DANISH EMISSION INVENTORY FOR SOLID WASTE DISPOSAL ON LAND

Results of inventories up to 2021

Scientific Report from DCE – Danish Centre for Environment and Energy No. 569 2023

AARHUS UNIVERSITY
DCE – DANISH CENTRE FOR ENVIRONMENT AND ENERGY

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Data sheet

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Abstract:	This report forms part of the documentation for the emission inventories for solid waste disposal on land. The report includes both methodological descriptions for estimating emissions of greenhouse gases and air pollutants and presents the resulting emission data as reported to the United Nations Framework Convention on Climate Change and the United Nations Economic Commission for Europe Convention on Long-Range Transboundary Air Pollution. The results of inventories up to 2021 are included.
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List of abbreviations

ADS	Affalds Data System (Waste Data System)
As	Arsenic
BC	Black Carbon
Cd	Cadmium
CH_4	Methane
CLRTAP	Convention on Long-Range Transboundary Air Pollution
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2 eqv.	CO_2 equivalents, calculated from all GHGs using GWPs
CORINAIR	CORe INventory on AIR emissions
Cr	Chromium
CRF	Common Reporting Format
Cu	Copper
DCE	Danish Centre for Environment and energy
DEA	Danish Energy Agency
DEPA	Danish Environmental Protection Agency
DOC	Degradable Organic Carbon
EF	Emission Factor
EEA	European Environment Agency
EMEP	European Monitoring and Evaluation Programme
ENVS	Department of ENVironmental Science, Aarhus University
EPA	Environmental Protection Agency
ESD	Effort Sharing Decision
EWC	European Waste Catalogue (In Danish: EAK)
FOD	First Order Decay
GDP	Gross Domestic Product
GHG	Greenhouse gas
GPW	Garden- and Park Waste
GWP	Global Warming Potential
HFCs	Hydrofluorocarbons
Hg	Mercury
IEF	Implied Emission Factor
INDC	Intended Nationally Determined Contribution
IPCC	Intergovernmental Panel on Climate Change
ISAG	InformationsSystem for Affald og Genanvendelse
LULUCF	Land Use, Land-Use Change and Forestry
MCF	Methane Correction Factor
N_2O	Nitrous oxide
NA	Not Applicable
NDC	Nationally Determined Contribution
NF_3	Nitrogen trifluoride
NFR	Nomenclature For Reporting
NH_3	Ammonia
Ni	Nickle
NMVOC	Non-Methane Volatile Organic Compounds
NO	Not Occurring
NO_x	Nitrogen Oxides
Pb	Lead
PCDD/F	Dioxins/Furans
PFCs	Perfluorocarbons
$PM_{2.5}$	Particulate Matter up to 2.5 µm in aerodynamic diameter
PM_{10}	Particulate Matter up to 10 µm in aerodynamic diameter
POPs	Persistent Organic Pollutants

QA	Quality Assurance
Se	Selenium
SF_6	Sulphur hexafluoride
SNAP	Selected Nomenclature for Air Pollution
SO_2	Sulphur dioxide
SWDS	Solid Waste Disposal Site(s)
TJ	Terajoul, 10^{12} J
TSP	Total Suspended Particles
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
Zn	Zinc

List of annexes

Annexes are available online at: https://envs.au.dk/en/research-areas/air-pollution-emissions-and-effects/air-emissions/reporting-sectors/waste (at the bottom of the page).

Preface

The Danish Centre for Environment and Energy (DCE), Aarhus University prepares the national inventories of emissions to the atmosphere and is responsible for the reporting to the UNFCCC (United Nations Framework Convention on Climate Change) and to the UNECE CLRTAP (United Nations Economic Commission for Europe Convention on Long-range Transboundary Pollutants) on an annual basis. Furthermore, the greenhouse gas emission inventory is reported to the European Union (EU's Monitoring Mechanism Regulation for greenhouse gases) and the Kyoto Protocol, while the air pollution inventory forms the basis of the reporting under the NEC directive (National Emission Ceilings Directive for certain atmospheric pollutants).

This report summarises the methods and the data used for quantification of emissions from solid waste disposal on land. Data given in this report cover the time-series until 2021. These data will form the basis for the submissions to the international bodies in 2023.

This is the first sectoral report documenting the data and methodologies used in estimating emissions from solid waste disposal on land. The report has been reviewed externally by Stefan Krüger Nielsen from the Danish Energy Agency and his comments have been addressed to the extent possible in the report.

Summary

The Danish Centre for Environment and Energy (DCE), Aarhus University prepares the national inventories of emissions to the air and carries out the reporting to the UNFCCC (United Nations Framework Convention on Climate Change) and to the UNECE CLRTAP (United Nations Economic Commission for Europe Convention on Long-range Transboundary Air Pollution) on an annual basis. Furthermore, the greenhouse gas emission inventory is reported to the EU Regulation on the Governance of the Energy Union and Climate Action, while the air pollution inventory is reported under the NEC directive (Directive on the reduction of national emissions of certain atmospheric pollutants).

Denmark has international obligations to annually estimate and report emissions to the atmosphere of a large number of pollutants. Distinct reporting obligations exist for greenhouse gases and air pollution. The Danish greenhouse gas emission inventories follow the IPCC Guidelines. While the air pollution inventories are based on the methodology outlined in the EMEP/EEA Guidebook. The national emission inventory covers six sectors as defined in the reporting formats for the UNECE CLRTAP and the UNFCCC; one of these six sectors being Waste.

Denmark is a party to two international conventions with regard to air emissions; the CLRTAP (the Geneva Convention) and the UNFCCC (the Climate Convention). Air pollutants reported under the CLRTAP are SO_2, NO_x, NMVOC, CO, NH_3, particles, heavy metals and POPs. Protocols under the Climate Convention set emission targets for the greenhouse gasses CO_2, CH_4, N_2O, and F-gasses. Only methane (CH_4), non-methane volatile organic carbon (NMVOC) and particles (TSP, PM_{10} and $PM_{2.5}$) are relevant for landfills and hence for the scope of this report. The information contained in this report only relates to Denmark, i.e. excluding Greenland and the Faroe Islands.

"Solid waste disposal on land" is a subsector in the Waste sector. The Solid waste disposal on land subsector covers emissions from the handling of waste and the degradation of organic waste at solid waste disposal sites (SWDS).

Waste management in Denmark has changed much over the last decades. In the first half of the 20th century, the landfills were more numerous, smaller and relatively primitive/uncontrolled, but up through the 20th century the landfills became more and more regulated and streamlined. The Danish waste strategies have shifted over the decades from a focus on waste as a necessary burden (deposition) to a resource for energy production (combustion) to now a resource (recycling).

With the adoption of the Environmental Protection Act in 1973, came the implementation of the first regulation on environmental approval of landfills requirements to location, design and operation in a controlled manner by the Danish Environmental Protection Agency. Since 1974, only managed waste disposal sites with bottom membranes and/or leachate collection systems have been constructed in Denmark.

The general development for solid waste at disposal sites is a result of action plans by the Danish government. Since the "Action plan for Waste and Recycling 1993-1997", a series of action plans have been developed, resulting in continuous development in the reduction of depositing of degradable waste.

This report provides detailed background information on the methodologies and references for the input data used for quantification of emissions from solid waste disposal on land. Including information on the calculation model, activity data, emission factors, and emissions for the time series 1990-2021. The emission factors are based either on national references or on international guidebooks, while activity data are country specific.

The calculation of CH_4 emissions from Danish landfills is based on a First Order Decay (FOD) model as recommended by the IPCC. Denmark is applying the model using country-specific activity data for both the current and historical waste disposed in landfills. This makes the Danish methodology equivalent to the IPCC Tier 2 methodology. The Danish FOD model includes national disposal data since 1940 in its calculations. These disposal data are allocated to twenty waste fractions consistently throughout the time series. The waste fractions include 10 inert and 10 degradable waste types; e.g. food waste, plastics, textiles, glass, etc. Each waste type is assigned a content of degradable organic content (DOC) and a half-life time ($t_{1/2}$). These are for the majority default values. The model also includes factors such as the fraction of degradable organic carbon, which decomposes (DOC_f) and the fraction of CH_4 in the generated landfill gas. These are also IPCC default values. With this information, gross CH_4 emissions are calculated using the national setup of the FOD model. The decrease in the CH_4 emission throughout the time series is much less than the general decrease in the amount of degradable waste deposited. This is due to the time involved in the processes generating the CH_4, which is reflected in the FOD model.

CH_4 collected at the landfill sites for the purpose of energy production and CH_4 oxidised in the top soil layers is subtracted from the gross CH_4 emission to arrive at the final net CH_4 emission.

In addition to the CH_4 emissions from landfills, there are also emissions of NMVOC and particulate matter. For NMVOC, the default Tier 1 value from EMEP/EEA Guidebook is applied, along with the total amount of annually deposited organic waste.

For the particle emissions, the emission factors are derived following the Tier 3 methodology from the EMEP/EEA Guidebook. This method includes default particle size multipliers for TSP, PM_{10} and $PM_{2.5}$, the average national wind speed and default moisture content. The applied activity data are the total amounts of annually deposited waste.

The total Danish greenhouse gas emission in 2021 is 46,271.2 kt CO_2 equivalents (CO_2 eqv.) including Land use, Land use change and forestry (LULUCF) and including indirect CO_2. In the same year, greenhouse gas emissions from SWDS is 15.5 kt CH_4, corresponding to 433.5 kt CO_2 equivalents or 0.9 % of total national emissions. In 1990, greenhouse gas emission from SWDS was 54.5 kt CH_4 (1.9 % of the total national CO_2 equivalent emission), corresponding to a decrease throughout the time series of 72 %.

As mentioned above, NMVOC and particles are also included in the inventory of SWDS. NMVOC emissions from SWDS in 2021 are 0.2 kt (0.2 % of the national total NMVOC emission). This is a decrease of 92 % (from 2.5 kt NMVOC) since 1985. The decrease is caused by a similar decrease in deposition of degradable waste.

While the amount of organic waste being deposited has been decreasing throughout the time series, the same development is not seen for total waste amounts. Although fractions like e.g. metal, glass and ash/slag have decreased due to increased recycling, the amounts of soil, sand & stone being deposited have increased counteracting this decrease. As a result, particle emissions from SWDSs are not much lower in 2021 than they were in 1990. The impact of the particle emissions from SWDS on national emission levels is however miniscule. The SWDS sector contribute 0.0003 % and 0.0002 % to the national total emissions of TSP and $PM_{2.5}$, respectively, in 2021 and about the same in 1990.

Sammenfatning

Nationalt Center for Miljø og Energi (DCE) på Aarhus Universitet udarbejder de nationale opgørelser for emissioner til luft og rapporterer hvert år til UNFCCC (De Forenede Nationers Rammekonvention om Klimaændringer) og til UNECE CLRTAP (De Forenede Nationers Økonomiske Kommission for Europa Konvention om Langtransporteret Grænseoverskridende Luftforurening). Derudover, rapporteres drivhusgasemissionsopgørelsen til EU's Forordning om forvaltning af energiunionen og klimaindsatsen og luftforureningsopgørelsen rapporteres under NEC-direktivet (Direktiv om nedbringelse af nationale emissioner af visse luftforurenende stoffer).

Danmark har tilsluttet sig internationale forpligtigelser til årligt at estimere og rapportere emissioner fra en lang række stoffer til atmosfæren. Der er særskilte rapporteringsforpligtelser for drivhusgasser og luftforurening. De danske drivhusgasemissionsopgørelser følger IPCC's retningslinjer. Mens luftforureningsopgørelserne er baseret på EMEP/EEA Guidebogen. Den nationale emissionsopgørelse dækker seks sektorer som defineret i rapporteringsformaterne for UNECE CLRTAP og UNFCCC; en af disse seks sektorer er affald.

