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GHG Emission Factors Review

Environmental Services Association (ESA)

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Glossary

Abbrev	Definition
AD	Anaerobic Digestion
ADEME	Agence de L'Environnement et de La Maitrise de L'Energie (Agency for Ecological Transition)
AFOLU	Agriculture, Forestry and Other Land Use
BEIS	Department for Business Energy & Industrial Strategy
C&I(W)	Commercial and Industrial (Waste)
CITEPA	Centre technique de référence en matière de pollution atmosphérique et de changement climatique (Technical Reference Centre for Air Pollution and Climate Change)
DOC	Degradable Organic Carbon
DUKES	Digest of UK Energy Statistics
EpE	Entreprises pour l'Environnement
E-PRTR	European Pollutant Release and Transfer Register
ESA	Environmental Services Association
ESP	Electrostatic Precipitator
ETS	Emissions Trading System
EU	European Union
FOD	First Order Decay
FNADE	Fédération Nationale des Activités de la Dépollution et de l'Environnement (French National Federation of Pollution Control and Environmental Services)
GHG	Greenhouse Gas
GHGI	Greenhouse Gas Inventory
GWP	Global Warming Potential
HFC/PFC	Hydrofluorocarbon/ Perfluorinated compound
HWI	Hazardous Waste Incineration
IPCC	Intergovernmental Panel on Climate Change
LCA	Lifecycle Assessment
MBT	Mechanical Biological Treatment
MODECOM	Mode de caractérisation des déchets ménagers et assimilés (Characterisation method for household and similar waste)
MSW	Municipal Solid Waste
MSWI	Municipal Solid Waste Incinerator
NAEI	National Atmospheric Emissions Inventory
NCV	Net Calorific Value
OMINEA	Organisation et méthodes des inventaires nationaux des émissions atmosphériques en France (Organisation and methods of national inventories of atmospheric emissions in France)

Abbrev	Definition
PE	Polyethylene
RDF	Refuse Derived Fuel
SCR	Selective Catalytic Reduction
SNCR	Selective Non-Catalytic Reduction
SWDS	Solid Waste Disposal Sites
UK	United Kingdom
VGF	Vegetable, fruit and garden wastes
WEEE	Waste Electrical and Electronic Equipment

1 Introduction

As part of the project "Quantification of greenhouse gas emissions from recycling and waste management in the UK", Ricardo was commissioned by the Environmental Service Association to perform an emissions factors review on the "Protocol for quantification of GHG emissions from waste management activities". This review examined defaults emissions factors and methodological approach from several recognised methodologies to measuring Direct emissions (Scope 1), Indirect emissions (Scope 2) and Avoided Emissions (Scope 3). Originally written as a stand-alone report, the text has been minimally adjusted to act now as an appendix to the final project report.

The waste management activities included in this review are fuel consumption, electricity and heat import, landfill, thermal treatment, composting, anaerobic digestion, recovery/recycling and mechanical biological treatment.

Table 1 below, illustrates the methodologies examined by emissions category.

Table 1: Methodologies reviewed by category of emissions

Scope	Methodologies
Direct emissions (Scope 1)	BEIS Conversion Factors Ecoinvent National Atmospheric Emissions Inventory (NAEI) Inter-governmental Panel Climate Change (IPCC) Protocol for quantification of GHG emissions from waste management activities Agence de l'Environnement et de la Maîtrise de l'Énergie (ADEME)
Indirect emissions (Scope 2)	BEIS Conversion Factors
Avoided emissions (Scope 3)	Scottish Carbon Metric

This report aims to provide a summary of the methodologies examined and if further information is needed, the references to the original documents are provided.

Ricardo has examined the methodologies mentioned in Table 1, in addition to the request of the ESA to consolidate the ESA's members methods to measuring thermal treatment emissions. Ricardo has anonymously consolidated the ESA's members' information in this report.

1.1 Global Warming Potential Emissions Factors

Emissions of different gases have different impacts on global warming, so scientists assign global warming potential (GWP) emission factors to account for those differences. The convention is that carbon dioxide is given a factor of '1' and other factors are calculated against that scale, enabling all contributions to be summed in units of "carbon dioxide equivalents".

The relative contribution of the different gases changes depending on the timeframe under consideration. The default timeframe chosen for reporting climate change is the next one hundred years, abbreviated to GWP100. However, alternative timeframes exist, including GWP500 (for five hundred years) and GWP20 (for twenty years). The latter has added interest because of the current focus on actions that limit the rise of global warming in the short-term. Under this timeframe, the relative significance of methane emissions is much increased, because their impacts are more short-term.

Over time, opinion has evolved as to the relative importance of the factors. The principle sources for factors are the periodic assessment reports published by the Intergovernmental Panel on Climate Change. Their fourth report (AR4 [(1)]) from 2007 is still the primary source used by the UK government for its calculations, so is the default recommended by Ricardo for ESA to employ. However, there is also the more recent fifth report, AR5 [(2).] from 2013.

The GWP emission factors (EF) that might be of interest to ESA members are compiled in Table 2 below. The highlighted first row contains the default values recommended for this project.

Table 2: Options for choice of GWP emissions factors

Report	Timeframe	CO_2	CH_4	N_2O	SF_6	NF_3	
AR4 (1)	**GWP100**	**1**	**25**	**298**	**22,800**	**17,200**	**← Default**
AR4 (1)	GWP20	1	72	289	16,300	12,300	
AR4 (1)	GWP500	1	8	153	32,600	20,700	
AR5 (2)	GWP100	1	28	265	23,500	16,100	
AR5 (2)	GWP20	1	84	264	17,500	12,800	

(1) Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz and R. Van Dorland, 2007: Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

(2) Myhre, G., D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang, D. Koch, J.-F. Lamarque, D. Lee, B. Mendoza, T. Nakajima, A. Robock, G. Stephens, T. Takemura and H. Zhang, 2013: Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

1.2 Consideration of reporting organisation and available data

Through discussions with the ESA, Ricardo has concluded that it is reasonable for different methodologies to be adopted for calculating different organisations' carbon footprints, in large part as a result of the data available, and that this flexibility extends to selecting emissions factors. To give one example, it is expected that an individual waste management company would have access to detailed information (as a result of the many regulations that must be followed) about any energy from waste (EfW) plants it operates. If the company knows the average fossil carbon content of its waste and how much waste it handled, it is most of the way to being able to estimate its GHG emissions from burning waste by using that data in an empirical calculation.

Contrast this with the challenge faced by the ESA, attempting to estimate the emissions from burning waste across the entire UK. It does not (as things stand) have access to the carbon content of waste at each EfW for all its members, let alone any other waste management businesses that are not members. Where individual companies can use measurement data, the ESA probably has to use total tonnages and average emission factors, because of the different data that the organisations can access.

Whilst the difference in data availability is clear between a waste management company and the trade association, there can also be differences in data availability between individual waste management companies and even between sites within one organisation. Whilst it would be ideal for all parties to use the same and most accurate calculation method, data limitations may enforce different approaches. This feels pragmatic, but ESA will need to monitor how its members report their data, because whenever there can be different ways of calculating an answer, (and therefore different answers), there is the risk that businesses will finesse their approach in order to be able to adopt the most preferential method.

Such monitoring is outside the scope of this current phase of work, but Ricardo concludes from this analysis that it would be appropriate to offer a hierarchy of possible methods for calculating emissions from different operations, depending on the data available. This is the approach adopted in this report.

2 Non-process specific factors

2.1 Government GHG Emissions Factors for Companies

The Department for Business, Energy & Industrial Strategy annually issues a set of GHG emissions conversion factors for company reporting purposes. This set of GHG emissions conversion factors is widely used for compliance purposes and voluntary GHG emissions assessment for companies' activities.

Ricardo is aware that any recommendations on the use of this set of GHG conversion factors must follow the referenced methodology papers for the relevant year assessed.

In addition, Ricardo recommends users follow the GHG Protocol guidance on the definitions of Direct emissions (Scope 1) and Indirect emissions (Scope 2). Wherever a company has accurate data on its consumption of a fuel or other energy, combining that with the appropriate BEIS emission factor will often be the simplest way of arriving at a robust estimation of its GHG emissions.

2.1.1 Scope 1. Fuels

The "2018 Government GHG Conversion Factors for Companies Reporting. Methodology paper for emissions factors final report[1]" provides the methodological approach the user must follow when estimating GHG emissions factors.

