailer		Supermarket		Total
	Premium	Regular	Premium	Regular	
Petrol					
Belfast*	2	3	1	3	**9**
Ellesmere Port	2	3	1	4	**10**
Grangemouth	2	3	1	4	**10**
Teesside	2	3	1	5	**11**
West Thurrock	2	3	1	4	**10**
Total	**10**	**15**	**5**	**20**	**50**
DERV					
Belfast*	2	3	N/A	3	**8**
Ellesmere Port	3	3	N/A	4	**10**
Grangemouth	3	3	N/A	4	**10**
Teesside	4	3	N/A	5	**12**
West Thurrock	3	3	N/A	4	**10**
Total	**15**	**15**	**0**	**20**	**50**

**In Belfast, only 3 of the 4 major supermarket chains were present within the area and only 2 premium diesel samples could be obtained. An additional regular petrol, regular diesel sample and premium diesel sample were taken from the Teesside area.*

Procedure to take samples

The sampling was not accredited to ISO 3170[46], as the ISO 3170 standard is not appropriate for sampling fuel directly from a filling station. The standard EN 14275/BS 2000-509[47] was taken into account when conducting sampling, though not all of the advised procedures to minimise loss of light fractions could be implemented for practical reasons. The SGS inspector attended each site and filled a new UN-certified 5 litre jerry can directly from the fuel pump, sealing it immediately. A chain of custody document was completed listing the inspector's name, site name and address, fuel type, pump number, time & date of sampling and any other relevant information. The samples were labelled and remained sealed before being transported to the laboratory for analysis.

Before laboratory analysis was undertaken, jerry cans were refrigerated overnight, homogenised by inverting the containers 10 times then sub-sampled into 2ml crimp top vials which were then sealed immediately and stored in the fridge until samples were analysed.

These procedures – in addition to only sampling from well-frequented filling stations - were deemed sufficient to keep loss of light fractions from petrol at a level which would

[46] ISO 3170:2004 Petroleum Liquids – Manual Sampling is the standard the specifies the manual methods for obtaining samples of liquids

[47] EN 14275/BS 2000-509 : Automotive fuels. Assessment of petrol and diesel fuel quality. Sampling from retail site pumps and commercial site fuel dispensers

not materially affect the results of the carbon and sulphur content analyses being undertaken. The additional precautions (use of nozzle extensions, running fuel through the hose prior to sampling, refrigeration in transport) recommended in EN 14275/BS 2000-509 are more important for certain tests such as vapour pressure (not carried out in this project) which are much more sensitive to light fraction loss.

Laboratory analysis

The laboratory analysis consisted of analysis of carbon content, sulphur content and biogenic content. Carbon content of the fossil fraction of the fuel (the desired analytical output) could not be measured directly, but was inferred from the total carbon content and biogenic content. Determining the biogenic carbon content is important, due to the need to know the carbon content of the fossil and biogenic fractions separately. The NAEI treats the fossil and biofuel constituents of petrol and diesel separately, to facilitate the different reporting requirements for CO_2 from fossil and biogenic sources in the inventory.

Table D2 below provides details of the laboratory analysis methods used. Information on measurement uncertainty for each method is presented separately in **Table D3**.

Table D2. Details of the laboratory analysis methods used to determine each fuel property, including the international standard, further description, lower limit of detection, and resolution. Resolution in this context means the degree of precision to which the results should be reported according to the standard test method.