Danmark er part i to internationale konventioner med hensyn til luftemissioner; CLRTAP (Genèvekonventionen) og UNFCCC (klimakonventionen). Luftforurenende stoffer rapporteret under CLRTAP er SO_2, NO_x, NMVOC, CO, NH_3, partikler, tungmetaller og POPer. Protokoller under klimakonventionen opstiller emissionsmål for drivhusgasserne CO_2, CH_4, N_2O og F-gasser. Kun metan (CH_4), ikke-metan flygtigt organisk kulstof (NMVOC) og partikler (TSP, PM_{10} og $PM_{2.5}$) er relevante for deponier og derfor inkluderet i nærværende rapport. Oplysningerne i denne rapport vedrører kun Danmark, dvs. eksklusive Grønland og Færøerne.

"Bortskaffelse af fast affald på land" er en delsektor i affaldssektoren. Delsektoren "Bortskaffelse af fast affald på land" dækker emissioner fra håndtering af affald og nedbrydning af organisk affald på deponeringsanlæg for fast affald (SWDS).

Affaldshåndteringen i Danmark har ændret sig meget gennem de sidste årtier. I første halvdel af 1900-tallet var lossepladserne større i antal, mindre og relativt primitive/ukontrollerede, men op gennem det 20. århundrede blev lossepladserne mere og mere regulerede og strømlinede. De danske affaldsstrategier er gennem årtierne skiftet fra fokus på affald som et nødvendigt onde (deponering) til en kilde til energiproduktion (forbrænding) til nu en ressource (genanvendelse).

Med vedtagelsen af miljøbeskyttelsesloven i 1973 kom implementeringen af den første forordning om miljøgodkendelse af lossepladsers overholdelse af krav til placering, udformning og drift på en kontrolleret måde af Miljøstyrelsen. Siden 1974, har der kun været opført kontrollerede affaldsdeponeringspladser med bundmembraner og/eller perkolatopsamling i Danmark.

Den generelle udvikling for mængden af deponeret affald er et resultat af handlingsplaner. Siden "Handlingsplan for affald og genanvendelse 1993-1997" er der udviklet en række handlingsplaner, der har resulteret i en løbende udvikling i reduktion af deponering af nedbrydeligt affald.

Denne rapport giver detaljeret baggrundsinformation om de anvendte beregningsmetoder og referencer for de inputdata, der anvendes til kvantificering af emissioner fra deponier. Herunder oplysninger om beregningsmodellen, aktivitetsdata, emissionsfaktorer og emissioner for tidsserien 1990-2021. Emissionsfaktorerne og værdier for parametre, der indgår i beregningen af emissioner, er enten baseret på nationale referencer eller på internationale guidebøger, mens aktivitetsdata er specifikke for Danmark.

Beregningen af CH_4-emissioner fra danske lossepladser er baseret på en første ordens henfaldsmodel (FOD) som anbefalet af IPCC. Danmark anvender modellen ved hjælp af aktivitetsdata for både det nuværende og det historiske affald, der deponeres på lossepladser i Danmark. Dette gør den danske metode til en IPCC Tier 2-metode. Den danske FOD-model inkluderer nationale deponidata siden 1940 i beregningerne. Disse deponidata er allokeret til tyve affaldsfraktioner konsekvent gennem tidsserien. Affaldsfraktionerne omfatter 10 inerte og 10 nedbrydelige affaldstyper; f.eks. madaffald, plast, tekstiler, glas osv. Hver affaldstype antages at have et indhold af nedbrydeligt organisk indhold (DOC) og en halveringstid ($t_{1/2}$). Disse er for størstedelens vedkommende internationale standardværdier. Modellen inkluderer også faktorer som fraktionen af nedbrydeligt organisk kulstof, der nedbrydes (DOC_f) og fraktionen af CH_4 i den genererede lossepladsgas; disse er også IPCC-standardværdier. Med disse oplysninger beregnes brutto CH_4-emissionerne ved hjælp af den nationale opsætning af FOD-modellen. Faldet i CH_4-emissionen gennem tidsserien er meget mindre end det generelle fald i mængden af nedbrydeligt affald, der deponeres. Dette skyldes den tid, der er involveret i de processer, der genererer CH_4, hvilket afspejles i FOD-modellen.

CH_4 opsamlet på lossepladserne med henblik på energiproduktion og CH_4 oxideret i de øverste jordlag trækkes fra brutto CH_4-emissionen for at nå frem til den endelige netto CH_4-emission.

Ud over CH_4-emissionerne fra lossepladser, er der også emissioner af NMVOC og partikler. For NMVOC, anvendes standard Tier 1-værdien fra EMEP/EEA Guidebogen sammen med den samlede mængde årligt deponeret organisk affald.

For partikelemissionerne, er emissionsfaktorerne udledt efter Tier 3-metoden fra EMEP/EEA Guidebogen. Denne metode inkluderer standard partikelstørrelsesmultiplikatorer for TSP, PM_{10} og $PM_{2.5}$, den gennemsnitlige nationale vindhastighed og standard fugtindhold. De anvendte aktivitetsdata er de samlede mængder af årligt deponeret affald.

Den samlede danske drivhusgasemission i 2021 er 46.271,2 kt CO_2-ækvivalenter inklusiv Arealanvendelse, Ændringer i Arealanvendelse og Skovbrug (LULUCF) og inklusiv indirekte CO_2. Samme år er drivhusgasemissionerne fra deponier 15,5 kt CH_4, svarende til 433,5 kt CO_2-ækvivalenter eller 0,9 % af de samlede nationale drivhusgasemissioner. I 1990, var drivhusgasemissionen fra deponier 54,5 kt CH_4 (1,9 % af den samlede nationale CO_2-ækvivalente emission), svarende til et fald i hele tidsserien på 72 %.

Som nævnt ovenfor, er NMVOC og partikler også inkluderet i opgørelsen fra deponier. NMVOC-emissioner fra deponier i 2021 er 0,2 kt (0,2 % af den nationale samlede NMVOC-emission). Dette er et fald på 92 % (fra 2,5 kt NMVOC) siden 1985. Faldet skyldes et tilsvarende fald i deponering af nedbrydeligt affald.

Mens mængden af deponeret organisk affald har været faldende gennem tidsserierne, ses samme udvikling ikke for den samlede affaldsmængde. Selvom fraktioner som f.eks. metal, glas og aske/slagge er faldet på grund af øget genanvendelse, er mængden af jord, sand og sten, der deponeres steget nok til at modvirke dette fald. Som følge heraf, er partikelemissionerne fra deponier ikke meget lavere i 2021, end de var i 1990. Partikelemissions bidrag fra deponier er dog minimalt sammenlignet med de nationale emissionsniveauer. Deponisektoren bidrager med 0,0003 % og 0,0002 % til de nationale samlede emissioner af henholdsvis TSP og $PM_{2,5}$ i 2021 og cirka det samme i 1990.

1 Introduction

Denmark has international obligations to annually estimate and report emissions to the atmosphere of a large number of pollutants. Distinct reporting obligations exist for greenhouse gases and air pollution. The national emission inventories follow internationally agreed guidelines for the format, quality and timeline of the reporting.

The Danish greenhouse gas emission inventories follow the IPCC Guidelines (IPCC, 2006). The inventories are based on the European programme for emission inventories, the CORINAIR system, which includes methodology, structure and software. The methodology is outlined in the EMEP/EEA Guidebook (EEA, 2019). The emission data are stored in a MS Access database, from where it is transferred to the reporting formats. In the national inventory, the emissions are organised in six categories, according to the reporting formats for the Convention on Long-range Transboundary Pollutants (UNECE CLRTAP) and the United Nations Framework Convention on Climate Change (UNFCCC). These categories cover emissions from Energy, Industrial Processes and Product Use (IPPU), Agriculture, Land use - Land use change and forestry (LULUCF), Waste, and Other. The Danish emission database is organized according to the Selected Nomenclature for Air Pollution (SNAP) as defined in the CORINAIR system. The emission inventories are prepared from a complete emission database based on the SNAP sectors. Aggregation to the sector codes used for both the CLRTAP in accordance with the Nomenclature for Reporting (NFR) and the UNFCCC in accordance with the Common Reporting Format (CRF) is based on a correspondence list between SNAP and NFR or CRF sectors.

Documentation reports for the National Emission Inventory 2023 are published on the homepage for The Danish Centre for Environment and Energy (DCE), Aarhus University, as are annual updated figures on emissions and emission factors: https://envs.au.dk/en/research-areas/air-pollution-emissions-and-effects/air-emissions/

Furthermore, the data reported can be found on the EIONET homepage:

UNFCCC reporting:
http://cdr.eionet.europa.eu/dk/Air_Emission_Inventories/Submission_UNFCCC/

CLRTAP reporting:
http://cdr.eionet.europa.eu/dk/un/clrtap/inventories/

EU MMR reporting:
http://cdr.eionet.europa.eu/dk/eu/mmr/art07_inventory/ghg_inventory/

1.1 International conventions and reduction targets

Denmark is a party to two international conventions with regard to air emissions; the CLRTAP (the Geneva Convention) and the UNFCCC (the Climate Convention).

CLRTAP is a framework convention and has expanded to cover eight protocols:

- EMEP Protocol, 1984 (Geneva).
- Protocol on the Reduction of Sulphur Emissions, 1985 (Helsinki).
- Protocol concerning the Control of Emissions of Nitrogen Oxides, 1988 (Sofia).
- Protocol concerning the Control of Emissions of Volatile Organic Compounds, 1991 (Geneva).
- Protocol on Further Reduction of Sulphur Emissions, 1994 (Oslo).
- Protocol on Heavy Metals, 1998 (Aarhus) and its 2012 amended version.
- Protocol on Persistent Organic Pollutants (POPs), 1998 (Aarhus) and its 2009 amended version.
- Protocol to Abate Acidification, Eutrophication and Ground-level Ozone, 1999 (Gothenburg) and its 2012 amended version.

The Climate Convention (UNFCCC) is a framework convention from 1992. The objective of the convention is "to achieve (…) stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". The convention does not hold obligations concerning reduction of emissions but encourage the parties to reduce the emissions of greenhouse gases to their 1990 level. An important point is that the Parties to the convention are obligated to make national inventories of anthropogenic emissions of sources and removals by sinks of greenhouse gases. Denmark has ratified the Climate Convention without territorial exceptions for Greenland and the Faroe Islands, and the national reporting to UNFCCC therefore includes the entire Kingdom of Denmark.

The information contained in this report only relates to Denmark. The Kyoto Protocol is a protocol to the Climate Convention. The Kyoto Protocol sets legally binding emission targets and timetables for the following greenhouse gases: CO_2, CH_4, N_2O, HFCs, PFCs and SF_6 (expanded to also cover NF_3 for the second commitment period (2013-2020)). The greenhouse gas emissions of the pollutants are converted to CO_2 equivalents, which can be summarised to total greenhouse gas (GHG) emissions.

Denmark (including Greenland, excluding the Faroe Islands) was a party to the Kyoto Protocol for the first commitment period and was obligated to reduce the emission of GHG in the years 2008-2012 by 8 % compared to the base year emission level (1990 for CO_2, CH_4 and N_2O and 1995 for the F-gases). EU was also a party to the Kyoto Protocol for the first commitment period with an individual reduction obligation of 8 %. The 15 EU countries (EU-15) that composed EU as a party to the Kyoto Protocol for the first commitment period have distributed this reduction obligation among themselves according to the Burden Sharing Agreement. Hereby, the countries have obligated themselves to submit emission data to the EU monitoring mechanism for CO_2 and other greenhouse gases. According to the Burden Sharing Agreement Denmark (excluding Greenland and the Faroe Islands) was obligated to reduce its GHG emission by 21 % in 2008-2012 according to the emission in the base year.