Ricardo has taken for the purpose of this report, relevant extracts, as follows:

- "The Government Greenhouse Gas Conversion Factors for Company Reporting2 represents the current official set of UK government emissions factors. These factors are also used in a number of different policies".
- "The GHG Conversion Factors have been provided on the GOV.UK site: https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting".
- "All the fuel conversion factors for direct emissions presented in the 2018 GHG Conversion Factors are based on the emission factors used in the UK GHG Inventory (GHGI) for 2016 (managed by Ricardo Energy & Environment[3])".
- "The CO_2 emissions factors are based on the same ones used in the UK GHGI and are essentially independent of application (assuming full combustion). However, emissions of CH_4 and N_2O can vary to some degree for the same fuel depending on the particular use (e.g. emission factors for gas oil used in rail, shipping, non-road mobile machinery or different scales/types of stationary combustion plants can all be different)".
- "The standard emission factors from the GHGI have been converted into different energy and volume units using information on Gross and Net Calorific Values (CV) from BEIS's Digest of UK Energy Statistics (DUKES) 2017[4]".

2.1.2 Scope 2. Electricity and Heat

The "2018 Government GHG Conversion Factors for Companies Reporting. Methodology paper for emissions factors final report[5]" provides the methodological approach the user must follow when estimating GHG emissions factors.

Ricardo has taken for the purpose of this report, relevant extracts, as follows:

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[1] 2018 Government GHG Conversion Factors for Companies Reporting. https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting
[2] Previously known as the 'Guidelines to Defra/DECC's GHG Conversion Factors for Company Reporting'.
[3] UK Greenhouse Gas Inventory for 2016 (Ricardo Energy & Environment), available at: https://uk-air.defra.gov.uk/library/reports?report_id=954 .
[4] Available at: https://www.gov.uk/government/collections/digest-of-uk-energy-statistics-dukes
[5] 2018 Government GHG Conversion Factors for Companies Reporting. https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting

- “The electricity conversion factors represent the average CO_2 emission from the UK national grid per kWh of electricity generated, classed as Scope 2 of the GHG Protocol and separately for electricity transmission and distribution losses, classed as Scope 3”.
- “The UK electricity emission factors provided in the 2018 GHG Conversion Factors are based on emissions from sector power stations and autogenerators in the UK Greenhouse Gas Inventory (GHGI) for 2016 (Ricardo Energy & Environment) according to the amount of CO_2, CH_4 and N_2O emitted per unit of electricity consumed (from DUKES 2017)[6]. These emissions from the GHGI only include autogeneration from coal and natural gas fuels, and do not include emissions for electricity generated and supplied by autogenerators using oil or other thermal non-renewable fuels. In previous updates, this was accounted for by removing this component from the DUKES GWh data. However, since the 2016 update, estimates of the emissions due to these components have been made using standard NAEI emission factors, and information from DUKES and BEIS’s DUKES team on the total fuel use (and shares by fuel type) for this component. An additional correction is made to account for the share of autogeneration electricity that is exported to the grid (~15.4% for the 2016 data year), which varies significantly from year-to-year”.
- The UK is a net importer of electricity from the interconnectors with France and Netherlands, and, to a more limited amount, with Ireland according to DUKES (2017). For the 2018 GHG Conversion Factors the total net electricity imports were calculated from DUKES (2017)”.

[6] DUKES (2017): https://www.gov.uk/government/collections/digest-of-uk-energy-statistics-dukes

3 Scope 1 Anaerobic Digestion Emission Factors

For the anaerobic digestion emission factor, the methods that were considered were: EpE, IPCC, Ecoinvent and NAEI. The analysis looked into the inclusion of several parameters that affect the emission factor, such as the technology used and the composition of the waste processed. The method advocated by the NAEI is to adopt the IPCC approach.

3.1 EpE

The methodology provided in the EpE tool can be used to calculate the direct emissions from anaerobic digestion installations, which include process emissions, emissions from biogas combustion units as well as emissions from fuel consumption.

The process emissions are calculated based on biogas yield and leakage percentage with CH_4 to CO_2 proportion, while the biogas combustion emissions are calculated based on an efficiency rate. However, the user needs to add the emission factors in order to calculate these emissions.

3.2 IPCC

The IPCC offers in Chapter 4 Biological Treatment for Solid Waste[7] the methodological approach to anaerobic digestion, composting and mechanical biological treatment.

Anaerobic treatment is usually linked with methane (CH_4) recovery and combustion for energy and thus the IPCC states that greenhouse gas emissions from the process should be reported in the Energy Sector. The CO_2 emissions are of biogenic origin and should be reported only as an information item in the Energy Sector. Emissions of CH_4 from anaerobic digestion facilities as a result of unintentional leakages during process disturbances or other unexpected events will generally be between 0-10% of the amount of CH_4 generated. The IPCC provides 5% as a default value in the absence of knowing the actual leakages for the CH_4 emissions. In addition, depending on the technical standards for biogas plants, if they can ensure that unintentional CH_4 emissions are flared, then CH_4 emissions are likely to be close to zero. The N_2O emissions from the process are assumed to be negligible. Table 3 provides the default emission factors considered in this exercise for comparison.

Anaerobic sludge treatment at wastewater treatment facilities is addressed in Chapter 6, Wastewater Treatment and Discharge, and emissions should be reported under the categories of Wastewater. However, when sludge from wastewater treatment is transferred to an anaerobic facility which is co-digesting sludge with solid municipal or other waste, any related CH_4 and nitrous oxide (N_2O) emissions should be reported under the category of the biological treatment of solid waste. Where these gases are used for energy, then associated emissions should be reported in the Energy Sector.

The IPCC offers Tier 1 default emissions factors from composting, and anaerobic digestion in biogas facilities. These emissions will depend on factors such as type of waste composted, amount and type of supporting material (such as wood chips and peat) used, temperature, moisture content and aeration during the process.

Again, Table 3 provides these default emission factors for comparison.

In addition, IPCC offers a Tier 2 alternative method, which provides the standards for the emissions factors based on representative measurements that cover relevant biological treatment options applied in the country and in Tier 3, emission factors are based on facility/site-specific measurements (on-line or periodic).

3.3 Ecoinvent

The dataset for anaerobic digestion is based on a Swiss plant, where thermophile, single stage digestion with post composting occurs. It includes the steps of reception, weighing, shredding, anaerobic digestion (AD), solid/liquid separation, rotting process, turning over, aeration and watering,

[7] IPCC Chapter 4: Biological Treatment of Solid Waste

post-processing and conditioning. The dataset contains data for electricity and diesel use, as well as air emissions, including CO_2, NO_2 and CH_4.

Table 3: Emission factors for anaerobic digestion (kg/tonne)

	EpE	IPCC	Ecoinvent	NAEI
CH_4	-	0.8	1.01	0.8
CO_2	-	-	210 (biogenic)	-
N_2O	-	negligible	0.033	negligible
CO_2e	-	20	35.1	20

3.4 Method recommendation

As mentioned in Section 2.1, Ricardo believes it is appropriate to offer a hierarchy of possible methods for calculations, depending on the organisation in question and the data available to them.

For individual waste management companies, purchasing records will reveal the amounts of fuels and power used by each facility. These figures should be combined with the relevant BEIS emission factors (also discussed in Section 2.1) to reveal the Scope 1 and Scope 2 emissions associated with those usages.

This leaves the emissions from the treatment facility itself. Operators who regularly measure their emissions will already have systems in place to calculate their annual methane emissions, and these can be scaled by the global warming potential in Table 2 to yield emissions in carbon dioxide equivalents.

Operators and other organisations (such as ESA) who do not have access to this data must use a generic emission factor to estimate their global warming potential, based on the amount of waste handled. The difference between the emission factors presented in Table 3 is not orders of magnitude but could nevertheless make a difference to a company's calculations. Rather than use the specific data from a particular AD plant (in Switzerland) provided by Ecoinvent, we recommend that the ESA adopts the emission factor used by both the IPCC and the NAEI, namely 20 kg CO_2eq/tonne of waste.