Fuel property	Test method standard	Further relevant description	Lower limit of detection (LoD) , resolution and other information
Carbon content of petrol blend	ASTM D6733 – Determination of individual components in spark ignition engine fuels by 50m capillary column, high-resolution GC[48]	Using this technique, once the peaks have been identified the carbon % was calculated from the proportion of each compound. This method also yields results for the quantity of compounds usually making up the biofuel component: ethanol, ETBE and MTBE in the sample (though MTBE cannot be differentiated from cyclopentane).	LoD: 0.1% m/m for each individual compound. Resolution: 0.01% m/m (2 d.p.)
Carbon content of diesel blend	ASTM D5291 – Instrumental determination of carbon, hydrogen and nitrogen in petroleum products[49]	This method is based on sample combustion; carbon content was measured directly after all of the carbon present in the blended fuel is converted to carbon dioxide. The method is designed to provide the best precision for carbon contents in the range 75-87%.	LoD: not relevant for the range of carbon contents present. Resolution: not specified in the ASTM standard, but typical reporting is to 2 d.p.

[48] ASTM D6733-01(2020) available here: https://www.astm.org/d6733-01r20.html
49 ASTM D5291-21 available here: https://www.astm.org/d5291-21.html

Fuel property	Test method standard	Further relevant description	Lower limit of detection (LoD) , resolution and other information
Sulphur content of petrol and diesel	ASTM D5453 - Determination of Total Sulphur in Light Hydrocarbons, Spark Ignition Engine Fuel, Diesel Engine Fuel, and Engine Oil by Ultraviolet Fluorescence[50]	No further description relevant.	LoD: 1 mg/kg Resolution: results below 10mg/kg are reported to 1dp, above 10mg/kg to the nearest whole number
Biogenic content of diesel	DIN 51637 - Biobased Content Testing of Hydrogenated Vegetable Oil (HVO)[51]	This method combines i) determination of FAME content using infrared spectrometry according to EN 14078:2014[52], and determination of total bio-based content using liquid scintillation detection of relative ^{14}C radioactivity in the sample compared with a biogenic HVO and a fossil diesel reference. HVO content is defined as the difference between the total bio-based content and the FAME content. In the report, the total of FAME content + HVO content is taken as the value for total biogenic content.	LoD: Not stated in standard. Resolution: 0.1% m/m Year of C^{14} specific activity: 2023
Biogenic content of petrol	SGS M2095 (based on DIN 51637) Biobased Content of Gasoline	This method uses liquid scintillation detection of ^{14}C radioactivity to estimate total bio-based content as per DIN 51637, but uses bio-ethanol as the biogenic reference. The result is the sum of the activity of all biogenic compounds present (not just bio-ethanol), but the specific activity of each compound cannot be determined.	LoD: Not stated in standard. Resolution: 0.1% m/m Year of C^{14} specific activity: 2023

The analysis of carbon content and sulphur was carried out at SGS Middlesbrough, and analysis of biogenic content by SGS Speyer (Germany). SGS Middlesbrough has ISO 17025 accreditation in ASTM D5453 (sulphur content) and ASTM D6733 (carbon content of gasoline). SGS Middlesbrough does not currently have accreditation in ASTM D5191 (carbon content of diesel) but apply the same standards of quality control to all methods carried out regardless of the accreditation status.

The quality control objectives for all of the methods used were followed in full, in addition certified reference materials and system suitability checks were run where appropriate. Repeat analysis of the same sample was carried out to prove the analysis

[50] ASTM D5453-19a available here: https://www.astm.org/d5453-19a.html
[51] available here: https://www.beuth.de/en/standard/din-51637/194490746.
[52] EN 14078:2014 available here: https://standards.iteh.ai/catalog/standards/cen/2bcb7edd-f6da-43f0-818c-e7ecafe87907/en-14078-2014

system met the repeatability requirements of each method. The precision, bias, and uncertainty values of the ASTM methods were applied in full.