At the Doha Climate Change Conference of Parties (COP18) in 2012, an amendment to the Kyoto Protocol was adopted. The Doha Amendment establishes the second commitment period of the Kyoto Protocol, covering the years 2013-2020. For the second commitment period, the EU has a target of 20 % reduction compared to the base year. The reduction commitment within the EU distinguishes between the emissions covered by the EU Emission Trading System (ETS) and the non-ETS emissions. For the ETS, there is a reduction in allowances of 24 % compared to 2005. For the non-ETS emissions, each Member State has a separate target set out in the Effort Sharing Decision (ESD, Decision No 406/2009/EC). In the ESD, Denmark has a reduction commitment of 20 % in 2020 compared to the emission level in 2005. In accordance with the Kyoto Protocol, Denmark's base year emissions include the emissions of CO_2, CH_4 and N_2O in 1990 in CO_2 equivalents and Denmark has chosen 1995 as the base year for the emissions of HFCs, PFCs and SF_6 and NF_3.

The Paris Agreement was adopted at the Paris Climate Change Conference of Parties (COP21) in 2015, establishing the new commitment period 2020-2030. The Paris Agreement entered into force on 4 November 2016. The EU submitted a provisional target under the Paris Agreement, called the Intended Nationally Determined Contribution (INDC), to reduce its greenhouse gas emissions by at least 40 % by 2030 compared to 1990. The Nationally Determined Contributions (NDCs) have to be updated or renewed every fifth year, next time in 2025. In December 2020, the EU submitted its updated and enhanced NDC of 55 % reduction by 2030 from 1990 levels. Thereby the EU and its Member States, acting jointly, are committed to a binding target of a net domestic reduction of at least 55 % in greenhouse gas emissions by 2030 compared to 1990.

To meet this international obligation, the EU has implemented regulations to ensure the compliance at Member State level. For the period 2021 to 2030, the EU established new reduction commitments for Member States in Regulation (EU) 2023/857. This regulation sets a target for Denmark of a reduction of 50 % in the non-ETS sector. For the ETS, there is a reduction in allowances of 43 % compared to 2005. A separate target exists for the land-use sector in Regulation (EU) 2023/839, where Denmark has a reduction target of 441 kt CO_2 equivalents compared to the average of 2016-2018.

1.2 Total Danish emissions

The national Danish emissions in 2021 as reported to the conventions are summarised in Table 1.1, 1.2, 1.3 and 1.4. The emissions are aggregated on sector level according to the reporting formats.

Table 1.1 GHG emission 2021 as reported to UNFCCC (Nielsen et al., 2023a).

Sector	CO_2	CH_4	N_2O	HFCs	PFCs	SF_6	NF_3	Total GHG
				kt CO_2 equivalents				
Energy	27 773	358	315					28 446
Industrial Processes and Product Use	1538	3	19	275	0	15	NO,NA	1851
Agriculture	276	7209	4590					12 074
Land Use, Land-Use Change and Forestry	2089	291	40					2420
Waste	22	1021	192					1234
Denmark Total excl. LULUCF	29 608	8591	5116	275	0	15	NO,NA	43 606
Denmark Total incl. LULUCF	31 697	8882	5156	275	0	15	NO,NA	46 026
Indirect CO_2	245							

NA: Not applicable, NO: Not occurring.

Table 1.2 Danish emissions of other air pollutants in 2021 as reported to CLRTAP (Nielsen et al., 2023b).

Sector	NO_x	NMVOC	SO_2	NH_3	$PM_{2.5}$	PM_{10}	TSP	BC	CO
					kt				
Energy	70.80	26.65	6.74	2.18	9.86	11.00	12.50	1.74	186.05
Industrial Processes and Product Use	0.07	33.09	0.95	0.41	0.75	2.77	7.11	0.01	3.67
Agriculture	18.33	46.44	0.01	67.51	1.06	8.29	64.24	0.01	1.15
Waste	0.10	0.44	0.88	0.70	0.30	0.30	0.30	0.00	1.31
Denmark Total	89.29	106.62	8.58	70.80	11.98	22.36	84.16	1.75	192.19

Table 1.3 Danish emissions of other air pollutants in 2021 as reported to CLRTAP (Nielsen et al., 2023b).

Sector	Pb	Cd	Hg	As	Cr	Cu	Ni	Se	Zn
					kt				
Energy	10.45	0.62	0.23	0.19	1.44	61.76	2.80	0.45	52.80
Industrial Processes and Product Use	1.93	0.02	0.01	0.10	0.19	2.36	0.19	0.04	2.31
Agriculture	0.002	0.015	0.002	0.0001	0.001	0.001	0.001	0.0003	0.01
Waste	2.17	0.01	0.002	0.003	0.01	0.08	0.01	0.0003	8.48
Denmark Total	14.55	0.67	0.24	0.30	1.64	64.19	3.00	0.49	63.60

Table 1.4 Danish emissions of other air pollutants in 2021 as reported to CLRTAP (Nielsen et al., 2023b).

Sector	PCDD/F	Benzo(a)-pyrene	Benzo(b)-fluoranthene	Benzo(k)-fluoranthene	Indeno-(1,2,3-cd)-pyrene	HCB	PCB
	g			t			kg
Energy	22.45	1.20	1.30	0.77	0.73	2.00	0.34
Industrial Processes and Product Use	0.22	0.03	0.03	0.02	0.02	0.01	0.06
Agriculture	0.03	0.01	0.02	0.01	0.01	0.27	0.00002
Waste	7.83	0.06	0.07	0.05	0.08	0.01	0.03
Denmark Total	30.53	1.29	1.41	0.85	0.84	2.28	0.43

The waste sector generally only has minor contributions to the total emissions, but with noticeable exceptions, e.g. for CH_4, SO_2, Pb, Zn and dioxins. However, for landfills the only relevant pollutants are CH_4, NMVOC and particulate matter. Only the emission of CH_4 is significant compared to the national total emissions.

2 Solid waste disposal in Denmark

Waste management in Denmark has changed much over the last decades. In the first half of the 20th century, the landfills were relatively primitive, but up through the 20th century the landfills became more and more regulated and streamlined. The Danish waste strategies have shifted over the decades from a focus on waste as a necessary burden (deposition) to a resource for energy production (combustion) to now a resource (recycling).

According to the Danish EPA, there are approximately 2500 old uncontrolled landfill (DEPA, 2013), typically constructed before 1973 (DEPA, 2001). With the adoption of the Environmental Protection Act in 1973 (MIM, 1985), came the implementation of the first regulation on environmental approval of landfills requirements to location, design and operation in a controlled manner by the Danish Environmental Protection Agency (DEPA, 1974). Since 1974, only managed waste disposal sites with bottom membranes and/or leachate collection systems have been constructed in Denmark (DEPA, 1974).

A recent survey of the opportunities and challenges in landfill mining in Denmark carried out by the Geological Survey of Denmark and Greenland reports a total of 4,000 waste disposal sites in Denmark corresponding to an area of 143 km^2 or 0.3 % of Danish land area (GEUS, 2020).

In 1999, the European Landfill Directive was adopted (EU, 1999) providing Member States a timeframe of 10 years to implement the rules. These were implemented in Denmark in 2001 in the form of the Executive Order on landfills (MIM, 2001). Besides setting up requirements for how the waste may be disposed of, the Deposit Order also contains requirements for providing security, which must ensure that sufficient funds are saved to cover the costs of decommissioning and post-treatment of the landfill (DEPA, 2002). As a consequence of the stricter rules for interior design, many landfills were closed by the end of the year 2000 and in the period until 2009. The closing of landfill sites in Denmark peaked around 1980, measured in number of landfills. In 2000 (i.e. the year before the implementation of MIM (2002)), a large peak in closed down deposit site capacity measured in m^2 occurs. (GEUS, 2020).

All waste deposited in Denmark is reported under the CRF source category *5.A.1 Managed waste disposal sites,* as all landfills in Denmark are managed assuming that all closed landfills have been through post-treatment and are covered by a 1 m top soil layer before 1990.

The amount of deposited organic waste has decreased markedly throughout the time series. The general development in the amount of solid waste disposed of at landfills is influenced by government instruments such as the "Action plan for Waste and Recycling 1993-1997" and "Waste 21 1998-2004" (Danish Government, 1999). The latter plan had, inter alia, the goal to recycle 64 %, incinerate 24 % and deposit 12 % of all waste. The goal for deposited waste was met in 2000. In 2003, the Danish Government set up targets for the year 2008 for waste handling in a "Waste Strategy 2005-2008" report (Danish Government, 2003). According to this strategy, the target for 2008 is a maximum of 9 % of the total waste to be deposited at landfills. In the ISAG data for the year 2003, data shows that this target was met, since 8.3 % of total waste was deposited in 2003 (ISAG). Waste Strategy 2009-2012, part I (Danish Government, 2009) was the sixth waste management plan or strategy adopted by the successive governments dating back to 1986. Waste Strategy 2009-2012 set up targets for 2012 according to which a maximum of 6 % of the total waste produced is to be deposited (The Danish Government, 2009). This target was met in 2012 as 5.7 % of all produced waste was deposited at landfills. Since 2013, the percentage of waste deposited at landfills has reached a more steady level at 3-4 % of the total waste produced in the country.

Waste Strategy 2009-2012, Part II included goals of continued decrease in the amount of waste being deposited in Denmark and an increase in reuse, recycling and recovery (Danish Government, 2010). This report includes an evaluation of the capacity of Danish solid waste disposal sites divided into waste classes: inert, mineral, mixed and hazardous waste. The same waste classes are defined in the Statutory Order for Landfill (MIM, 2011), which leads to the Statutory Order for Waste (MIM, 2012) regarding characterisation of the waste according to the EWC-system. A list of EWCs is included in Annex 2 of MIM (2012).

Initiatives to recycle more waste have previously been focusing on industrial waste and waste from the building and construction sector. Denmark without Waste I and II (Danish Government, 2013 and 2015) is a strategy, which focuses on increasing recycling in households and the service sector. The strategy sets recycling goals for households, the service sector, restaurants, WEEE (waste electrical and electronic equipment), sewage sludge and shredder waste by 2018/2022. Since the strategy focuses on waste types that for the most part are already being incinerated or recycled and not landfilled e.g. household waste, food packaging, textiles, food waste and WEEE, this strategy will have a limited effect on deposited waste as it mostly aims to increase recycling by reducing incineration. But for some fractions, e.g. shredder waste, this strategy will have an impact on landfilled (inert) waste amounts.

Action Plan for Circular Economy (Danish Government, 2021) is the Government's latest waste strategy which focuses on prevention and handling of waste. This strategy is also expected to have a limited effect on emissions from deposition, as it focuses on increasing recycling by reducing combustion of e.g. plastic. One of the focus points of the strategy that might have a reducing effect on emission from deposited waste, is reduction of waste production from construction. As unsorted waste from construction and demolition containing wood is often deposited.

Annex 1 presents all nationally produced waste since 1994, categorised according to handling method; i.e. recycled, combusted, etc.

3 Activity data

Danish emissions from solid waste disposal are calculated using the First Order Decay (FOD) model. This requires activity data for 50 years prior to the first year of reporting, i.e. back to 1940 since the CH_4 emission time series starts in 1990.

Information on deposited waste is available from the following sources:

- DEPA (1974) for 1970
- DEPA (1993) for 1985
- The ISAG database for 1994-2009
- The ADS data system from 2010 onward

Data from the four different sources are not directly comparable, e.g. because some sources contain large amounts of soil/stone while other sources omit this fraction. Detailed descriptions of the waste amounts and waste compositions available from the different sources are presented in Sections 3.1 and 3.2 below.

3.1 Waste amounts

Information on amounts of deposited waste available from the different sources are described individually in sections 3.1.1-3.1.4 and the connection of the different datasets into a time series is described in section 3.1.5.

Figure 3.1.1 presents total deposited waste amounts for the entire time series. Annual data are only available since 1994. Between 1970 and 1985 and between 1985 and 1994, the data have been interpolated. Before 1970, the data has been extrapolated, see Chapter 3.1.5 for more information.