Table 4: Summary of methodologies for anaerobic digestion (AD)

Method	Description	Source
EpE	Default emission factors are not provided.	
IPCC	The IPCC offers Tier 1 default emissions factors from composting and anaerobic digestion in biogas facilities. These emissions will depend on factors such as type of waste composted, amount and type of supporting material (such as wood chips and peat) used, temperature, moisture content and aeration during the process. Table 3 provides the default emission factors considered in this exercise for comparison. In addition, IPCC offers a Tier 2 alternative method, which provides the standards for the emissions factors based on representative measurements that cover relevant biological treatment options applied in the country and in Tier 3, emission factors are based on facility/site-specific measurements (on-line or periodic). $$CH_4\ Emissions = \sum_i (M_i \times EF_i) \times 10^{-3} - R$$	IPCC vol. 5 Waste, chapter 4 Biological treatment of solid waste https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_4_Ch4_Bio_Treat.pdf
Eco-invent	All the steps of the process are considered. The dataset contains the full set of factors required.	• Raboni, M. and Urbini, G., 2014. Production and use of biogas in Europe: a survey of current status and perspectives. Revista ambiente & agua, 9(2), pp.191-202. • Kaegi, T., Zschokke, M., Dinkel, F., 2019. Technical Report – Life Cycle Inventories for Biogas and Biomethane Processes. • Amlinger, F. and Peyer, S., 2003. Umweltrelevanz der dezentralen Kompostierung - Klimarelevante Gasemissionen, flüssige Emissionen, Massenbilanz, Hygienisierungsleistung • Wagner, R., 2011. Treibhausgas Emissionen aus der Grunngutbewirtschaftung
NAEI	NAEI follow the guides of IPCC Tier 1, default emission factors.	IPCC vol. 5 Waste, chapter 4 Biological treatment of solid waste https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_4_Ch4_Bio_Treat.pdf

4 Scope 1 Composting Emission Factors

The methods that were considered for the emission factor for the composting process were: EpE, IPCC, Ecoinvent and NAEI. The IPCC provides a range in the default emission factors and an average value in order to reflect all types of facilities including in-vessel, open windrow and both. The method advocated by the NAEI is to adopt the IPCC approach.

4.1 EpE

The methodology provides default emissions factors for calculating CH_4, N_2O and biogenic CO_2, depending on the type of waste sent to composting. It also includes the calculation of fuel consumption by units of fuel used. These factors come from a list of sources:

- ADEME (2005), Impacts environnementaux de la Gestion Biologique des Déchets;
- CITEPA, OMINEA 2013 which refers to the study above;
- Heres (2007) Research determining indicator for methane and laughing gas composting plants;
- Guide d'aide à la déclaration annuelle des émissions polluantes et des déchets des installations de compostage, FNADE, validation ADEME, Février 2009

These documents are not available online. The methodology does not provide separate calculations for Open Windrow and In Vessel composting.

4.2 IPCC

The IPCC defines composting as "an aerobic process and a large fraction of the degradable organic carbon (DOC) in the waste material is converted into carbon dioxide (CO_2). CH_4 is formed in anaerobic sections of the compost, but it is oxidised to a large extent in the aerobic sections of the compost. The estimated CH_4 released into the atmosphere ranges from less than 1 percent to a few per cent of the initial carbon content in the material (Beck-Friis, 2001; Detzel et al., 2003; Arnold, 2005[8]). Composting can also produce emissions of N_2O. The range of the estimated emissions varies from less than 0.5 percent to 5 percent of the initial nitrogen content of the material (Petersen et al., 1998; Hellebrand 1998; Vesterinen, 1996; Beck-Friis, 2001; Detzel et al., 2003[9]). Poorly working compost sites are likely to produce more both of CH_4 and N_2O (e.g., Vesterinen, 1996[10])[11]".

4.3 Ecoinvent

Ecoinvent only provides processes for open window composting. The data comes from composting plants in Switzerland. The steps included in the study are the reception, weighing, shredding, rotting process, turning over, aeration, watering, post-processing and conditioning. The dataset contains data for electricity and diesel use, as well as air emissions, including CO_2, NO_2 and CH_4.

Table 5: Emission factors for composting (kg/tonne)

	EpE	IPCC	Ecoinvent	NAEI
CH_4	5.11	4	1	4
CO_2	247 (biogenic)	-	220 (biogenic)	-
N_2O	0.024	0.24	0.025	0.24
CO_2e	149.5	171.5	32.5	171.5

8 Beck-Friis, B.G. (2001). Emissions of ammonia, nitrous oxide and methane during composting of organic household waste. Uppsala: Swedish University of Agricultural Sciences. 331 p. (Doctoral Thesis).
9 Petersen, S.O., Lind, A.M. and sommer, S.G. (1998). 'Nitrogen and organic matter losses during storage of cattle and pig manure', J. Agric. Sci., 130: 69-79.
10 Vesterinen, R. (1996): Impact of waste management alternatives on greenhouse gas emissions: Greenhouse gas emissions from composting. Jyväskylä: VTT Energy. Research report ENE38/T0018/96. (In Finnish). 30p
11IPCC Chapter 5 Waste, (https://www.ipcc-nggip.iges.or.jp/public/gp/english/5_Waste.pdf)

4.4 Method recommendation

Like anaerobic digestion, composting facilities should already have data on their usages of fuel and energy, which can be used with the BEIS EFs to estimate the associated emissions. In addition, if they regularly measure their emissions, they will be able to use this data directly to calculate their GWP emissions. Organisations without access to this data must use a generic EF.

One of the emission factors in Table 5, from Ecoinvent, is clearly out of line with the alternatives, and is again based on a Swiss plant, so is discounted. The remaining factors show a relatively narrow spread. The EpE factor is derived from sources that are not available online. Furthermore, the IPCC and NAEI use the same method and have the same results, and were also the chosen method for the similar calculation above, for the AD emission factor. For these reasons, we recommend that the ESA adopts the emission factor used by both the IPCC and the NAEI, namely 171.5 kg CO_2eq/tonne of waste.

5 Scope 1 Mechanical Biological Treatment (MBT)

The mechanical component of MBT plants will involve measured consumption of fuels and power that can be combined with the BEIS EFs for reporting purposes.

Once again, monitoring data should be used, where available, to calculate the methane emissions from the biological treatment stage. The fall-back option where such information is unavailable should be to use the generic emission factors reported above for anaerobic digestion or composting, according to the technology being used.

Table 6: Summary of methodologies for composting

Method	Description	Source
EpE	Default emission factors are included in the method for composting. However, their sources are not available so cannot be reviewed.	•ADEME (2005), Impacts environnementaux de la Gestion Biologique des Déchets; •CITEPA, OMINEA 2013 which refers to the study above; •Heres (2007) Research determining indicator for methane and laughing gas composting plants; •Guide d'aide à la déclaration annuelle des émissions polluantes et des déchets des installations de compostage, FNADE, validation ADEME, Février 2009
IPCC	The IPCC offers Tier 1 default emissions factors from composting and anaerobic digestion in biogas facilities. These emissions will depend on factors such as type of waste composted, amount and type of supporting material (such as wood chips and peat) used, temperature, moisture content and aeration during the process. Table 5 provides the default emission factors considered in this exercise for comparison. In addition, the IPCC offers a Tier 2 alternative method, which provides the standards for the emissions factors based on representative measurements that cover relevant biological treatment options applied in the country and in Tier 3, emission factors are based on facility/site-specific measurements (on-line or periodic).	IPCC vol. 5 Waste, chapter 4 Biological treatment of solid waste https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_4_Ch4_Bio_Treat.pdf
Eco-invent	Data available only for open window composting. All the steps of the process are considered. The dataset contains the full set of factors required.	Dinkel, F., Zschokke, M. and Schleiss, K., 2012. Ökobilanzen zur Biomasseverwertung. Autragnehmer: Carbotech AG. Publikation, 290577.
NAEI	NAEI follow the guides of IPCC Tier 1, default emission factors.	IPCC vol. 5 Waste, chapter 4 Biological treatment of solid waste https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_4_Ch4_Bio_Treat.pdf

6 Scope 1 Thermal Treatment Emission Factors

The methodologies that were examined for the thermal treatment emission factor were: EpE, IPCC, Ecoinvent and NAEI. Given the complexity of the process and the range of the emission factors, Ricardo was asked to research the emission factors used by the ESA members, to further help identify the most appropriate methodology.

6.1 EpE

The methodology provides two ways of calculating direct emissions from incineration. The first way is by providing default emission factors for household waste, non-hazardous industrial waste, hazardous and hospital waste incineration, or on a case by case scenario provided the user has access to the carbon and biogenic content going to the incinerator and the combustion efficiency percentage. The second way is by annual flue gas volume monitoring. However, this way does not offer default values for CO_2/m^3 or % of biogenic content.

The methodology also offers default emissions factors for calculating N_2O, PFC and NF_3 emissions from waste incineration. However, it does not offer default emission factors for HFC.

The direct emissions also include any additional fuel consumption.

The sources of the emission factor are not accessible online.

6.2 IPCC

The methodology described in Chapter 5, Volume 5 of the 2006 IPCC Guidelines is applicable in general to incineration both with and without energy recovery.

The IPCC explains that "emission factors in the context of incineration and open burning of waste relate to the amount of greenhouse gas emitted to the weight of waste incinerated or open-burned. In the case of CO_2, this applies data to the fractions of carbon and fossil carbon in the waste. For CH_4 and N_2O, this primarily depends on the treatment practice and the combustion technology[12]".