Calculation of carbon and sulphur content in the fossil fraction of petrol and diesel

Carbon

As mentioned in **Section 1.1.2**, the aim of the sampling and analysis campaign is to estimate carbon emission factors which can be applied to the 100% fossil portion of petrol and diesel, to align with the way fuel consumption data is presented in DUKES. For both petrol and diesel, this was calculated from the lab analysis results with the following general approach:

Equation D1

$$\%C_{fossil\ fraction} = 100 \times \frac{\%FossilC_{Total}}{\%Fossil_{Total}}$$

$$= 100 \times \frac{(\%C_{Total} - \%BioC_{Total})}{(100 - \%Bio_{Total})}$$

Where $\%C_{fossil\ fraction}$ is the percentage on a mass/mass basis of carbon of the fossil fraction of the fuel, $\%FossilC_{Total}$ is the percentage on a mass/mass basis of fossil carbon in the total sample mass, and $\%Fossil_{Total}$ is the percentage on a mass/mass basis of fossil compounds in the total sample mass.

$\%Fossil_{Total}$ is calculated as 100% minus the percentage on a mass/mass basis of biogenic compounds in the whole sample ($\%Bio_{Total}$), which was directly provided by the lab analysis. $\%FossilC_{Total}$ was calculated as the percentage C content of the whole sample on a mass/mass basis ($\%C_{Total}$) minus the percentage of biogenic C in the whole sample on a mass/mass basis ($BioC_{Total}$). $BioC_{Total}$ was calculated by multiplying the $\%Bio_{Total}$ by an appropriate carbon content for the biogenic compounds present.

For petrol, $\%Bio_{Total}$ represents the sum of all bio-based compounds added. Ethanol makes up the vast majority of biofuel added currently[53], but other bio-derived compounds (such as methyl-tert-butyl-ether; MTBE) are likely present in some samples. For the purposes of calculating $\%Bio_{Total}$ using method SGS M2095, pure bio-ethanol is used as the biogenic reference compound, and so implicitly this method assumes that the carbon content of ethanol (52%, based on the molecular formula) should be used to convert between $\%BioC_{Total}$ and $\%Bio_{Total}$. See section “Discussion of biogenic content of petrol” below for more detail.

For diesel, $\%Bio_{Total}$ was given by the total of FAME and HVO content[54], although FAME was found to make up the vast majority of biogenic compounds in diesel. Carbon contents of FAME and HVO used in the calculation were 77% and 85% respectively, as stated in DIN 51637.

[53] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1161315/2021-final-rf-01-rtfo-tables-revised.ods, tab RF_0111
[54] FAME and HVO content of diesel were determined on a volume basis initially, then converted to mass basis using typical densities also given by DIN 51637 of 883 g/l and 780 g/l respectively.

Sulphur

Unlike for carbon, there was no measurement made of sulphur content of the biogenic fraction of petrol or diesel from which to estimate sulphur content of the fossil fraction; only the total sulphur content of the fuel blend was measured. There is also no theoretical expectation of the likely sulphur content of the biogenic component, because it is present as an impurity rather than as part of the fuel compounds themselves. Sulphur occurs in bio-ethanol and FAME due to sulphur-containing compounds from the original feedstock not being fully eliminated by processing. For FAME and bio-ethanol, the sulphur content limit in the specifications (EN 14214 and EN 15376 respectively) are 10 mg/kg; the same limits as apply to the blended diesel and petrol (EN 590 and EN 228 respectively).

Given the consistent sulphur limits between the biofuels and the fossil fuel blends, the simplest assumption (in the absence of data) is that sulphur content of the fossil and biogenic fractions are similar. Under this assumption, the total sulphur content values can be applied equally to the separate DUKES statistics on fossil diesel and biodiesel consumption.

Aggregation and weighting of results

As discussed in the **Sampling Strategy** section above, it was not feasible to ensure that the samples taken were fully representative of fuel consumed in the UK due to limitations on the budget for sample collection and analysis, lack of data on total sales volumes of the batches of fuels represented by each sample, and lack of winter samples. However, some data on fuel sales according to relevant factors were used to help improve the representativeness of the results to the extent possible, by calculating a weighted average rather than a simple average, using fuel sales volumes as a weighting factor to adjust the influence of individual samples on the average.