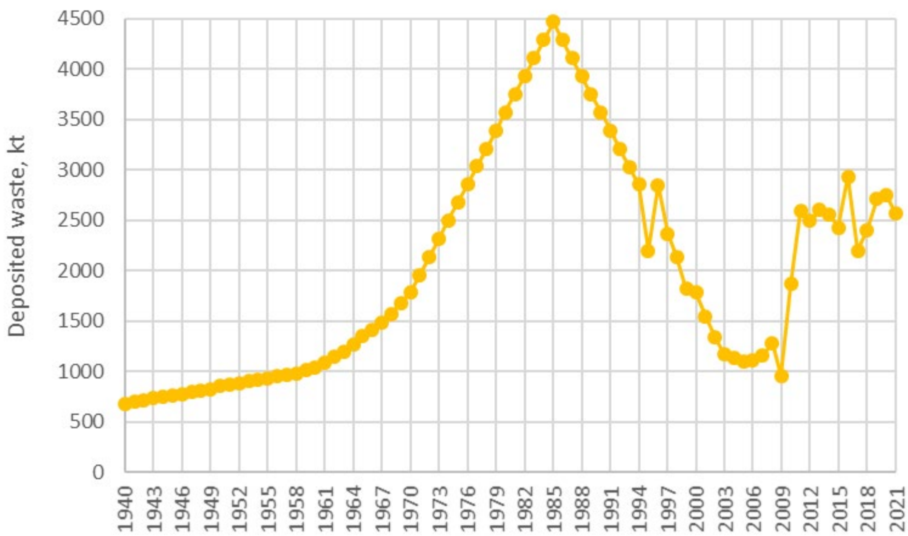

Figure 3.1.1 Deposited waste amount, kt.

A fluctuation is seen in the first years after the introduction of ISAG (1994-1996). It is likely that the shift from one data reporting system to a new (ISAG) has caused temporary problems for the users.

A sharp decline (-25%) in total deposited waste is seen from 2008-2009. The global financial crisis is expected to be the main explanation for the temporary lower amounts of waste.

The general level of deposited waste increases from 1100-1200 kt in the years 2003-2008 to 2500-2600 kt in the years 2011-2014. However, the increase is caused by in increased registration of inert waste and is not decisive for the emission trend.

3.1.1 ADS

The New Danish Waste Reporting System (ADS) is based on the EWC-system. The Danish EPA has collected waste statistics according to the EWC-system in ADS since 2010. The design of ADS is considerably different from its predecessor, the ISAG Waste Information System. ADS provides statistics of waste amounts according to the waste producer and the amount of waste according to treatment type, e.g. landfilling. Both ADS and ISAG refer to the receiver, i.e. receivers of produced waste, waste collection companies and receivers of waste for treatment, e.g. landfill operators. Statistics on treatment types are assumed to be final treatment; i.e. meaning that none of the waste is temporary landfilled (Nissen, 2017).

Detailed annual data on waste disposal were extracted from ADS by DEPA (2022) and sent to DCE. Overall deposited waste amounts are presented in Table 3.1.1. These data are later allocated to 20 different waste types using the coupled EWCs, as described in Chapter 3.2.

Table 3.1.1 Amounts of waste deposited in 2010-2021 (ADS, 2022), kt.

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Building and construction	36.9	58.1	58.7	63.6	79.8	109.9	131.9	146.9	166.8	139.5	131.8	119.0
Domestic waste	0.0	0.1	0.1	0.9	0.0	0.0	0.1	0.0	0.6	0.4	0.3	0.0
Sludge	6.2	13.2	11.7	9.3	6.6	4.1	6.0	5.3	7.3	1.8	3.7	3.7
Electronic and hazardous waste	66.8	98.6	64.2	36.0	47.0	27.3	34.6	25.3	31.5	1.7	1.5	2.5
Glass and metal	0.0	0.0	0.1	0.0	0.1	0.2	0.1	0.0	0.0	0.0	0.0	0.0
Garden and park waste	5.2	7.7	2.7	5.5	3.1	5.1	1.4	0.0	0.0	0.0	0.0	0.0
Combustible waste	2.7	12.7	9.8	1.6	0.2	0.3	0.2	3.4	0.1	0.1	0.1	0.2
Other	412.0	356.8	327.5	324.6	349.8	240.9	203.5	216.9	196.0	164.3	145.3	215.6
Soil and stone	1335	2029	1983	2133	2036	2016	2530	1778	1983	2388	2447	2213
Slag from combustion	0.0	16.4	34.8	29.1	36.4	21.4	23.7	23.5	15.6	16.7	17.8	18.3
Total	1865	2592	2493	2603	2559	2425	2931	2199	2401	2712	2748	2572

3.1.2 ISAG

Statistical waste data for 1994-2009 are available online in the ISAG database (ISAG, 2022). Data collected from the ISAG database includes both "direct sources" and "plant sources"; however, all "plant sources" are considered climate inert.

Direct Sources consists of the occupational sources: Households, Institutions, Trade and office, Manufacturing, Construction, Treatment plants and Other. While Plant Sources are defined as residual products or removal from treatment plants, consisting of the commercial sources: Incineration/energy, Reprocessing plants, Composting/Biogas plants, Sludge incineration, Landfills and Plants for special treatment.

Deposited waste amounts divided into the 13 business sources are presented in Table 3.1.2 and Annex 4.

Table 3.1.2 Amounts of waste deposited in 1994-2009 (ISAG, 2022), kt.

Source	Business Source	1994	1996	1998	2000	2002	2004	2006	2008	2009
Direct source	Other	3.5	1.7	6.6	2.1	6.8	5.9	6.2	3.8	2.7
Plant source	Facilities for special treatment	0	0	0	1.8	0.3	1.1	0.1	0.9	0.5
Direct source	Building and construction	363	328	266	269	229	172	204	177	126
Plant source	Landfill facilities	17	26	36	75	39	40	57	62	57
Plant source	Combustion/energy	116	176	128	113	27	17	11	6	13
Direct source	Manufacturing etc.	830	822	746	611	520	452	375	389	337
Direct source	Households	507	422	355	361	215	165	195	159	127
Direct source	Commercial, institutional and office	150	130	161	152	137	140	151	152	122
Plant source	Composting/biogas	15	4.4	2.2	7.4	0.7	0.6	0.4	0.8	0.9
Plant source	Reprocessing plants	73	119	104	95	68	41	41	136	99
Direct source	Sewage treatment plants	133	117	124	94	48	42	39	33	25
Direct source	Slag, fly ash etc. (coal)	643	703	210	0	38	46	31	158	40
Plant source	Sludge combustion	0	0	0	0	6.8	7.9	3.0	4.2	5.6
	Total	2851	2850	2139	1781	1336	1132	1114	1281	955

3.1.3 1985

Information on total production of waste and total deposition of waste is available from DEPA (1993) and presented in Table 3.1.3.

Slag from the combustion of waste is considered secondary waste. Secondary waste is not always included in presentations of total waste, but should be included. Although slag is inert in relation to greenhouse gas emissions, it is relevant when calculating particle emissions from waste handling.

Table 3.1.3 Amounts of waste produced and deposited in 1985 (DEPA, 1993)

	Waste production, kt	Waste deposited, kt	Deposition fraction
Domestic waste	1203	235	19%
Bulky waste	172	129	75%
Garden and park waste	549	275	50%
Commercial and office waste	506	101	20%
Industrial waste	2304	961	42%
Building and construction waste	1747	1484	85%
Waste from energy production	1531	458	30%
Sludge from wastewater treatment plants	1263	366	29%
Slag from waste combustion	455	455	100%
Total	9730	4464	46%

3.1.4 1970

Information on waste deposition in 1970 is scarce. DEPA (1974) presents the amounts of waste suitable for deposition, but not what is actually deposited. Estimated deposited waste amounts are calculated using deposition-fractions from 1985 (Table 3.1.3).

Data from DEPA (1974) does not contain soil, sand and stone, garden waste or waste from energy production. These fractions are therefore also estimated using data from 1985. The total amount of deposited waste in 1985 excluding soil, sand and stone, garden waste or waste from energy production (i.e.

matching the known total for 1970), is 2586 kt. Deposited amounts of the three excluded fractions for 1970 can be estimated by assuming they amount to the same fraction as for 1985, see Table 3.1.4.

Table 3.1.4 Estimation of deposited waste amounts for 1970.

	Unit	Total deposited[1]	Soil, sand and stone	Garden waste	Waste from energy production
1985	kt	2586	756	209[2]	458
	-		29%	8%	18%
1970	kt	1050	307	85	186

[1]excl. soil, sand and stone, garden waste, waste from energy production and slag from waste combustion.
[2]This number is only for the decomposable garden waste deposited in 1985, i.e. excluding soil, sand and stone.

Slag from waste combustion (i.e. secondary waste) is estimated separately. From DEPA (1993), it is known that slag from waste combustion amounted to 455kt in 1990, and that the activity of waste combustion started in Denmark in 1960. From this, it is assumed that slag from waste combustion in 1970 amounts to one third of the amount from 1990 thereby assuming a linear increase from 1960 to 1990.

All waste amount data for 1970 are presented in Table 3.1.5 below.

Table 3.1.5 Amounts of deposited waste in 1970, kt.

	Suitable for SWDS DEPA (1974)	Estimated deposited
Domestic waste	1500	285[1]
Commercial and office waste	<100	20[1]
Industrial waste	300	126[1]
Farming waste	<100	19[1]
Building and construction waste, excl. soil	400	340[1]
Street waste	<100	50[1]
Hospital waste, of household type	<100	19[1]
Sludge	<400	116[1]
Bulky waste	<100	75[1]
Soil, sand & stone	-	307[1]
Garden & park waste	-	85[1]
Waste from energy production	-	186[1]
Slag from waste combustion	-	152[2]
Total	<3100	1779

[1]Estimated using DEPA (1974) and DEPA (1993).
[2]Estimated using DEPA (1993).

3.1.5 1940-1969

Waste statistical data are known for 1970, 1985 and 1994-2021. For 1971-1984 and 1986-1993, data are interpolated. Data for 1940-1969 are estimated as the average between two extrapolations; based on gross domestic product (GDP) and population respectively.

Figure 3.1.2 presents estimated waste amounts deposited, calculated using GDP, population and an average of the two. The difference between the grey and yellow lines is the climate inert secondary waste that has been estimated separately for 1961 forward.

The extrapolation of data to 1940 involves much uncertainty, this has therefore been chosen as a point for the sensitivity analysis in Chapter 7.2.

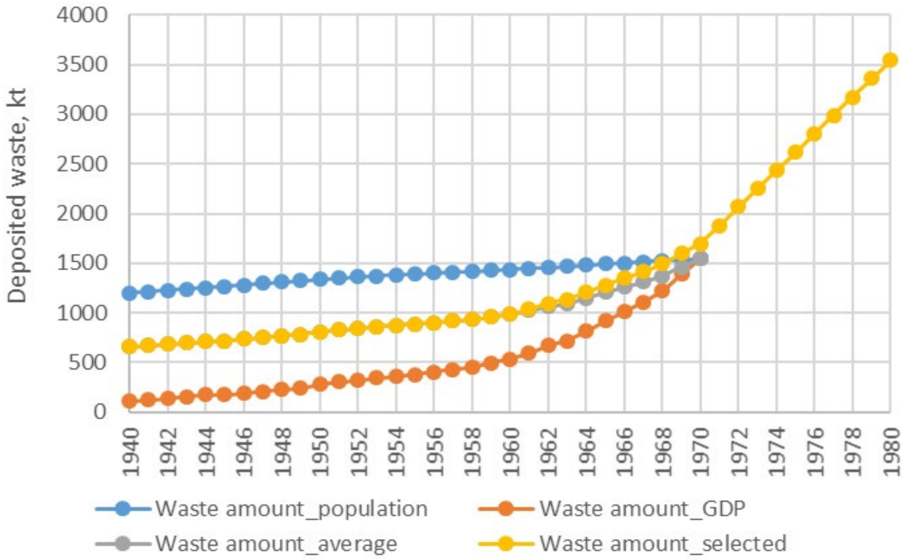

Figure 3.1.2 Deposited waste amount 1940-1980, kt.

3.2 Waste composition

Deposited waste amounts are divided between 20 waste types; 10 of which are degradable. The method for allocation of the waste amounts into waste types differs for the different sources and are described individually in Sections 3.2.1-3.2.4 below.