The IPCC 1996 Guidelines clearly states that only "CO_2 emissions resulting from oxidation of carbon in waste of fossil origin (e.g., plastics, certain textiles, rubber, liquid solvents, and waste oil) are considered net emissions and should be included in the national CO_2 emissions estimate. The CO_2 emissions from combustion of biomass materials (e.g., paper, food, and wood waste) contained in the waste are biogenic emissions and should not be included in national total emission estimates".

However, if incineration of waste is used for energy purposes, both fossil and biogenic CO_2 emissions should be estimated. Only fossil CO_2 should be included in national emissions under Energy Sector while biogenic CO_2 should be reported as an information item also in the Energy Sector.

The IPCC recommends calculating emissions by determining the emissions on a plant-by-plant basis and/or differentiated for each waste category (e.g., MSW, sewage sludge, industrial waste, and other waste including clinical waste and hazardous waste). The methods for estimating CO_2, CH_4 and N_2O emissions from incineration and open burning of waste vary because of the different factors that influence emission levels. "Estimation of the amount of fossil carbon in the waste burned is the most important factor determining the CO_2 emissions. The non-CO_2 emissions are more dependent on the technology and conditions during the incineration process".

6.3 Ecoinvent

The incineration of waste is a different process for each material on the Ecoinvent database. There are three main processes for the materials used in this study:

[12] Chapter 5, Volume 5 of the 2006 IPCC

1. For municipal solid waste: The process is adjusted to the UK in terms of waste composition, but uses the technology mix encountered in Switzerland in 2010, with the following characteristics:
    a. Inventoried waste contains 92.8% average municipal solid waste, combustible part; 7.23% average municipal solid waste, non-combustible (inert) part;
    b. Waste composition (wet, in ppm): upper heating value 13.05 MJ/kg; lower heating value 11.7 MJ/kg; H2O 225260; O 261060; H 43105; C 338960; S 1532.3; N 3206.1; P 757.42; B 7.3826; Cl 6670; Br 129.32; F 366.39; I 0.012418; Ag 0.73279; As 1.4061; Ba 152.96; Cd 8.0053; Co 1.3807; Cr 139.58; Cu 930.87; Hg 0.65684; Mn 266.19; Mo 2.0065; Ni 52.342; Pb 413.61; Sb 53.368; Se 0.3281; Sn 99.553; V 9.4572; Zn 1127.9; Be 470.85; Sc n.a.; Sr n.a.; Ti 2616.4; Tl n.a.; W n.a.; Si 49786; Fe 23628; Ca 18346; Al 11395; K 2132.7; Mg 2568.9; Na 4741.6;
    c. Biogenic carbon: 61.1%;
    d. Share of metals in waste not oxidised and bulk-recyclable (exclude very small or thin parts) Iron: 72.06%; Alu: 38.71%; Copper: 45.44%;
    e. One kg of this waste produces 0.2221 kg of slag and 0.02224 kg of residues, which are landfilled. Additional solidification with 0.008896 kg of cement;
    f. Net energy production: 1.39MJ/kg electric energy and 2.85MJ/kg thermal energy;
    g. Recovery of metal scrap to recycling: 9.7909g iron scrap, 1.2162g aluminium scrap, 0.12319g copper scrap;
    h. Average Swiss MSWI plants in 2010 (grate incinerators) with electrostatic precipitator for fly ash (ESP), wet flue gas scrubber and 25% SNCR , 42.77% SCR-high dust , 32.68% SCR-low dust -DeNOx facilities and 0% without DeNOx (weighted according to mass of burnt waste, representing Swiss average). Efficiency of iron scrap separation from slag: 58%. Efficiency of non-ferrous scrap separation from slag: 31%. Gross electric efficiency technology mix 15.84% and Gross thermal efficiency technology mix 28.51%.
2. Hazardous waste: Process modelled for Europe, but based on two Swiss Hazardous Waste Incineration (HWI) plants with a total annual capacity of 53,000 tonnes of hazardous waste with the following characteristics:
    a. waste composition (wet, in ppm): lower heating value 17 MJ/kg; H2O 250000; O 40000; H 61000; C 416000; S 32000; N 7400; P 2200; B 7; Cl 104000; Br n.a.; F 3700; I n.a.; Ag n.a.; As n.a.; Ba n.a.; Cd 0.37; Co 74; Cr 123.95; Cu 267.47; Hg 0.74; Mn n.a.; Mo n.a.; Ni 126.81; Pb 296.64; Sb n.a.; Se n.a.; Sn n.a.; V n.a.; Zn 2378.3; Be n.a.; Sc n.a.; Sr n.a.; Ti n.a.; Tl n.a.; W n.a.; Si 80425; Fe n.a.; Ca n.a.; Al n.a.; K n.a.; Mg n.a.; Na n.a.;
    b. Biogenic carbon: 0%;
    c. One kg of this waste produces 0.189 kg of residues, which are landfilled. Additional solidification with 0.07561 kg of cement.
    d. Net energy produced in HWI: 17.11MJ/kg thermal energy and 1.27MJ/kg electric energy;
    e. Swiss HWI plant in 2000 with wet flue gas scrubber and low-dust SCR DeNOx facility. Gross thermal efficiency 74.4% and gross electric efficiency 10%.
3. For all other materials: Same technology as the one used for (1) but not adjusted to UK data.

The technologies in all three processes are based on Swiss facilities. However, the data has been adjusted so that it can be used for facilities around the world. The process data and the emission factors are detailed enough so that the user can select only the data suitable to the modelling requirements. Biogenic air emissions are also reported separately.

Table 7: Ecoinvent v3 emissions factors for thermal treatment (kg/ tonne)

	CO_2e	CH_4 (fossil)	CH_4 (biogenic)	CO_2 (fossil)	CO_2 (biogenic)	N_2O
Biowaste	15.5	-	0.0006	-	516	0.052
Paper	16.7	-	0.0005	-	1,472	0.056

	CO_2e	CH_4 (fossil)	CH_4 (biogenic)	CO_2 (fossil)	CO_2 (biogenic)	N_2O
Cardboard	11.5	-	0.0005	-	1,579	0.039
Glass	0.019	0.0003	0.0005	-	-	-
Textiles	650	0.0001	0.0003	351	907	1.057
Mixed plastics	2,336	0.0002	-	2,309	-	0.091
Polyethylene (PE)	3,002	0.0001	-	2,996	-	0.019
Wood	4.4	-	0.0005	-	1,463	0.015

6.4 WRATE

The WRATE life cycle assessment software[13] is another source of information on waste fraction elemental composition, and has the advantage over Ecoinvent of being based on UK analysis. Ricardo took its estimates of the percentage of elemental carbon in each waste fraction, applied the splits for each fraction of biogenic vs fossil carbon and then uplifted the figures by (44/12) to convert from carbon to carbon dioxide. Assuming that combustion is 100% efficient, the emission factors for carbon dioxide are as presented in Table 8.

Table 8: Emission factors derived from WRATE for thermal treatment (in kg CO_2 per tonne of waste)

Material	Biogenic CO_2	Fossil CO_2
Paper	1,052	
Card	1,212	
Plastic Film		1,753
Dense Plastic		2,010
Textiles	731	731
Metals		
Wood	1,606	
Glass	10	
Food	509	
Garden	630	
Combustible	845	563
Non combustible	154	103
Sanitary	544	136
Fines	504	
WEEE		580
Hazardous		

6.5 ESA Members

Ricardo circulated a guidance document to ESA's EfW Working Group to collect information on the methodological approaches to measuring direct emissions (scope 1) from thermal treatment. In addition, the members were asked to describe their approach to estimating the CO_2 fossil content and

[13] The Waste & Resources Assessment Tool for the Environment (WRATE): see www.wrate.co.uk

the CO_2 biogenic content proportion on MSW. Understanding the differences between the members' current approach will help Ricardo to identify the most appropriate method for the ESA to recommend to its members. The members are anonymised. It is worth noting that the methodologies described below only take into account the emissions arising from the combustion of waste and not the emissions from the combustion of fuels under scope 1.

Table 9 presents the emission factors that the ESA members estimate by using the different methodologies available.

Table 9: Emission factors as estimated by ESA members

Member	Methodology	Emission Factor (kg CO_2e/tonne)
No.1	Chemical conversion equation	473
No.2	EpE (for MSW)	340
No.3	-	-
No.4	EU ETS/ GPE	783 / 784
No.5	Chemical conversion equation	587
Tolvik Consulting	Own methodology	527

6.5.1 Member No.1

The first member to respond stated that, as operators, they conduct an independent compositional and chemical analysis of the MSW entering the facility annually, following UKAS accredited methods. From these analyses, they obtain the fossil/biogenic carbon ratio, which for 2020 was 46.91% fossil/ 53.09% biogenic. Also, they use the equation of:

275kg C+ (275kg C*32/12) kg Oxygen =1,008 kg CO_2/ tonne of waste

where 275kg is the average carbon content per tonne of the MSW accepted in the facility over the past six years.