These data included:

i) DESNZ statistics on country-level (England, Scotland and Northern Ireland; Wales was not sampled for logistical reasons) petrol and diesel consumption[55];

ii) The fraction of petrol and DERV sales through supermarkets and other retailers (DUKES table 3.4[56]); and

iii) The proportion of regular and premium (Super) unleaded petrol sold[57] from Fuels Industry UK.

These three separate data on fuel sales were combined to estimate the proportion of total petrol sales in each combination of country, retailer type (supermarkets vs. branded retailers) and fuel grade (regular versus premium). This assumes that there are no associations / correlations between these three factors, for example that the share of regular and premium petrol sold does not differ between supermarkets and other

55 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1165225/road-transport-fuel-consumption-tables-2005-2021.xlsx
56 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1174053/DUKES_3.4.xlsx
57 This data was provided by the DUKES petroleum statistic team, originally provided by Fuel Industry UK. It is unpublished data provided for use in this project.

retailers, and does not vary between different countries of the UK. This assumption is not easy to verify, but no other data were available to support a different approach.

For DERV, a breakdown by regular and premium grades was not available, and the supermarket versus non-supermarket proportions reported by DUKES table 3.4 are more heavily weighted towards non-supermarket, which may relate to a significant fraction of diesel being delivered in bulk (e.g., for HGV and van fleets) rather than through forecourts. For these reasons, only fuel sales by country were used to weight the DERV sample results. However, due to the low variability observed between fuel grades and retailer types for diesel (see **Table 11**), if data had been available on sales by these factors, it may not have made much difference to the overall results.

Whilst the calculations for petrol and diesel do not provide a fully robust average, they do provide a single number to compare qualitatively with the currently used NAEI carbon and sulphur emission factors.

The calculation method for weighted averages is shown in **Equations D2 and D3** below.

Equation D2

$$Weighted\ mean = \frac{\sum_{i=1}^{N} x_i w_i}{\sum_{i=1}^{N} w_i}$$

Where:

x_i is the fuel property of interest from sample *i* (out of *N* total samples);

and w_i is the weight applied to fuel sample *i*. w_i was calculated as per Equation D3 below:

Equation D3

$$w_i = \frac{PropFuelSales_{Ci,Gi,Ri}}{PropSamples_{Ci,Gi,Ri}}$$

Where:

$PropFuelSales_{Ci,Gi,Ri}$ is the proportion of total fuel sales in the combination of country (out of the total England, Scotland and Northern Ireland sales), grade (regular vs. premium) and retailer type (supermarket vs. branded retailer) applicable to fuel sample *i*. This assumes that the share across grades and retailer types is the same in each country;

$PropSamples_{Ci,Gi,Ri}$ is the proportion of total samples represented by the combination of country, grade and retailer type applicable to fuel sample *i.*

Tables D2 and D3 below shows the weighting factors (w_i) applied to samples representing each combination of factors and how these were derived, for petrol and DERV respectively.

Table D2 Weighting factors applied to petrol samples representing each combination of factors, and derivation from proportion of fuel sales and proportion of samples. Ratio is the ratio of proportion of fuel sales to samples as described in Equation D3.

Country	Retailer type and grade	Proportion of fuel sales	Proportion of samples	Ratio (weighting to apply)
Scotland	Branded Retailer_Regular	0.035	0.06	**0.58**
Scotland	Supermarket_Regular	0.028	0.08	**0.36**
Scotland	Branded Retailer_Premium	0.010	0.04	**0.26**
Scotland	Supermarket_Premium	0.008	0.02	**0.42**
England	Branded Retailer_Regular	0.377	0.18	**2.09**
England	Supermarket_Regular	0.306	0.26	**1.18**
England	Branded Retailer_Premium	0.111	0.12	**0.93**
England	Supermarket_Premium	0.091	0.06	**1.51**
Northern Ireland	Branded Retailer_Regular	0.014	0.06	**0.23**
Northern Ireland	Supermarket_Regular	0.011	0.06	**0.19**
Northern Ireland	Branded Retailer_Premium	0.004	0.04	**0.10**
Northern Ireland	Supermarket_Premium	0.003	0.02	**0.17**

Table D3 Weighting factors applied to DERV samples representing each combination of factors, and derivation from proportion of fuel sales and proportion of samples. Ratio is the ratio of proportion of fuel sales to samples as described in Equation D3.