Figure 3.2.1 presents total deposited waste amounts divided into the individual degradable waste fractions and the total climate inert waste fraction. Data, including the individual climate inert waste fractions, are also presented in Annex 2.

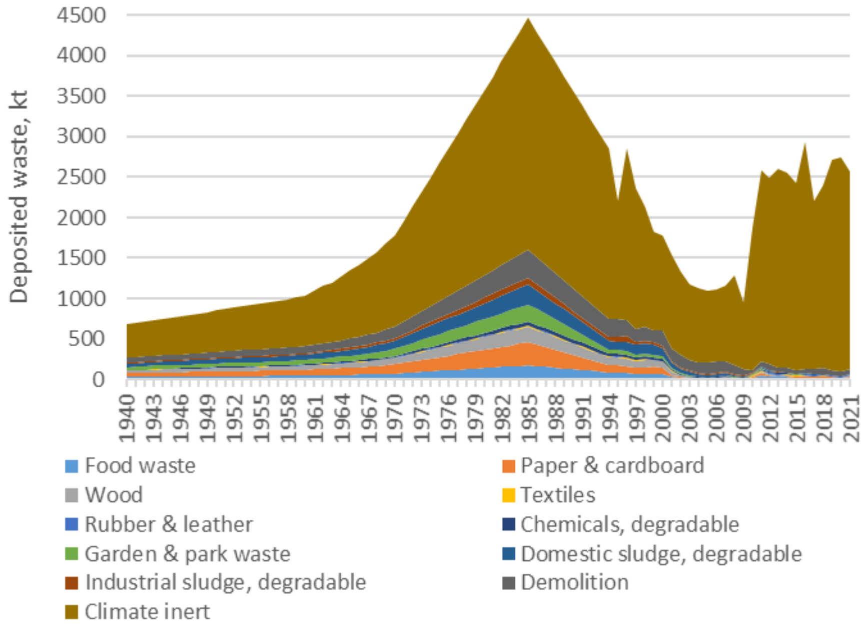

Figure 3.2.1 Deposited waste composition, kt.

A significant increase in general level of deposition of inert waste is seen from 2009 to 2010. This is caused by a difference in waste registration between the ISAG and ADS systems, where ADS registers large quantities of soil, sand and stone that were not subject to registration in ISAG. Deposited amounts of soil, sand and stone increases from an average of 201 kt in 2005-2009 (ISAG) to 1936 kt in 2010-2014 (ADS).

There are however also rises and falls in the degradable waste fractions in the transitions between datasets. From Figure 3.2.2, Annex 2 and Annex 6, it is clear that the general level of deposited food waste, paper/cardboard, wood, textiles, rubber/leather and GPW increases with the introduction of ADS data (2010), but also that the general level of deposited sludge and demolition waste decreases. The four data sources have waste fractions grouped differently and are all dominated by mixed fractions that have to be divided into the 20 DCE waste classifications. This work is bound to result in discrepancies between datasets.

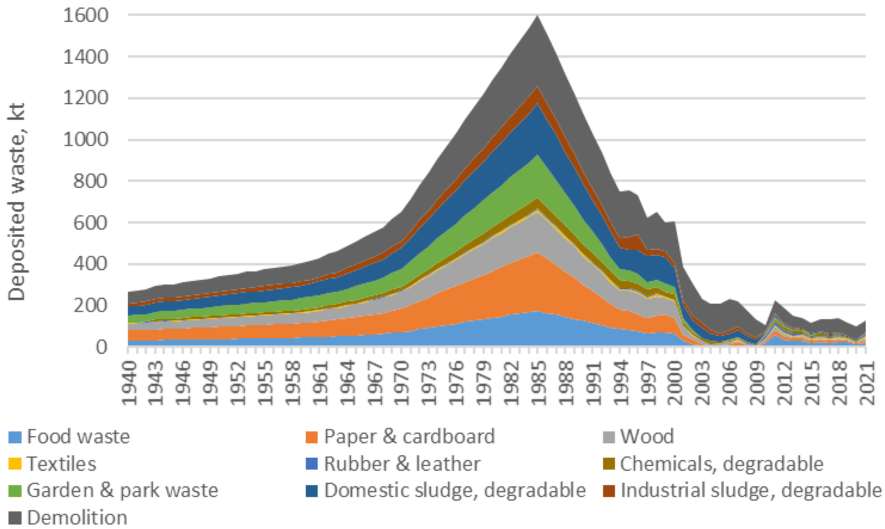

Figure 3.2.2 Deposited degradable waste composition, kt.

3.2.1 ADS

All waste registered in the ADS reporting system is assigned to an EWC. The EWC is a hierarchical list of waste types, which categorises wastes based on a combination of what it is, and the process or activity that produces it. The EWCs are divided into 20 main chapters, most of which are industry-based, although some are based on materials and processes. Each EWC consists of a six-digit code: the first two digits specify the chapter, the next two specify the subchapter, and the last two are specific to the waste type. The full list of all EWCs is available with European Commission (2015), and a list with only the EWCs relevant for Denmark is available in Annex 3.

Annex 3 also lists to which DCE waste type a given EWC is allocated. Some EWCs are divided between more than one waste type; this is reflected in the factor column. A small section of Annex 3 is presented in Table 3.2.1 below.

Table 3.2.1 Section of Annex 3, presenting the allocation of waste types to EWCs

EWC	Chapter	Subchapter	Waste type	DCE classification	Factor
01 01 01	Wastes resulting from exploration, mining, quarrying, physical and chemical treatment of minerals	Wastes from mineral excavation	Wastes from mineral metalliferous excavation	Soil, sand & stone	1
02 04 01	Wastes from agriculture, horticulture, aquaculture, forestry, hunting and fishing, food preparation and processing	Wastes from sugar processing	Soil from cleaning and washing beet	Soil, sand & stone	1
02 04 03	Wastes from agriculture, horticulture, aquaculture, forestry, hunting and fishing, food preparation and processing	Wastes from sugar processing	Sludges from on-site effluent treatment	Industrial sludge, degradable	1
02 04 99	Wastes from agriculture, horticulture, aquaculture, forestry, hunting and fishing, food preparation and processing	Wastes from sugar processing	Wastes not otherwise specified	Industrial sludge, degradable	0.5
02 04 99	Wastes from agriculture, horticulture, aquaculture, forestry, hunting and fishing, food preparation and processing	Wastes from sugar processing	Wastes not otherwise specified	Soil, sand & stone	0.5
20 03 01 & 20 03 99	Municipal wastes (household waste and similar commercial, industrial and institutional wastes) including separately collected fractions	Other municipal wastes	Municipal wastes not otherwise specified	Food waste	0.458
20 03 01 & 20 03 99	Municipal wastes (household waste and similar commercial, industrial and institutional wastes) including separately collected fractions	Other municipal wastes	Municipal wastes not otherwise specified	Electric waste	0.009
20 03 01 & 20 03 99	Municipal wastes (household waste and similar commercial, industrial and institutional wastes) including separately collected fractions	Other municipal wastes	Municipal wastes not otherwise specified	Garden & park waste	0.035
20 03 01 & 20 03 99	Municipal wastes (household waste and similar commercial, industrial and institutional wastes) including separately collected fractions	Other municipal wastes	Municipal wastes not otherwise specified	Other waste, inert	0.036
20 03 01 & 20 03 99	Municipal wastes (household waste and similar commercial, industrial and institutional wastes) including separately collected fractions	Other municipal wastes	Municipal wastes not otherwise specified	Textiles	0.022
20 03 01 & 20 03 99	Municipal wastes (household waste and similar commercial, industrial and institutional wastes) including separately collected fractions	Other municipal wastes	Municipal wastes not otherwise specified	Wood	0.057
20 03 01 & 20 03 99	Municipal wastes (household waste and similar commercial, industrial and institutional wastes) including separately collected fractions	Other municipal wastes	Municipal wastes not otherwise specified	Rubber & leather	0.057
20 03 01 & 20 03 99	Municipal wastes (household waste and similar commercial, industrial and institutional wastes) including separately collected fractions	Other municipal wastes	Municipal wastes not otherwise specified	Paper & cardboard	0.17
20 03 01 & 20 03 99	Municipal wastes (household waste and similar commercial, industrial and institutional wastes) including separately collected fractions	Other municipal wastes	Municipal wastes not otherwise specified	Plastics	0.124
20 03 01 & 20 03 99	Municipal wastes (household waste and similar commercial, industrial and institutional wastes) including separately collected fractions	Other municipal wastes	Municipal wastes not otherwise specified	Metal	0.018
20 03 01 & 20 03 99	Municipal wastes (household waste and similar commercial, industrial and institutional wastes) including separately collected fractions	Other municipal wastes	Municipal wastes not otherwise specified	Glass	0.014

The assigning of DCE classifications is done manually, one EWC at the time. This work is based on DCE judgements and causes significant uncertainty, it has therefore been chosen as a point for the sensitivity analysis presented in Chapter 7.2. EWCs are assigned to DCE classification in different ways.

1. Some are straight forward; like e.g. 01 01 01. 01 01 01 is allocated 100% to "Soil, sand and stone" as indicated with the factor 1 in Table 3.2.1.
2. Some "other"/mixed categories are split equally into more than one waste type, based on the waste types otherwise applied in the subchapter. So, when e.g. 02 04 99 is equally divided into Degradable industrial sludge and Sand, soil & stone, it is because EWCs 02 04 01 and 02 04 03 are the only EWCs otherwise used in subchapter 02 04, and these are allocated to Sand, soil & stone and Degradable industrial sludge respectively.
3. Very large quantities of waste are registered as 20 03 01 and 20 03 99. The allocation into waste types is therefore based on MST (2018) rather than applying an equal distribution. MST (2018) divides municipal waste into 11 waste fractions of 0.9% to 45.8% per fraction, see Table 3.2.1.

Data on deposited waste allocated to the 20 DCE waste categories are presented in Table 3.2.2.

Table 3.2.2 Composition of waste deposited since 2010, kt.

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Food waste	20.4	56.0	34.8	26.8	28.7	18.1	22.5	20.3	22.4	21.9	11.1	19.5
Paper & cardboard	9.1	23.6	15.2	12.4	13.5	9.3	10.7	9.2	10.4	9.3	5.2	12.8
Wood	9.0	18.4	14.6	9.8	9.2	9.4	9.7	6.9	7.4	4.6	5.2	11.0
Textiles	4.9	8.7	6.8	5.7	6.2	5.4	4.9	4.9	4.8	2.9	2.2	10.0
Rubber & leather	6.4	13.2	9.7	7.4	7.9	6.5	6.5	6.0	6.2	4.3	2.9	10.8
Chemicals, degradable	6.4	12.0	16.8	11.3	9.6	6.0	13.8	5.2	6.1	4.2	4.6	4.8
Garden & park waste	6.5	11.9	5.0	7.7	5.2	5.9	3.0	1.5	1.7	2.1	1.2	1.2
Domestic sludge, degradable	7.2	12.0	9.3	5.7	4.1	3.7	4.8	5.0	3.8	3.2	2.4	1.1
Industrial sludge, degradable	5.5	6.2	3.1	4.0	3.0	2.2	2.6	3.1	4.3	2.0	1.9	1.5
Demolition	30.2	62.8	75.6	60.1	51.1	51.2	56.2	73.9	74.3	61.2	60.6	52.1
Plastics	12.0	24.3	21.9	12.4	13.2	9.9	10.2	9.9	10.2	7.8	5.6	13.3
Glass	6.9	10.6	7.2	6.0	6.1	6.4	5.7	5.0	5.4	2.9	3.4	11.1
Chemicals, inert	2.5	4.3	3.6	1.9	1.9	3.3	2.4	1.8	2.2	1.4	1.0	2.8
Electrical waste	3.1	5.4	4.6	2.9	2.5	2.2	2.4	2.7	2.4	1.3	0.8	1.5
Metal	80.2	89.5	86.6	102.2	124.9	50.2	41.2	12.9	8.5	22.3	46.3	52.3
Sludge, inert	0.04	6.0	13.3	6.6	4.9	3.5	6.2	7.8	7.9	7.8	8.1	7.4
Particulate matter & dust	60.0	75.8	51.9	25.4	38.4	42.6	29.0	68.8	80.5	31.4	1.6	3.6
Ash & slag	5.9	23.9	21.1	36.2	48.0	33.3	29.6	30.2	25.2	20.4	18.7	19.4
Soil, sand & stone	1491	2010	1983	2147	2049	2045	2558	1812	2001	2403	2461	2233
Other waste, inert	97.9	117.8	108.7	111.7	132.5	110.5	111.7	111.8	116.4	98.7	104.0	103.6
Total	1865	2592	2493	2603	2559	2425	2931	2199	2401	2712	2748	2572

3.2.2 ISAG

All waste registered into the ISAG database is given one of 13 Business Sources (e.g. Construction, Households, etc.) and one of 44 Waste Fractions (e.g. Combustible, PVC, etc.). In addition, ISAG also categorises waste as either Direct Source or Plant Source. Plant Source waste is e.g. waste from coal-fired power plants or soil from large construction projects. Plant Source waste is considered inert but is relevant when calculating particle emissions from waste handling. Plant Source data were not previously included in the inventories but is included in this report and will be included starting from the 2023 submissions.