Consequently, they calculate that, for 2020, 1 tonne of MSW emitted 1,008 kg CO_2, of which 472.9kg is fossil carbon dioxide and 535.1kg is biogenic carbon dioxide.

The member stated that they are planning to add a CO_2 sensor to their Continuous Emission Monitoring Systems in 2021 and conduct waste compositional analyses at an increased frequency (quarterly or 6 monthly) to improve their methodology.

6.5.2 Member No.2

The second member to respond provided a detailed table of the emission factors based on the type of waste incinerated. The emission factors originate from the EpE tool.

Table 10: Waste type specific emission factors for incineration (all weights in tonnes)

Indicator Name	EF / Methodology	EF (TCO_2eq/Unit)
Non-hazardous health care waste	DAS incineration - average factor	0.88 CO_2 + 0.06 N_2O * 265 GWP
Hazardous Health care wastes	DAS incineration - average factor	0.88 CO_2 + 0.06 N_2O * 265 GWP
Gaseous Hazardous wastes	HW incineration - average factor	0.81 CO_2 + 0.051 N_2O * 265 GWP

Indicator Name	EF / Methodology	EF (TCO_2eq/Unit)
Liquid Hazardous wastes	HW incineration - average factor	0.81 CO_2 + 0.051 N_2O * 265 GWP
Polluted Soils	HW incineration - average factor	0.81 CO_2 + 0.051 N_2O * 265 GWP
Solid hazardous wastes	HW incineration - average factor	0.81 CO_2 + 0.051 N_2O * 265 GWP
Commercial & Industrial waste (C&I)	NHW incineration - average factor	0.332 + 0.031 N_2O * 265 GWP
MSW	NHW incineration - average factor	0.332 + 0.031 N_2O * 265 GWP
Other wastes	NHW incineration - average factor	0.332 + 0.031 N_2O * 265 GWP
C&I waste	NHW incineration - average biogenic factor	0.458
MSW	NHW incineration - average biogenic factor	0.458
Other wastes	NHW incineration - average biogenic factor	0.458

6.5.3 Member No.3

The third member to respond stated that, in two of their sites, the biogenic fraction is measured using an accredited method, yielding typical values that range from 50-70%.

In other sites they use an estimate which either uses the base-case Defra[14] assumption (50%) or an internal estimate based on averages from the real data they hold (which would be closer to 60%).

6.5.4 Member No.4

The fourth member stated that they use the EU ETS method for calculating emissions from waste used as fuels but have also shown this next to the GPE approach, proving that they produce near enough the same outcome. The biogenic content and carbon content data come from regular waste sampling results. The EU ETS[15,16] methodology suggests the calculation of a 'preliminary emission factor', EF_{pre}, expressed as t CO_2/TJ, which corresponds to the total CO_2 emitted from this source stream regardless of whether it is stemming from fossil or biomass sources, using the following formula:

$$EF_{pre} = CC_{total} * f / NCV$$

Where:

f: the factor of 3.664 t CO_2/ t C

CC_{total}: the carbon content of waste

NCV: Net Calorific Value of the waste.

The emissions can then be calculated using the following formula:

$$Em = FQ * NCV * EF_{pre} * (1 - BF) * OF$$

Where:

FQ: fuel quantity

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[14] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/284612/pb14130-energy-waste-201402.pdf
[15] https://ec.europa.eu/clima/sites/clima/files/ets/monitoring/docs/faq_mmr_en.pdf
[16] https://ec.europa.eu/clima/sites/clima/files/ets/monitoring/docs/gd1_guidance_installations_en.pdf

NCV: Net Calorific Value of the waste

EF_{pre}: preliminary emission factor

BF: biomass fraction

OF: oxidation factor.

From the calculations using the formulas above, this member estimates that for every tonne of waste input 783 kg CO_2 are emitted.

The GPE approach is slightly different than the EU ETS methodology but yields the same results (784 kg CO_2/tonne). The quantity of the waste sent to incineration is multiplied with the emission factor, as calculated using the following formula:

$$EF = CC * (1 - BF) * Comb_{eff} * f$$

Where:

CC: the carbon content of waste

BF: biomass fraction

$Comb_{eff}$: Combustion efficiency

f: factor of 44/12 (3.667) t CO_2/ t C.

6.5.5 Member No.5

Another member that responded provided results for the incineration of refuse derived fuel (RDF). Their methodology is similar to that of Member No.1's. Using laboratory tests, the carbon content of the waste input is specified, together with the biogenic content, which is 52.5% of the input. The total tonnage input is multiplied with the weighted average of the carbon content of waste and the factor of 3.667 t CO_2/ t C. Consequently, they calculate that, for 1 tonne of RDF they emitted 1,234 kg CO_2, of which 587kg is fossil carbon dioxide and 647kg is biogenic carbon dioxide.

6.5.6 Tolvik Consulting

Tolvik Consulting issues an annual report called "UK Energy from Waste Statistics"[17], which includes a calculation of the carbon intensity of EfW. This calculation takes into account:

1. The average CO_2 & other GHG emitted from Pollution Inventory[18];
2. The fossil content of waste from a WRAP study[19];

The study estimated that, by multiplying the average CO_2 emissions with the fossil content of waste and adding the other GHG emissions, under Scope 1, 527kg CO_2e are emitted for each tonne of waste input.

6.5.7 Residual waste composition

In a later enquiry, Ricardo approached the ESA Steering Group to ask for compositional data for residual waste. The responses provided were combined into two estimations of waste composition, one for residual municipal solid waste and the other for residual commercial and industrial waste. The results are presented in Table 11 and Figure 1.

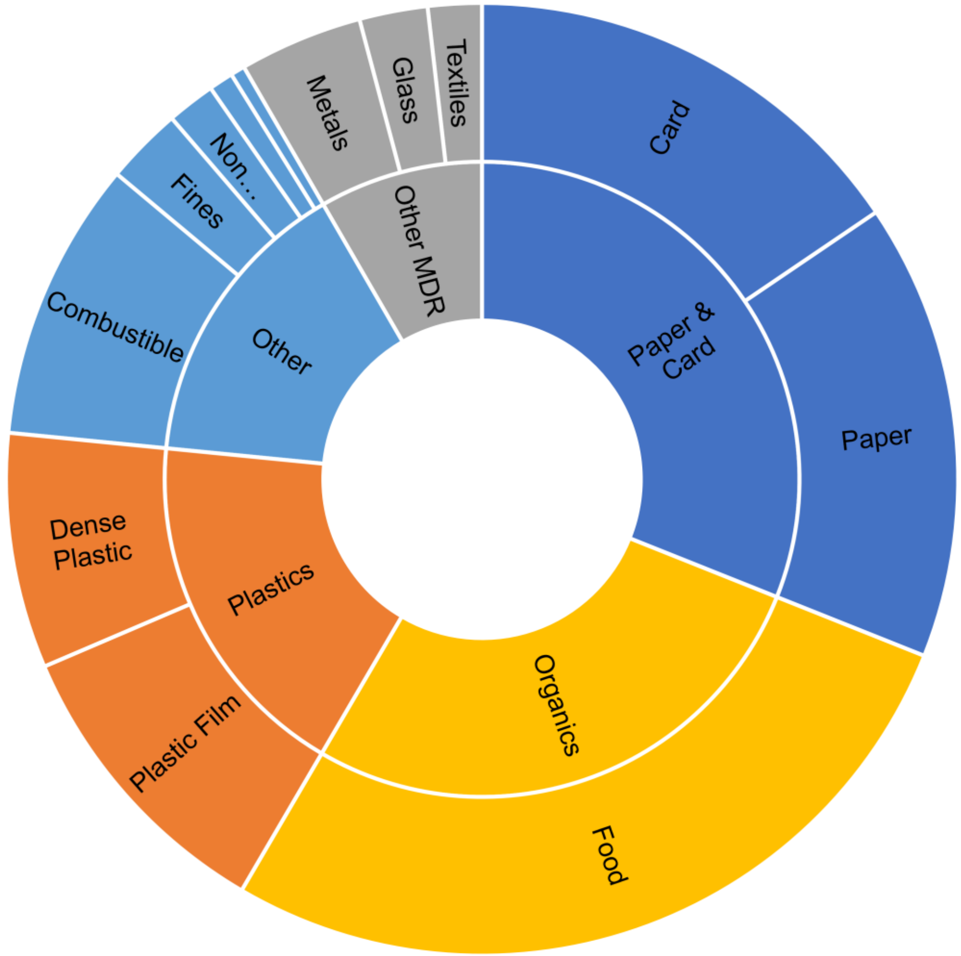
Table 11: Derived waste compositions of residual MSW and residual C&IW