Country	Proportion of fuel sales	Proportion of samples	Ratio (weighting to apply)
Scotland	0.10	0.2	**0.48**
England	0.87	0.64	**1.36**
Northern Ireland	0.04	0.16	**0.22**

Uncertainties

The observed variation across samples in petrol and diesel lab analysis results is likely to result from a combination of real variation in composition on the one hand, and variation due to measurement error of the laboratory methods used. Where random (rather than a systematic bias in one direction), measurement error contributes to variation across samples, and therefore can be thought of as a component of it. To enable comparison of sample results with the NAEI emission factors, the key parameter is estimating the 95% confidence interval around the mean values obtained from the sampling; this is how uncertainty is usually defined in the IPCC Guidelines. This means the range in which 95% of sample means would fall if the sampling campaign were to be repeated.

An indicative 95% confidence interval around a mean value can be approximated as two times the standard error of the mean. The “standard error of the mean” is a measure of the spread of sample means obtained if the sampling were to be repeated many times. For a constant amount of variation across individual samples (i.e. the standard deviation), the standard error of the mean value becomes smaller as sample size increases, in proportion to the square root of the sample size, and can be approximated as:

$$Standard\ error\ of\ the\ mean = \frac{Standard\ deviation}{\sqrt{number\ of\ samples}}$$

Where the number of samples is 50.

This same approximation can be applied to both observed standard deviation of sample results, and to the measurement standard deviation values defined in laboratory analysis standards (assuming that the measurement error is random rather than systematic) – see **Table D4**.

It is technically challenging and requires many assumptions to estimate the contributions of measurement error and other source of real variation across samples separately, and combine into a single estimate of uncertainty. There are several sources of uncertainty which cannot be quantified, but nonetheless would contribute to overall uncertainty in the mean values obtained from the sampling:

- The lack of winter blend samples
- The non-random sampling, which whilst geographically varied did not cover every part of the UK or every fuel supplier
- Lack of data available on the sales volumes of each specific product, ensure the sampling undertaken was representative of a typical tank of fuel sold.
- Lack of bulk-delivered DERV in the samples

Therefore, although definitive confidence intervals are not feasible to calculate, in discussions with NPL it was decided to estimate “indicative” confidence intervals which would allow broad comparisons to NAEI emission factors. Firstly, the standard error of the mean was calculated in two ways separately:

i) The standard deviation of observed values by the square root of the number of samples. This is referred to in sections 4 and 5 as “sampling uncertainty”, and may include a contribution of measurement error where this is random and small.

ii) Dividing the repeatability (reproducibility where repeatability not available) standard deviation of the measurement techniques used values by the square root of the number of samples. This is referred to in sections 4 and 5 as “sampling uncertainty”.

Then, whichever is the largest standard error of the two approaches was used as the estimate of uncertainty, multiplied by 2 to give a 95% confidence interval for the mean. This is a conservative approach.

Estimating measurement uncertainty

Measurement standard deviations for individual lab analysis techniques were obtained from the analysis standard documentation. These measurement standard deviations for individual techniques could then be used – either alone or in combination – to calculate the measurement standard deviation of the fuel properties in question (sulphur content, and carbon content of the fossil fraction). In turn, these were then used (as described above) in the calculation of the confidence intervals around mean values obtained from the sampling campaign, by dividing through by the square root of the sample size.

Where available, the repeatability standard deviation (relating to variation in result for the same sample material, machine, location and operator) was used, but if not available the reproducibility standard deviation was used instead, as a conservative estimate. **Table D4** below shows the uncertainty values used. Unfortunately, the bio-based carbon analysis methods (DIN 51637 and SGS M2095) do not provide standard uncertainty values, so reproducibility values from the similar EN 16440 have been used as a conservative estimate of uncertainty for these methods.