The allocation of waste registered in ISAG to the 20 DCE waste types is presented in Annex 4. A minor section of the allocation is also presented in Table 3.2.3 below. The allocation of registered waste to DCE classification is based on DCE judgement. This distribution clearly results in a significant uncertainty, which is why is has been chosen as a point for the sensitivity analysis in Chapter 7.2.

Table 3.2.3 Section of Annex 4, presenting the allocation of waste types to ISAG categorisation.

Source	Business Source	Waste Fraction	DCE classification	Factor
Plant Source	Reprocessing plants	Shredder waste	Metal	1
Direct Source	Building and construction	Oil- and chemical waste	Chemicals, degradable	1
Direct Source	Households	Combustible	Food waste	0.20
Direct Source	Households	Combustible	Paper & cardboard	0.20
Direct Source	Households	Combustible	Garden & park waste	0.15
Direct Source	Households	Combustible	Wood	0.10
Direct Source	Households	Combustible	Plastics	0.35
Plant Source	Combustion/energy	Slag	Ash & slag	1

3.2.3 1985

Waste data from DEPA (1993) is available on waste type for some types, while the remaining types are piled under other combustible and other not combustible. Table 3.2.4 and Table 3.2.5 present the waste composition of the combustible and non-combustible waste fractions respectively. Waste amount data are available from DEPA (1993), while the breakdown of the "other" categories are estimates.

Table 3.2.4 Waste composition of the combustible waste fraction in 1985.

	Food waste	Paper & cardboard	Plastics	Other combustible	Wood	Textiles	Rubber & leather	Garden & park waste	Domestic sludge, degradable	Industrial sludge, degradable
	kt	kt	kt	kt	% of other combustible					
Domestic waste	89	96	16	8	40%	10%	5%	-	45%	-
Bulky waste	-	40	6	59	85%	10%	5%	-	-	-
Garden and park waste	-	-	-	209	-	-	-	100%	-	-
Commercial and office waste	26	47	5	10	100%	-	-	-	-	-
Industrial waste	60	99	12	56	50%	5%	2.5%	-	-	42.5%
Building & construction waste	-	-	-	104	100%	-	-	-	-	-
Sludge from wastewater treatment plants	-	-	-	303	-	-	-	-	80%	20%

Table 3.2.5 Waste composition of the non-combustible waste fraction in 1985.

	Glass	Metal	Other not combustible	Demolition	Chemicals, inert	Chemicals, degradable	Electric waste	Sludge, inert	Particulate matter & dust	Ash & slag	Soil, sand & stone	Other waste inert
	kt	kt	kt	% of other not combustible								
Domestic waste	4	11	11									100%
Bulky waste	11	11	2				10%					90%
Garden and park waste	-	-	66								100%	
Commercial & office waste	5	5	5				10%					90%
Industrial waste	36	176	522		10%	10%	5%	15%				60%
Building & construction waste	-	-	1380	25%							50%	25%
Waste from energy production	-	-	458						10%	80%		10%
Sludge from WWTPs	-	-	63					100%				
Slag from waste combustion	-	-	455							100%		

The calculated composition of waste deposited in 1985 is presented in Table 3.2.6 below.

Table 3.2.6 Composition of waste deposited in 1985.

	Amount, kt	Fraction
Food waste	175	4.4%
Paper & cardboard	282	7.0%
Wood	195	4.9%
Textiles	10	0.2%
Rubber & leather	5	0.12%
Garden & park waste	209	5.2%
Domestic sludge, degradable	246	6.1%
Industrial sludge, degradable	84	2.1%
Demolition	345	8.6%
Plastics	39	1.0%
Glass	56	1.4%
Chemicals, inert	52	1.3%
Chemicals, degradable	52	1.3%
Electric waste	27	0.7%
Metal	203	5.1%
Sludge, inert	141	3.5%
Particulate matter & dust	46	1.1%
Ash & slag	821*	9.1%
Soil, sand & stone	756	18.8%
Other waste, inert	721	18.0%
Total	4466	100%

*Incl. Secondary waste.

The fractions presented in Table 3.2.6 are calculated without including secondary waste; i.e. the 455 kt slag from waste combustion. This is done because the general waste composition for 1985 is used to estimate the composition in 1970. Slag from waste combustion is estimated separately.

Plastic, glass and electric waste appear a little low for 1985 compared with 1994, as these three categories are the only ones to have lower amounts deposited in 1985 than 1994. However, allocating more of "other waste, inert" to plastic, glass and electric waste cannot be justified considering the uncertainty coupled to the allocation and that these waste fractions are all inert.

3.2.4 1940-1984

There is no information available on the composition of waste deposited before 1985. The composition from 1985 is therefore applied to the total amount of waste deposited in 1940-1984. Table 3.2.7 below presents the composition of waste deposited in 1970.

Table 3.2.7 Composition of waste deposited in 1970.

	Amount, kt	Fraction
Food waste	71	4.4%
Paper & cardboard	114	7.0%
Wood	79	4.9%
Textiles	3.9	0.2%
Rubber & leather	1.9	0.1%
Garden & park waste	85	5.2%
Domestic sludge, degradable	100	6.1%
Industrial sludge, degradable	34	2.1%
Demolition	140	8.6%
Plastics	16	1.0%
Glass	23	1.4%
Chemicals, inert	21	1.3%
Chemicals, degradable	21	1.3%
Electric waste	11	0.7%
Metal	82	5.1%
Sludge, inert	57	3.5%
Particulate matter & dust	19	1.1%
Ash & slag	300*	9.1%
Soil, sand & stone	307	18.8%
Other waste, inert	293	18.0%
Total	1779	100.0%

*Incl. Secondary waste; 152kt.

4 Emission model

The emission estimation model used in the Danish greenhouse gas inventory is developed in accordance with the methodological guidance provided by the IPCC (2006). The model has been developed as a relational database in MS Access, more details on the model setup is provided in Chapter 4.3.3.

4.1 Methodological guidance from the IPCC

The IPCC (2006) recommends estimating emissions using a first order decay model. This method assumes that the degradable organic carbon (DOC) in waste decays slowly depending on the material, during which CH_4 and CO_2 are formed. If conditions are constant, the rate of CH_4 production depends solely on the amount of carbon remaining in the waste and the rate of degradation. As a result, emissions of CH_4 from waste deposited in a landfill are highest in the first few years after deposition, and then gradually decline as the degradable carbon in the waste is consumed by the bacteria responsible for the decay.

This model is rather simple as it approximates the decomposition process assuming first order kinetics. In reality the processes are much more complex, but this has proven to be a good approximation and has been widely accepted (IPCC, 2006).

IPCC (2006) distinguishes between three methodological levels, so called tiers. The three methodological tiers are defined as follows:

- Tier 1: the estimation is based on the IPCC FOD method using mainly default activity data and default parameters.
- Tier 2, the estimation is based on the IPCC FOD method and some default parameters but require good quality country-specific activity data on current and historical waste disposal at SWDS. Historical waste disposal data for 10 years or more should be based on country-specific statistics, surveys or other similar sources. Data are needed on amounts disposed at the SWDS.
- Tier 3: the estimation is based on the IPCC FOD method including use of good quality country-specific activity data (see Tier 2). In addition, Tier 3 also make use of either (1) nationally developed key parameters, or (2) measurement derived country-specific parameters. The inventory compiler may use country-specific methods that are of equal or higher quality to the above defined FOD-based Tier 3 method. Key parameters should include the half-life, and either methane generation potential (Lo) or DOC content in waste and the fraction of DOC, which decomposes (DOC_f).

4.2 Key parameters used in the IPCC model

The key parameters used in the FOD model as suggested by the IPCC (2006) are the content of degradable organic carbon (DOC_i), the fraction of degradable organic carbon which decomposes (DOC_f), the methane correction factor (MCF), the fraction of CH_4 in generated landfill gas (F), the oxidation factor (OX), half-life ($t_{½}$), methane recovery (R) and delay time.

4.2.1 Degradable organic carbon (DOC)

DOC is a measure for the amount of carbon in the waste that is available for biochemical decomposition. The DOC varies for different waste materials and a number of waste fractions can be considered inert, i.e. with no degradable organic carbon. This is the case for such waste fractions as glass, metal and plastics.

4.2.2 Fraction of degradable organic carbon which decomposes (DOCf)

The DOC_f is used to take into account that some degradable carbon is actually not degraded or degrades very slowly at anaerobic conditions in the landfill. The IPCC (2006) recommends a value for DOC_f of 0.5, it is noted by the IPCC that the fraction depends on many factors like temperature, moisture, pH, composition of waste, etc.

4.2.3 Methane correction factor (MCF)

The MCF is used to account for the fact that in unmanaged landfills a part of the degradation of carbon will occur under aerobic conditions and hence will not produce CH_4. For managed anaerobic landfills, the MCF value is 1, managed semi-aerobic has a MCF of 0.5 and unmanaged landfills have MCF values of between 0.4 and 0.8 for shallow and deep landfills, respectively (IPCC, 2006).

4.2.4 Fraction of CH_4 in generated landfill gas

According to the IPCC (2006), most waste in SWDS generates a gas with approximately 50 percent CH_4. Only material including substantial amounts of fat or oil can generate gas with substantially more than 50 percent CH_4. The IPCC encourages the use of the default value for the fraction of CH_4 in landfill gas of 0.5.

4.2.5 Oxidation factor

The oxidation factor (OX) reflects the amount of CH_4 from SWDS that is oxidised in the soil or other material covering the waste (IPCC, 2006). The IPCC default value is to assume an oxidation factor of zero. However, the IPCC notes that for covered, well-managed landfills the use of an oxidation value of 0.1 can be justified. It is noted that the use of an oxidation factor higher than 0.1, should be clearly documented, referenced, and supported by data relevant to national circumstances.

The use of a biocover on landfills could increase the oxidation factor above 0.1. However, as noted this requires substantial data documenting the effect and use of such a measure.

4.2.6 Half-life

The half-life value, $t_{½}$ is the time taken for the DOCm in waste to decay to half its initial mass. In the IPCC FOD model, the reaction constant k is used. The relationship between k and $t_{½}$ is:

$$k = \ln(2)/t_{½}$$

The half-life is affected by a wide variety of factors related with the composition of the waste, climatic conditions at the site where the SWDS is located, characteristics of the SWDS, waste disposal practices, etc. (IPCC 2006).

The fastest rates of degradation is seen for rapidly degradable waste such as food waste deposited in wet climate, whereas the slowest rates are found for dry climate landfills and slowly degradable waste such as wood.