Category	Material	Residual MSW	Residual C&IW
Paper & Card	Paper	12.1%	15.5%
	Card	7.1%	15.5%

[17] https://www.tolvik.com/wp-content/uploads/2020/05/Tolvik-UK-EfW-Statistics-2019-Report-June-2020.pdf
[18] 2018 Pollution Inventory Dataset – Version 1 https://data.gov.uk/dataset/cfd94301-a2f2-48a2-9915-e477ca6d8b7e/pollution-inventory
[19] WRAP: National municipal waste composition, England 2017 https://wrap.org.uk/content/quantifying-composition-municipal-waste

Category	Material	Residual MSW	Residual C&IW
Plastics	Plastic Film	7.9%	10.1%
	Dense Plastic	7.8%	8.0%
Other MDR	Textiles	7.1%	1.8%
	Metals	3.3%	4.2%
	Wood	2.9%	
	Glass	2.7%	2.3%
Organics	Food	27.5%	27.4%
	Garden	3.6%	
Other	Combustible	7.1%	9.5%
	Non combustible	3.8%	1.6%
	Sanitary	3.5%	
	Fines	2.1%	2.6%
	WEEE	1.3%	0.8%
	Hazardous	0.3%	0.5%

Figure 1: Waste compositions of residual municipal solid waste (MSW, left) and commercial and industrial waste (C&IW, right)



6.6 Method recommendation

It is clear from this review that there is quite a breadth of values for the emission factor(s) that should be used for the thermal treatment of waste. Fundamentally, and as recommended for AD and composting, it seems right to apply an empirical calculation, where the data are available, as proposed by the ESA members. Adopting the syntax of Member No.4:

$$\frac{EfW\ Emission\ Factor}{(in\ kg\ CO_2/t\ of\ waste)} = CC \times (1 - BF) \times Comb_{eff} \times f$$

…where: CC = the carbon content of the waste (in kg C per t of waste)
BF = fraction of carbon that is biogenic (0-100%)
$Comb_{eff}$ = the combustion efficiency of the EfW (0-100%)
f = (44/12) = 3.67 = the ratio of the molecular weights of CO_2 and C

Ideally, ESA members would make the calculation at the waste fraction level. If the composition of the waste is known, a bottom-up calculation can be performed using specific EFs for each fraction. Member No.1 mentioned using an independent compositional and chemical analysis of the MSW entering the facility, following UKAS accredited methods. Our recommendation is to use the WRATE emission factors presented in Table 8.

Where organisations do not have the necessary level of detail to estimate the composition of their feedstock, the above calculation requires that CC and BF be determined or estimated. For its own summary calculations, and for net zero scenarios, the ESA could plan to derive a weighted average emission factor from its members' calculations. Until the underlying data are available, however, we recommend adopting the typical waste compositions presented in Table 11. This enables us to determine default figures for mixed residual MSW and residual C&IW (remembering the assumption of 100% combustion efficiency), as presented in Table 12.

Table 12: Recommended emission factors for thermal treatment (in kg CO_2 per tonne of waste)

Material	Biogenic CO_2	Fossil CO_2		Residual MSW	Residual C&IW
Paper	1,052			12.1%	15.5%
Card	1,212			7.1%	15.5%
Plastic Film		1,753		7.9%	10.1%
Dense Plastic		2,010		7.8%	8.0%
Textiles	731	731		7.1%	1.8%
Metals				3.3%	4.2%
Wood	1,606			2.9%	
Glass	10			2.7%	2.3%
Food	494			27.5%	27.4%
Garden	630			3.6%	
Combustible	845	563		7.1%	9.5%
Non combustible	154	103		3.8%	1.6%
Sanitary	544	136		3.5%	
Fines	504			2.1%	2.6%
WEEE		580		1.3%	0.8%
Hazardous				0.3%	0.5%
Sewage sludge	1,133				
Soil	256				
Rubble		256			
Clinical		256			
Residual MSW	**565**	**404**			
Residual C&IW	**603**	**412**			

Another benefit of this approach is that, during scenario analysis, it enables the estimation of the carbon benefits of (for example) diverting waste plastics from incineration feedstocks, once the compositional change is modelled. For these reasons, this is our recommended default method for the calculation of the emission factor for thermal treatment processes.

Inspection of the list of materials in Table 12 reveals that most common waste streams are covered. The factors are also mostly comparable with those reported in Table 14. One missing stream is **chemical waste**, for which Table 14 offers the NAEI value of 341 kg CO_2eq per tonne of waste, which seems reasonable. However, there is a question concerning **hazardous waste**. Table 12 imagines that the hazardous waste fraction of mixed waste has a negligible carbon content, where ecoinvent and the EpE tool have much higher values. We recommend that, when modelling dedicated hazardous waste streams, if better data are not available, the EpE figure of 824 kg CO_2eq per tonne of waste be adopted.

Table 13: Summary of methodologies for thermal treatment

Method	Description	Source
EpE	Default emission factors are included in the method for thermal treatment. However, their sources are not available so cannot be reviewed.	
IPCC	The common method for estimating CO_2 emissions from incineration and open burning of waste is based on an estimate of the fossil carbon content in the waste combusted, multiplied by the oxidation factor, and converting the product (amount of fossil carbon oxidised) to CO_2. The activity data are the waste inputs into the incinerator or the amount of waste open-burned, and the emission factors are based on the oxidised carbon content of the waste that is of fossil origin.	
Eco-invent	The technologies in all three processes are based on Swiss facilities. However, the data has been adjusted so that it can be used for facilities around the world. The process data and the emission factors are detailed enough so that the user can select only the data suitable to the modelling requirements. Biogenic air emissions are also reported separately.	Itten, R., Frischknecht, R., Stucki, M., Scherrer, P. and Psi, I., 2012. Life cycle inventories of electricity mixes and grid. Doka, G., 2013. Updates to Life Cycle Inventories of Waste Treatment Services-part II: waste incineration. Doka Life Cycle Assessments, Zurich, 2013. Doka, G., 2007. Life cycle inventories of waste treatment services: ecoinvent report no. 13. Swiss Centre for Life Cycle Inventories, Dubenfort.
NAEI	Incineration of Municipal Solid Waste only occurs on EFW which are reported under Power Stations: The activity data reported in the UK inventory is a combination of non-biodegradable (fossil) and biodegradable wastes and apply IPCC default carbon factors for each type of waste. The default emission factors are calculated based on the energy generated.	
WRATE	Not the method used within WRATE (where values are based on measured emissions from selected individual incinerators), but derived from waste compositional data on carbon content and biogenic fraction.	

Table 14: Emission factors for thermal treatment (kg/tonne)

	EpE	IPCC	Ecoinvent[20]	NAEI
MSW				
CH_4	-	-	0.0002 (fossil) 0.0003 (biogenic)	-
CO_2	-	-	478 (fossil) 752 (biogenic)	-
N_2O	-	-	0.048	-
CO_2e	-	-	776	196[21]
Clinical waste				
CH_4	-	-	-	0.025
CO_2	880	-	-	240
N_2O	0.06	-	-	0.03
CO_2e	896	-	-	249
Chemical waste				
CH_4	-	-	-	0.194
CO_2	-	-	-	309
N_2O	-	-	-	0.1
CO_2e	-	-	-	341
Hazardous waste				
CH_4	-	-	-	-
CO_2	810	-	1,509	-
N_2O	0.051	-	0.026	-
CO_2e	824	-	1,516	-
Household waste				
CH_4	-	-	-	-
CO_2	332 (fossil) 458 (biogenic)	-	-	-
N_2O	0.031	-	-	-
CO_2e	340	-	-	-

[20] Also check Table 7 for Ecoinvent factors for different materials.

[21] Originally 0.022 kt CO_2/ TJ_{net}. The conversion was calculated using a net calorific value of 8.9 GJ/tonne, as suggested in the Tolvik Consulting "UK Energy from Waste Statistics – 2019" See footnote #17.

7 Scope 1 Landfill Emission Factors

Ricardo examined methodologies from ADEME, IPCC, Ecoinvent and NAEI to compare the different methods for assessing GHG emissions generated in landfill. Brief reviews of the alternatives are presented in the sections below and summarised in Table 18.