Table D4 Measurement uncertainty values used in the uncertainty analysis, and the confidence interval calculated as twice the standard error of the mean

Method	Fuel	Repeatability standard deviation (SD)	Reproducibility standard deviation (SD)	Confidence interval of the mean =2*(SD/sqrt(50))
Sulphur content of petrol and diesel ASTM D5453	Petrol and diesel	0.6 mg/kg @ 5mg/kg sulphur	1.9 mg/kg @ 5mg/kg sulphur	±0.17 mg/kg
Carbon content of diesel ASTM D5191	Diesel	0.564 %m/m @ 85% carbon %m/m	1.4671 %m/m @ 85% carbon %m/m	Not applicable to this test alone
Carbon content of petrol ASTM D6733	Petrol	Standard deviations cited in the standard are for the concentration of individual compounds. Most of the compounds would have similar carbon contents. It is difficult to calculate the uncertainty of overall carbon content, but it would certainly be small compared to the biobased content error, and also likely smaller than the uncertainty in carbon content of diesel[58]. Therefore, measurement uncertainty from this method has been excluded.		Not applicable to this test alone
Biobased content of petrol and diesel (EN 16440 used as a proxy)	Petrol and diesel	Not available	2.3 %m/m for bio-diesel (most applicable substance)	±0.65 % m/m; used for the confidence interval for carbon content of the fossil fraction of petrol

[58] SGS, personal communication. There are many more variables involved in the combustion analysis of carbon content of diesel, so it is the expert judgement of the SGS staff involved in this project that uncertainty in carbon content of the overall petrol blend would be lower than for diesel.

Method	Fuel	Repeatability standard deviation (SD)	Reproducibility standard deviation (SD)	Confidence interval of the mean =2*(SD/sqrt(50))
Carbon content of the fossil fraction of diesel	Diesel	3.04 %m/m standard deviation combining the standard deviation of EN 16440 as per the row above, and the standard deviation of the carbon content of diesel ASTM D5191.		±0.86 % m/m

For **sulphur content** of petrol and diesel, the standard deviations of ASTM D5453 in **Table D4** above could be used unmodified to represent the measurement standard deviation when calculating confidence intervals, because no other lab analysis techniques feed into calculating sulphur content.

To obtain the measurement standard deviation of the **carbon content of the fossil fraction of petrol and diesel**, this requires combining the measurement uncertainties of all of the lab analysis techniques feeding into the calculation (see **Equation D1**). For carbon content of the fossil fraction of **diesel**, the overall standard deviation (3.04%m/m) was calculated by combining the standard deviations of the total carbon content analysis and the bio-based content analysis (used to calculate fossil content), using error-propagation methods as defined in IPCC 2006 Guidelines, Vol 1, Chapter 3, equations 3.1 and 3.2. This approach would ideally also apply to uncertainty calculation for the carbon content of the fossil fraction of **petrol**. However, because the uncertainty in the total carbon content of petrol could not be quantified, only the measurement standard deviation associated with the bio-based content analysis is considered (which is likely much greater than the error in the overall carbon content analysis).

Discussion of biogenic content of petrol

Whilst other bio-derived compounds are added to petrol (such as methyl-tert-butyl-ether; MTBE), ethanol makes up the vast majority of biofuel added currently[Error! Bookmark not defined.].

For petrol, the laboratory analysis methods undertaken enabled two different approaches to estimating the biogenic content of the samples collected.

1. **Gas chromatography – flame ionisation detection (GC-FID),** method ASTM D6733 yields results for the quantity of compounds usually making up the biofuel component: ethanol, ETBE and MTBE in the sample (though MTBE cannot be differentiated from cyclopentane).
2. **Liquid scintillation detection of ^{14}C radioactivity**, method SGS M2095 (based on DIN 51637) Biobased Content of Gasoline. This yields an estimate of the total content of biogenic compounds in petrol (“bio-based content”), which can include ethanol, methanol, bio-ETBE and bio-MTBE.