4.2.7 Methane recovery

CH_4 can be recovered from landfills and either flared or used for energy purposes, i.e. generation of electricity and heat. The IPCC (2006) has a default value of zero for CH_4 recovery and notes that CH_4 recovery should only be considered when there is documentation available. This documentation could be in the form of metering of all gas recovered for energy and flaring, or reporting of gas recovery based on the monitoring of produced amount of electricity from the gas.

4.2.8 Delay time

When waste is deposited to a landfill, the CH_4 generation does not start immediately. To account for this, the IPCC model uses a delay time with a default value of six months. It is noted by the IPCC (2006) that there is significant uncertainty associated with the time delay as it will vary based on waste composition and climatic conditions. The IPCC (2006) considers that an assumed delay time of between 0 and six months can be considered as good practice. A choice of delay time exceeding six months would require additional evidence.

4.3 The Danish first order decay model

The estimation of CH_4 emissions from Danish landfills is based on a First Order Decay (FOD) model as recommended by the IPCC (2006).

Denmark is applying the model using country-specific activity data for both the current and historical waste disposed in landfills. This makes the Danish methodology equivalent to the IPCC Tier 2 methodology (IPCC, 2006). For a description of the national activity data used in the model see Chapter 3.

According to the IPCC (2006), the FOD method requires data to be collected or estimated for historical disposals of waste over a time period of 3 to 5 half-lives in order to achieve an acceptably accurate result. The IPCC therefore consider it good practice to use disposal data for at least 50 years. As the reporting of emissions begin in 1990, this implies that the model should start in 1940, which has been chosen as the starting point for the Danish FOD model.

4.3.1 Waste types

The source for activity data varies throughout the time series as described in Chapter 3. For that reason, it is necessary to operate with waste fractions that can be applied consistently throughout the time series. The waste fraction used in the Danish model shows close alignment to the categories used by IPCC (2006) in the standard model. Table 4.3.1 below shows the waste fractions included in IPCC (2006) together with the waste fractions used in the Danish model.

Table 4.3.1 Comparison of IPCC and Danish waste fractions.

IPCC waste fractions	DCE waste fractions	Comment
Paper/cardboard	Paper & cardboard	
Textiles	Textiles	
Food waste	Food waste	
Wood	Wood	
Garden and Park waste	Garden & park waste	
-	Chemicals, degradable	Degradable chemicals are not available separately in the IPCC Guidelines
Nappies	-	Nappies are not available separately in the waste statistics
Rubber and leather	Rubber & leather	
Plastics	Plastics	
Metal	Metal	
Glass	Glass	
Other inert waste	Soil, sand & stone, Particulate matter & dust, Sludge, inert, Ash & slag, Chemicals, inert, Other waste, inert	
Sludge	Domestic sludge, degradable Industrial sludge, degradable	
Construction and demolition	Demolition	
Hazardous waste	Electrical waste	
Clinical waste	-	

4.3.2 Key parameters used in the Danish model

The Danish model used to estimate emissions from landfills are mostly using default values from the IPCC (2006). The key parameters included in the Danish model are documented and explained in the following chapters.

Degradable organic carbon (DOC)

There is no country-specific data available that would allow using national values for DOC. Therefore, the Danish model relies on the IPCC default values. As explained in Chapter 3 and Chapter 4.3.1, the activity data have been aggregated to 20 waste types. The link between the Danish waste categories used in the model and the IPCC waste categories are described in Chapter 4.3.1.

Table 4.3.2 below shows the DOC values used in the Danish model for the 20 waste fractions considered. The DOC values express the mass fraction of DOC per wet waste, so that a DOC_i value for food waste of 15 means that 15 % of wet food waste is degradable organic carbon.

Table 4.3.2 DOC values.

Waste fractions	DOC_i	Reference
Food waste	15	IPCC default, Vol. 5, Chapter 2, Table 2.4
Paper & cardboard	40	IPCC default, Vol. 5, Chapter 2, Table 2.4
Wood	43	IPCC default, Vol. 5, Chapter 2, Table 2.4
Plastics	0	Considered inert
Textiles	24	IPCC default, Vol. 5, Chapter 2, Table 2.4
Rubber & leather	39	IPCC default, Vol. 5, Chapter 2, Table 2.4
Garden & park waste	20	IPCC default, Vol. 5, Chapter 2, Table 2.4
Chemicals, degradable*	10	Pipatti (2001)**
Chemicals, inert	0	Considered inert
Electrical waste	0	Considered inert
Glass	0	Considered inert
Metal	0	Considered inert
Demolition	4	IPCC default, Vol. 5, Chapter 2, Table 2.5
Soil, sand & stone	0	Considered inert
Particulate matter & dust	0	Considered inert
Sludge, inert	0	Considered inert
Domestic sludge, degradable	5	IPCC default, Vol. 5, Chapter 2, Section 2.3.2
Industrial sludge, degradable	9	IPCC default, Vol. 5, Chapter 2, Section 2.3.2
Ash & slag	0	Considered inert
Other waste, inert	0	Considered inert

*Mainly oil and organic solutions, ** Table F-2, Oil and grease (industry).

Fraction of degradable organic carbon which decomposes (DOC_f)

There is no country-specific data available to allow for a national value for DOC_f. Therefore, the IPCC (2006) default value of 0.5 is used in the Danish model.

Methane correction factor (MCF)

All Danish landfills are considered managed and anaerobic throughout the time series. This means that a MCF of 1 is used for all years in the model calculation.

Fraction of CH_4 in generated landfill gas

As no national data are available, the IPCC (2006) default of 0.5 is used in the Danish model calculations.

Oxidation factor

As mentioned, the IPCC notes that for covered, well-managed landfills the use of an oxidation value of 0.1 can be justified.

In Denmark, all landfills have been required to cover the deposited material with soil at least since 1974 (DEPA, 1974) and by all indications even before then. Therefore, an oxidation factor of 0.1 is used in the Danish model.

Half-life

No Danish data are available that would allow for the estimation of national half-life values for specific waste fractions. Therefore, default half-life values from the IPCC (2006) are used. For a description of the link between the IPCC waste categories and the categorisation used in the Danish model, please refer to Chapter 4.3.1.

Denmark has a mean annual temperature below 20 degrees Celsius (the average was 7.7 degrees between 1961 and 1990 increasing to 8.7 for the period 1991-2020) and therefore the relevant default values for Denmark is the values for boreal and temperate climate. IPCC (2006) distinguishes between wet and dry climate using the ratio between annual precipitation and evapotranspiration as a proxy. A ratio greater than 1 is categorised as wet.

The Danish Climate Atlas (DMI, 2021 & Thejll et al., 2021) shows that the annual precipitation is higher than the potential evapotranspiration for both the reference period (1981-2010) and in the future. The ratio for the reference period is calculated to 1.24 (2.03 mm precipitation per day divided by 1.64 mm potential evapotranspiration per day). Therefore, it can be concluded that Denmark as a whole meets the criteria for wet climate. It should be noted that there are regional differences in Denmark, with the eastern part generally having a ratio close to 1, whereas the western part has a significantly higher ratio. A few municipalities were identified to have ratios below 1 mostly located in western and southern Zealand, Lolland and Falster. The municipalities with a ratio below one for the period 1981-2010 are Guldborgsund (0.99), Kalundborg (0.97), Lolland (0.96), Odsherred (0.998), Slagelse (0.97), Stevns (0.998) and Vordingborg (0.99). As the activity data do not allow the split for historical years on municipality level, it is not possible to take regional differences into account. Furthermore, the ratios are so close to 1 that it could not be justified using the half-life values for dry climate.

Table 4.3.3 Half-lives ($t_{½}$).

Waste fraction	$t_{½}$, [yr, ww]	Reference
Food waste	4	IPCC default, Vol. 5, Chapter 3, Table 3.4
Paper & cardboard	12	IPCC default, Vol. 5, Chapter 3, Table 3.4
Wood	23	IPCC default, Vol. 5, Chapter 3, Table 3.4
Plastics	NA	Considered inert
Textiles	12	IPCC default, Vol. 5, Chapter 3, Table 3.4
Rubber & leather	23	Half-life similar to that of wood
Garden & park waste	7	IPCC default, Vol. 5, Chapter 3, Table 3.4
Chemicals, degradable	7	Pipatti 2001 (k=0.1)
Chemicals, inert	NA	Considered inert
Electrical waste	NA	Considered inert
Glass	NA	Considered inert
Metal	NA	Considered inert
Demolition	23	The degradable fraction is assumed to be wood
Soil, sand & stone	NA	Considered inert
Particulate matter & dust	NA	Considered inert
Sludge, inert	NA	Considered inert
Domestic sludge, degradable	4	IPCC default, Vol. 5, Chapter 3, Table 3.4
Industrial sludge, degradable	4	IPCC default, Vol. 5, Chapter 3, Table 3.4
Ash & slag	NA	Considered inert
Other waste, inert	NA	Considered inert

Methane recovery

The Danish Energy Agency registers the biogas amounts recovered at disposal sites in energy units (TJ). The amount of gas expressed in terms of energy is converted to volume of gas using the net calorific value of 15.19 MJ per Nm^3, which has been calculated as the average of measurements from three different landfill sites (DGC, 2009; Vattenfall, 2011; Verdo, 2012). As for the FOD model, the content of CH_4 in the gas recovered is estimated to 41 % (DGC, 2009) and the density of CH_4 is calculated to 0.678 kg per m^3 at 15 degrees Celsius.

Delay time

No specific information is available on the delay time specific to Danish conditions. Therefore, the IPCC default value of six months is used in the Danish model.

4.3.3 Model setup

The Danish model to estimate emissions from landfills is a MS Access database. The database contains tables with the amount of waste distributed to waste fractions as explained in Chapter 3 as well as the necessary calculation parameters and variables explained in Chapter 4.2.

A calculation procedure has been created that calculates the emissions for all years from 1941 to the latest historic year (2021 at present) using the equations presented in Chapter 4.3.4. The database also contains queries to extract data needed for creation of tables and graphs in the annual documentation reports submitted to the EU, UNFCCC and UNECE (Nielsen et al., 2023a & 2023b).

4.3.4 Model calculations

The degradation of a deposited waste type of quantity N is modelled according to first order kinetics. The mathematical formulation of this type of exponential decay is

$$\frac{dN}{dt} = -k \cdot N \qquad \text{Eq. 4.3.1}$$

where k is the decay constant. Equation 4.3.1 can be solved for the simple case of a momentarily single deposition at time t (W_t) yielding:

$$N(t) = W_t \cdot e^{-k\,t} \qquad \text{Eq. 4.3.2}$$

where k relates to the half-life for the content of degradable organic carbon (DOC) in the bulk waste, as:

$$t_{1/2} = \frac{ln2}{k} \Rightarrow k = \frac{ln2}{t_{1/2}} \qquad \text{Eq. 4.3.3}$$

The amount of generated methane decreases exponentially over time according to first order decay kinetics of the content of degradable organic carbon in the deposited waste.

At a given year (t) the amount of degradable organic carbon (D*DOCm*(t)) which decomposes is a result of accumulated contributions from all former years deposit of waste (*W*(*x*)), where *x* is years since depositing. The residue of organic matter, i.e. decomposable DOC, left from waste deposited at landfill sites *x* years ago, is calculated using the exponential decomposition rule (Eq. 4.3.4).

$$DDOCm(t) = W_i \cdot DOC_i \cdot DOC_f \cdot MCF + DDOCm(t-1) \cdot e^{-k} \qquad \text{Eq. 4.3.4}$$

where MCF is the methane correction factor, DOC_i is the mass fraction of degradable organic carbon in the deposited waste types, DOC_f represents the fraction of the degradable organic carbon that will decompose at the SDWS.