7.1 ADEME (EpE)

The ADEME landfill model uses the 1st order equation from the IPCC model to estimate the CH_4 emissions from landfill. It takes into account four greenhouse gases; CO_2, CH_4, SO_x and NO_x. The sources of these gases are the organic waste degradation (CO_2 and CH_4) and the combustion of the biogas generated (CO_2, SO_x and NO_x). The source document contains a series of formulae which can be used to estimate the emissions and all the parameters required in the formulas, shown in Table 18.

The version of this model that is incorporated into the EpE tool calculates only the landfill methane emissions to be emitted in the given reporting year from waste landfilled during that reporting year, and therefore excludes the future emissions resulting from the degradation of waste landfilled in and prior to the reporting year. However, the user can choose to calculate the future emissions of that quantity of waste by using the formula in Table 18 and use its output in the model, thus accounting for all the emissions of the landfilled waste, concentrated within one year.

7.2 IPCC

Ricardo examined the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC Guidelines). This document outlined two methods to estimate CH_4 emissions from solid waste disposal sites, namely the default method (Tier 1) and the First Order Decay (FOD) method (Tier 2).

The text explains the methods as follow: “The main difference between the two methods is that the FOD method produces a time-dependent emission profile that better reflects the true pattern of the degradation of materials landfilled process over time, whereas the default method is based on the assumption that all potential CH4 is released in the year the waste is disposed. The default method will give a reasonable annual estimate of actual emissions if the amount and composition of deposited waste have been constant or slowly varying over a period of several decades. If the amount or composition of waste disposed of at SWDS is changing more rapidly over time, however, the IPCC default method will not provide an accurate trend”.

The IPCC 2006 landfill tool was refined in 2019; the main modification was as follows:

“Estimation of CH_4 emission from landfill: Guidance on the use of methane correction factor (MCF) in different management conditions of solid waste disposal sites (SWDS) has been updated. New default values for the MCF to estimate CH4 emissions from active aeration landfill have been provided by level of landfill management (poorly and well managed). The IPCC Waste Model has been updated according to the refinement. Default values for the fraction of degradable organic carbon which decomposes (DOCf) for different waste components and their uncertainties have been updated, and relevant guidance has been added”[22].

7.3 Ecoinvent

Ecoinvent has one process published for sanitary landfill anywhere in the world, based on a Swiss facility with leachate and gas collection systems. The dataset includes short-term emissions from landfill gas incineration and landfill leachate, as well as burdens from short-term treatment of leachate in wastewater treatment plant, including the sludge disposal in a municipal incinerator. Short-term emissions are defined as those occurring within 100 years. The air emissions are split between fossil

[22] IPCC vol. 5 Waste, chapter 4 Biological treatment of solid waste https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/5_Volume5/V5_4_Ch4_Bio_Treat.pdf

and biogenic, thus facilitating the exclusion of those CO_2 emissions associated with the degradation of organic materials.

Ecoinvent also has emission factors for certain specific material streams. These are reproduced in Table 15.

Table 15: Ecoinvent v3 emissions factors for landfill (kg/tonne)

	CO_2e	CH_4 (fossil)	CH_4 (biogenic)	CO_2 (fossil)	CO_2 (biogenic)
MSW	545	0.944	20.6	6.2	135
Paper	1,048	-	41.9	-	273
Cardboard	1,350	-	54	-	352
Mixed plastics	86.7	2.4	-	15.9	-
Polyethylene (PE)	99.6	3.2	-	20.6	-
Wood	57.8	-	2.3	-	15.1

7.4 NAEI

The National Atmospheric Emissions Inventory follows the IPCC Tier 2 approach based on national data on waste quantities, composition, properties and disposal practices over several decades.

The tool developed by the NAEI team is called MELMod. It holds annual data for the tonnage and composition of MSW and C&IW landfilled in the UK since 1945. Five types of landfill are modelled over that period, reflecting the evolution of landfill design. The amounts of methane formed from each year's deposited waste, for every year following its initial deposit, are calculated by waste fraction, according to its properties, including its lignin content. Taking biodegradability data from a 2011 Eunomia Report[23], MELMod assumes that some of the lignin's carbon is held within the landfill for the long-term (in effect sequestered).

For this project, Ricardo used MELMod to estimate how much methane is formed over 70 years (found to be sufficiently long for residual emissions to be near zero) per tonne of each waste fraction deposited. From Ricardo's annual calculations for the NAEI, we estimate that 42.7% of the methane formed is not captured, and a further 10% is oxidised, meaning that 38.4% of the formed methane is actually emitted.

In discussions with the ESA about this approach, ESA members disputed whether lignin in landfills actually sequesters any carbon, arguing instead that its release is not prevented but simply postponed and therefore should be included. Ricardo was able to adjust calculations to offer both results, with and without the extra carbon sequestration that MELMod assumes. The results, by waste fraction, are presented in Table 16.

Table 16: Lifetime methane emissions from landfilled waste (in kg methane per tonne of waste)

Group	Material	MELMod default	Without extra sequestration
Paper & Card	Paper	41.2	53.5
Paper & Card	Card	38.8	50.3
Plastics	Plastic Film		

[23] "Inventory Improvement Project – UK Landfill Methane Emissions Model", Eunomia Research and Consulting, January 2011

Group	Material	MELMod default	Without extra sequestration
Plastics	Dense Plastic		
Other MDR	Textiles	17.1	17.1
Other MDR	Metals		
Other MDR	Wood	32.0	52.3
Other MDR	Glass		
Organics	Food	24.3	25.9
Organics	Garden	22.3	30.1
Other	Combustible	28.2	28.2
Other	Non combustible		
Other	Sanitary	11.0	11.0
Other	Fines	16.2	16.2
Other	WEEE		
Other	Hazardous		

7.5 Method recommendation

Although compost may take a little time to release all its emissions, it is fair to say that landfill is effectively unique among the considered waste treatment methods, in that landfilled waste can take decades to fully release its emissions. This presents an immediate difficulty, if trying to determine total landfill emissions in a given year armed only with the tonnage of waste landfilled in that year. This in turn emphasises the importance of understanding for what reason the emissions are being estimated.

7.5.1 Total annual landfill emissions

For waste management companies wishing to report the annual emissions from their landfill sites (for example for national emissions auditing), the most robust method is probably to rely on monitoring data at the landfill. The sensors will not differentiate between waste from different years, and instead simply report the actual emissions they detect. Appropriate aggregation and extrapolation techniques can be used if required to scale the discrete readings to estimates of total annual emissions.

For organisations that do not have access to such monitoring data, but still need to generate an estimation of the total emissions due to waste that is in landfills, Ricardo recommends following the IPCC, as the main authority on such accounting techniques. Furthermore, as the NAEI also adopts this approach, and follows the Tier 2 alternative, a practical approach would be to adopt the same method as suggested in the next section, which uses a time-dependent emission profile that better reflects the true pattern of the degradation of the materials landfilled over time.

7.5.2 Landfill emissions modelling

When it comes to considering, for example, net zero projections, the aim is to estimate the impacts of sending quantities of waste to different fates, and projecting how their emissions evolve over time, as the volumes, compositions and fates change. Each calculation is usually done for a given year, multiplying the waste sent to each fate by the corresponding emission factor for that fate. The emission factor for landfill obviously needs to account for the emissions from landfill in the year the waste is landfilled, but it seems only fair that it should also account for the emissions from that same waste that occur in subsequent years.

The adjusted NAEI method outlined in Section 7.4 derives methane emissions per tonne of waste for different waste fractions, with options to include or discount the sequestering of carbon in lignin. If the amounts of the individual components are not known, then the calculation could use the compositions for residual MSW and C&IW presented in Table 11. This leads to the figures in Table 17.