In general, there was a high correlation between the ethanol content from method 1 and the biogenic content results of method 2 (**Figure D1**).

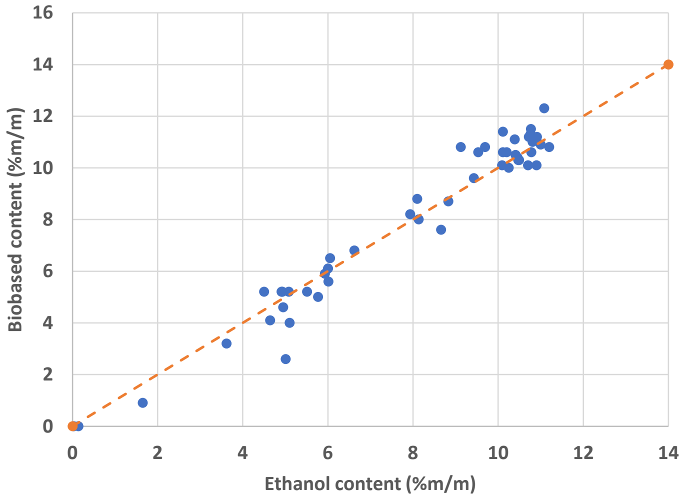


Figure D1. Relationship between ethanol content and total biogenic content results obtained from the two different analysis methods for petrol samples.

It would be expected for most samples to lie above the dashed 1:1 equality line in **Figure D1**, as the biobased content results should also include other biogenic compounds like bio-MTBE and bio-ETBE. Contrary to expectations, for many samples the second technique yielded lower estimates of biogenic content than the first technique did for ethanol alone – sometimes considerably so (points below the line). This could potentially be explained by i) measurement error or ii) some ethanol in the petrol samples originating from fossil sources.

Based on discussions with SGS, the GC-FID technique is thought to have lower measurement error than the liquid scintillation method. The measurement uncertainty of the method DIN 51637 (on which SGS M2095 is based) has not been officially defined, but the reproducibility standard deviation of biocarbon content (%m/m) provided by a similar standard technique (EN 16440) for biodiesel is 2.3 percentage points; no repeatability value is provided. In ASTM D6733 the GC-FID analysis has a repeatability (r) and reproducibility (R) standard deviation of 0.04 and 0.16 times the result respectively for the concentration of ethanol (so for 10% ethanol this would be 0.4 and 1.6 percentage points for r and R respectively).

In addition, the sampling error (2 x standard error) of the liquid scintillation results was slightly higher than the sampling error for the GC-FID results; between 0.26 and 0.49 percentage points of carbon content in fossil fraction (across different grades and location types) for the liquid scintillation-based calculations, compared to between 0.22 and 0.34 percentage points for the GC-FID based calculations.

However, use of the ethanol content as a proxy for bio-based content due to lower measurement uncertainty would require assuming:

i) that none of the ethanol present in the fuel blend is from fossil sources, and

ii) that no other bio-based compounds were present.

Despite searching online, no evidence from the literature could be found on the ethanol content of fossil petrol.

Regarding the second assumption, there is no simple way to establish from the results whether other bio-based compounds were present or not in some samples.

On balance, it was decided to use the bio-based content results from SGS M2095 as the basis for calculating the carbon content of the fossil fraction of petrol. Despite the likely higher uncertainty of the analysis method itself, this is more easily quantified and justified (especially in an inventory review context) than use of the other method requiring the two assumptions listed above.

Nevertheless, it should be noted that the results of the two methods do not differ substantially when aggregated up: The weighted-average carbon content of the fossil fraction obtained using the bio-based content analysis is 86.17%, compared to 86.15% when using the ethanol content as a proxy.

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