Table 17: Recommended emission factors for landfill (in kg methane per tonne of waste)

Material	MELMod default	Without extra sequestration		Residual MSW	Residual C&IW
Paper	41.2	53.5		12.1%	15.5%
Card	38.8	50.3		7.1%	15.5%
Plastic Film				7.9%	10.1%
Dense Plastic				7.8%	8.0%
Textiles	17.1	17.1		7.1%	1.8%
Metals				3.3%	4.2%
Wood	32.0	52.3		2.9%	
Glass				2.7%	2.3%
Food	24.3	25.9		27.5%	27.4%
Garden	22.3	30.1		3.6%	
Combustible	28.2	28.2		7.1%	9.5%
Non combustible				3.8%	1.6%
Sanitary	11.0	11.0		3.5%	
Fines	16.2	16.2		2.1%	2.6%
WEEE				1.3%	0.8%
Hazardous				0.3%	0.5%
Residual MSW	**20.1**	**23.7**			
Residual C&IW	**22.5**	**26.6**			

Table 18: Summary of landfill methodologies

Method	Description	Source
ADEME	Tier 2 type model, based on captured landfill gas. The CH_4 production uses the same formula as the IPCC landfill model: $P_{CH4} = \sum_{i=1}^{n} FE_0 * (\sum A_i * p_i * k_i * e^{-k(t-x)})$ $FE_0 = 0.934 * C_0 * (0.014 * T + 0,28)$ …where: FE_0: Potential of CH_4 emissions by a tonne of waste corresponding to its total degradation C_o: Organic carbon, biodegradable T: Degradation temperature, T=30ºC A_i: standardisation factor ensuring that the sum of discrete values on each year can match the potentially emitted CH_4 from waste for the complete degradation, $A_i = (1-e^{-k})/k$ p_i: fraction of waste having a degradation constant of k_i k_i: degradation constant; x: year of waste landfilling; t: year of emissions inventory	ADEME, (2003). Outil de calcul des émissions dans l'air de CH_4, CO_2, SOx , NOx issues des centres de stockage de déchets ménagers et assimilés. (https://www.fnade.org/ressources/_pdf/1/331,Annexe-2-du-guide-methodologique-rel.pdf)
IPCC	"The IPCC Guidelines do not provide default values or methods for the estimation of some key parameters needed to use the FOD method. These data are very dependent on country-specific conditions, and currently there are not enough data available to give reliable default values or methods for them. Inventory agencies are encouraged to obtain data from country-specific or regional research, because the inability of inventory agencies to use the FOD method where otherwise indicated by good practice would reduce comparability between national inventories. Inventory agencies selecting a method other than those described in the IPCC Guidelines should justify their selection based on comparable or increased accuracy and completeness of the emissions estimates[24]."	IPCC Chapter 5 Waste (https://www.ipcc-nggip.iges.or.jp/public/gp/english/5_Waste.pdf)
Eco-invent	Contains direct air emissions from leachate treatment for the first 100 years and the release or incineration of landfill biogas. The process is based on technology encountered in Switzerland in 2000.	Doka, G., 2003. Life cycle inventories of waste treatment services. Final report ecoinvent, (13)
NAEI	The UK approach to calculating emissions of methane from landfills uses IPCC "Tier 2" methodology based on national data on waste quantities, composition, properties and disposal practices over several decades.	UK GHGI, 1990 to 2018 Annual Report for Submission under the UNFCCC[25].

[24] IPCC Chapter 5 Waste, (https://www.ipcc-nggip.iges.or.jp/public/gp/english/5_Waste.pdf)
[25] See https://naei.beis.gov.uk/reports/reports?report_id=998

8 Scope 1 Dismantling of Refrigerators Emission Factors

Scope 1 emissions also arise from the dismantling of refrigerators and the associated loss of HFC refrigerant. Waste management companies that already have protocols in place to estimate these emissions should continue to use them, but it was also necessary to estimate the scale of emissions that might be anticipated in the UK overall. To arrive at such an estimation, Ricardo made reference to published data, IPCC guidance and a couple of internal estimations.

Firstly, from data published on UK WEEE arisings[26], it was determined that, of the ~500kt of household WEEE arising in 2019, 135kt (27%) was 'cooling appliances containing refrigerants'. For non-household waste, the figures were 3,300kt out of 8,900kt, or 37%.

From IPCC Guidance on refrigerant emissions[27], we estimated that a typical domestic fridge loses 0.07kg of HFC that are not recovered, at its end of life. For a commercial A/C unit, the equivalent figure was 12kg of HFC.

The final data required was an estimation of the typical weights of refrigerant-containing equipment for households (fridges, 135kg) and commerce (A/C units, 125kg).

Combining these figures, we concluded that (135,000 x 0.07 / 135 =) 71t of HFC were emitted from household WEEE, and 321t from commercial WEEE. Together, these amount to 392t from 505kt of WEEE, or 0.78kg per tonne of WEEE.

9 Scope 3 Avoided Emissions

9.1 Materials

The emission factors for scope 3 associated with avoided emissions as a result of materials diversion activities were retrieved from the Scottish Carbon Metric Factors[28] for 2018, which measures the whole-life carbon impacts, from resource extraction and manufacturing emissions to waste management emissions. It includes emissions generated through the extraction of the raw material, its manufacture into product, its transportation and distribution and its waste recovery/disposal method. It excludes product specification, product-based biogenic carbon (that is released through plant degradation), forming, filling and packing. It is assumed that recyclate is 'closed loop' recycled (recycled back into the same product) unless otherwise stated. The emissions generated from the recycling process and transport of recyclate are included in the carbon factor. The benefits of avoided landfill are considered through the reduction in tonnages sent to landfill and are not directly included in the recycling carbon factors as this would be double counting. The method followed for composting (open windrow or in-vessel) is not specified.

Table 19: Avoided emissions

Recycling	Emission Factor (kg CO_2e/tonne)
Batteries and accumulators wastes - hhld	-579
Batteries and accumulators wastes - non-hhld	-1,436
Combustion wastes	-4
Discarded equipment (excluding discarded vehicles, batteries and accumulators wastes)	-181

[26] https://www.gov.uk/government/statistical-data-sets/waste-electrical-and-electronic-equipment-weee-in-the-uk
[27] https://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/3_Volume3/V3_7_Ch7_ODS_Substitutes.pdf
[28] https://zerowastescotland.org.uk/our-work/carbon-metric-publications

	Emission Factor (kg CO_2e/tonne)
Discarded vehicles	-1,623
Glass	-755
Household and similar wastes - hhld	-653
Household and similar wastes - non-hhld	-599
Industrial effluent sludges	159
Mineral waste from construction and demolition - non-hhld	-76
Mixed and undifferentiated materials	-1,212
Rubber wastes	-514
Sorting residues	-924
Spent solvents	-1,286
Textile wastes	-5828
Used oils	-725
Wood wastes - hhld	-288
Wood wastes - non-hhld	-337
Paper	-547
Cardboard	-547
Steel	-1,771
Aluminium	-9,964
Mixed metals - hhld	-2,540
Mixed metals - non-hhld	-2,201
Mixed plastics - hhld	-537
Mixed plastics - non-hhld	-997
Composting	
Animal and mixed food waste	-18
Vegetal wastes	-51

9.2 Energy (Electricity and Heat)

Waste that is used to create electricity and/or heat (in, for example, anaerobic digestion and energy from waste plants and landfills) offsets the need for alternative methods of producing such energy, and therefore qualifying for avoided emissions credits. In determining how large a credit to award, the calculations need to take into account what would otherwise have be used to create the energy. This leads to the concept of marginal energy.

If a new AD plant comes online and starts exporting electricity to the National Grid (and assuming for this hypothesis that demand stays constant), one or more alternative sources of electricity need to be "turned down" by the same amount. In reality, baseload generators such as nuclear power stations run continuously at their set levels and would not be changed to accommodate such changes in supply. Likewise, the UK government is committed to maximising its' utilisation of renewable energy, so it is unlikely that solar PV or wind farms would be turned down. This leaves gas stations and imports as the most likely generators to be reduced. Whatever the precise combination, this is referred to as the marginal energy mix.

In a previous study conducted by Ricardo in 2015, we created a long range forecast for marginal energy carbon intensity by adopting some assumptions made by DECC, and presented in Table 20. We recommend that this approach be revisited and, if necessary, updated, in order to create a new long-range forecast for marginal UK grid electricity.

Table 20: Possible estimation methodology for marginal electricity emissions factor

Period	Marginal Emissions Factor
2010	CCGT
2011–2029	Mix of technologies, found via exponential interpolation between 2010 and 2029
2030	Modelled marginal emission factor (through the Dynamic Dispatch Model (DDM), based on a series of demand reduction scenarios)
2031-2039	Constant annual percentage change between marginal emissions factor in 2030 and average emissions factor in 2040
2040-2049	Average emissions Factor
2050 onwards	Flatlined/Constant Emissions Factor

For annual calculations, it should be sufficient to use the current UK marginal EF. However, if ESA wishes to explore the relative merits of different waste technologies (for example, whether to treat all residual waste by landfill or by incineration), it would be appropriate to factor in the future decarbonisation of the UK grid, and accordingly to progressively reduce the offset EF value of any electricity generated in successive years.

Turning to heat energy, the calculations are likely to be somewhat more straightforward. Here, the avoided emission factor should be that of the alternative fuel that would otherwise be used to produce the heat. Much of the time, this will be natural gas, but particular scenarios might also offset the use of heavy fuel oil, peat or other fuels. Emission factors for all such fuels can be found via the BEIS Greenhouse Gas Reporting: Conversion Factors website[29].

[29] For 2020, see https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2020