Eq. 4.3.4 assumes that the deposition of degradable organic carbon takes place momentarily once a year and just after the time *t,* where *t* is defined as whole years (integer: *t*=1,2...), so Eq. 4.3.4 consists of two overall contributions that may be expressed as

DDOCm(t) = New deposit + Remaining part of former years deposit

The total amount of degraded organic matter during year *t* (*DDOCm decomp$_T$*) is assumed to be equal to the degradation during year t of the organic matter that was deposited at the beginning of the year (*DDOCm*(*t*-1)):

$$DDOCm\ decomp_T = DDOCm(t-1)\cdot(1-e^{-k}) \qquad \text{Eq. 4.3.5}$$

Based on Equation 4.3.4 and 4.3.5 it is possible to calculate the degraded amount of organic matter in a step wise manner based on last year result. The degraded amount of organic matter is assumed to generate the CH_4 as described by

$$CH_4\ generated_T = DDOCm\ decomp_T \cdot F \cdot 16/12 \qquad \text{Eq. 4.3.6}$$

where F is the fraction of methane in the gas from landfills and 16/12 is the conversion factor from units of C to CH_4.

For deriving the net emissions, the amount of recovered or collected methane as well as the amount of oxidised methane in the top layer of the landfill needs to be subtracted from the generated methane:

$$CH_4\ Emission = \left(\sum_x CH_4\ generated_{x,T} - R_T\right)\cdot(1-OX_T) \qquad \text{Eq. 4.3.7}$$

where *CH_4 Emissions* is the methane emitted in year *T,* in units of kt, *T* is the inventory year, *x* is the waste category or type. R_T is the amount of recovered CH_4 at the Danish disposal sites and OX_T is the assumed oxidation of CH_4 in the top layer.

The amount of CH_4 recovered, *R(t),* is calculated as:

$$R_T = \frac{B\cdot 0.41\cdot 0.678\text{kg/m}^3}{15.19\text{MJ/m}^3} \qquad \text{Eq. 4.3.8}$$

where B is the collected amount of biogas as reported by the DEA in units of MJ. The constants applied in Eq. 4.3.8 were previously described in Chapter 4.3.2 in the section on *Methane recovery*.

The content of degradable organic matter, DOC_i values, in each waste type is kept constant for the whole time series. The methane generation potential per unit waste type *i* is obtained from equation 7.2.9:

$$\frac{L_{o,i}}{W_i} = DOC_f \cdot MCF \cdot F \cdot \frac{16}{12}\cdot DOC_i = \frac{1}{3}\cdot DOC_i \qquad \text{Eq. 4.3.9}$$

The methane generation potentials for each deposited degradable waste fraction is presented in Figure 5.1.1.

4.4 Air pollutants

In addition to the CH_4 emissions from landfills, there are also emissions of certain air pollutants.

The Danish inventory includes emissions of NMVOC and particulate matter in accordance with the methodological guidance included in the EMEP/EEA air pollutant emission inventory guidebook 2019 (EEA, 2019).

For NMVOC, the default Tier 1 value of 1.56 kg per tonne organic waste is applied.

For the particle emissions, the emission factors are derived following the Tier 3 methodology (EEA, 2019) using Equation 4.4.1:

$$EF = k(0.0016)\ [U/2.2]\text{^}1.3\ /[M/2]\text{^}1.4 \qquad \text{Eq. 4.4.1}$$

where k is the particle size multiplier, U is the average Danish wind speed of 1.95 m/s based on daily measurements in the time period 2006-2017 (Annex 5) as recommended (EEA, 2019) and M is the moisture content for municipal solid waste, which were set equal to the default value of 11% (EEA, 2019). An overview of parameters and resulting emission factors, E, are provided in Table 4.4.1.

Table 4.4.1 Input parameters to Equation 4.4.1 and resulting emission factor values for TSP, PM_{10} and $PM_{2.5}$.

Parameter	Explanation, Unit	Unit	Value
*M**	Moisture content	%	11
*U***	Mean wind speed, 2006-2017	m/s	1.95
	TSP		0.74
*k**	PM_{10}		0.35
	$PM_{2.5}$		0.053
	E(TSP)	kg/kt	0.09
EF	E(PM_{10})	kg/kt	0.04
	E($PM_{2,5}$)	kg/kt	0.007

*Default values (EEA, 2019).

**Annex 5.

5 Emissions

The main pollutant from solid waste disposal sites (SWDS) is CH_4. According to IPCC (2006) there are also emissions of non-methane volatile organic compounds (NMVOCs) as well as smaller amounts of nitrous oxide (N_2O), nitrogen oxides (NO_x) and carbon monoxide (CO). No methodology is provided for N_2O emissions from SWDS because they are not significant. (IPCC, 2006).

Only emissions of CH_4, NMVOCs and particulate matter are calculated from Danish solid waste disposal sites. The results from the emission calculations are presented in Chapter 5.1 and 5.2 below.

5.1 Methane emissions

As described in Chapter 4, the emission estimation model for CH_4 assumes first order kinetics in the degradation of organic carbon. This means that the emission in any year does not depend specifically on the deposited amount of waste in that year, but is a function of the amounts and types deposited over several decades.

The annual amounts of deposited waste types (Figure 3.2.1 and Annex 2) and their emission generation potentials per mass unit (Eq. 4.3.9) are used to calculate the deposited CH_4 generation potential (Annex 6) and the actual generated CH_4 emission from the annual amount of deposited waste (Eq. 4.3.6).

Figure 5.1.1 shows the time trend in annual amounts of deposited methane generation potential for each of the deposited waste type per year. These data are also available in numbers in Annex 6.

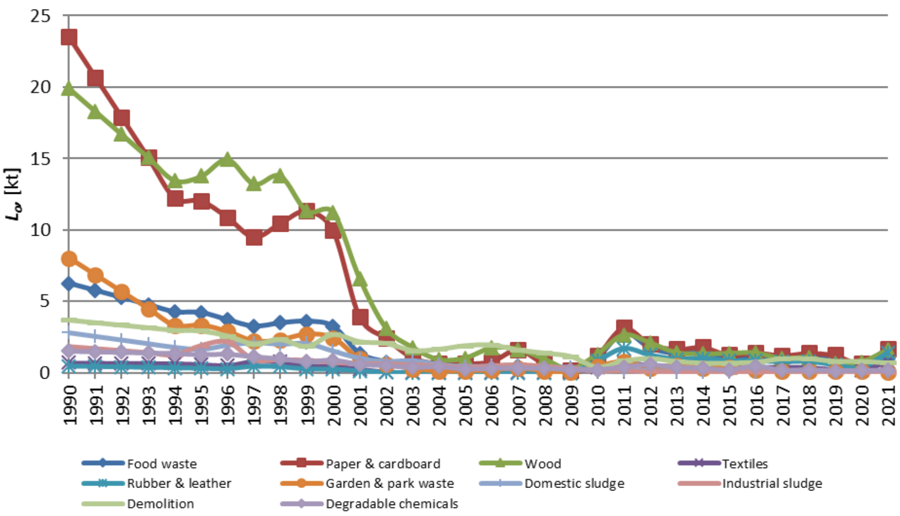

Figure 5.1.1 Annual amounts of deposited methane generation potential per waste type.

Figure 5.1.1 shows that the amounts of yearly deposited methane generation potential has decreased significantly in the period from 1990 to 2004. Only a fraction of the deposited methane generation potential is released per year, i.e. a function of the degradation rate constants of the individual waste types, the content of degradable organic carbon and according to first order degradation kinetics for each waste type (Eq. 4.3.1 to 4.3.6 and Table 4.3.2). The seemingly significant fluctuations in the yearly amounts of deposited methane generation potentials become insignificant when looking at the annual implied emission factors, calculated from the net methane emission per waste type divided by the accumulated amount of decomposable organic matter per waste type (Table 5.1.1), as illustrated in Figure 5.1.2.

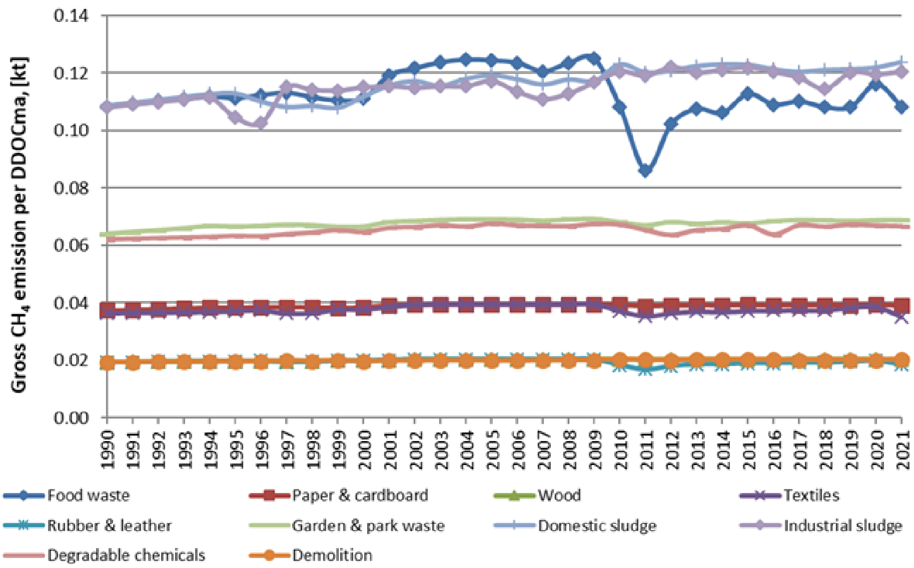

Figure 5.1.2 Annual gross implied emission factors for each waste type.

Figure 5.1.2 shows the time trend in the gross implied methane emission factor calculated as the gross methane emission divided by the accumulated (or remaining) amount of degradable organic carbon (DDOCma) within each waste type (the sums across waste types are provided in Table 5.1.1).

The year 2011 was the first year of the waste reporting system ADS. Waste amounts registered as being deposited this year increased significantly for all degradable fractions except sludge and demolition compared to ISAG data that ended in 2009. The effect of this increase on the implied emission factor is most significant for food waste, cf. Figure 5.1.3. Due to the mechanics of the FOD model, an increase in deposited degradable waste leads to an instant increase in DDOCm and DDOCma, but the methane generation only increases slightly the first year. As the level of deposited degradable waste types stabilises, so does the implied emission factor.

As may be observed from comparing Figure 5.1.2 with Figure 5.1.1, food waste and sludge has the highest gross methane emission factors but wood and paper & cardboard have the highest yearly methane generation potentials. The higher methane emission factor (Figure 5.1.2) for food waste and sludge throughout the time series may be explained by the lower half-life (high CH_4 release rate) compared to other waste types. While the higher annual amounts of deposited methane generation potential for wood and paper & cardboard is a result of the higher DOC values compared to other waste types.

The net CH_4 emission (Eq. 4.3.7) is obtained upon subtraction of the recovered CH_4, utilized for energy production at some of the sites, and the amount of oxidized methane in the SWDS top layers from the gross methane emission. The annual total amounts of deposited waste, accumulated degradable organic waste, degraded organic matter and the calculated CH_4 emissions are presented in Table 5.1.1.

Table 5.1.1 Waste deposited, total degradable matter, annual degraded organic matter and resulting CH_4 emissions. Full time series in Annex 7

	Total landfilled waste	Annual amount of degraded D*DOCm*. Eq. 7.2.5	Accumulated amount of decomposable D*DOCm* Eq. 7.2.4	Annual deposited CH_4 potential Eq. 7.2.9	Annual Gross CH_4 emission Eq. 7.2.6	Recovered methane	Annual net emission before oxidation Eq. 7.2.7	Annual net emission after oxidation	Implied Emission Factor	
	kt	kt	kt	kt CH_4	kt CH_4	kt CH_4	kt CH_4	kt CH_4	kt CH_4/ kt waste	kt CH_4/kt DDOCm
1990	3569	103.2	1644	68.8	61.1	0.5	60.6	54.5	0.02	0.03
1995	2200	63.1	1574	42.1	56.8	7.6	49.2	44.3	0.02	0.03
2000	1781	50.2	1454	33.5	50.1	11.3	38.8	34.9	0.02	0.02
2005	1095	7.5	1192	5.0	39.2	10.0	29.2	26.3	0.02	0.02
2010	1865	9.1	982	6.1	30.0	5.7	24.3	21.8	0.01	0.02
2015	2425	9.3	846	6.2	25.1	3.4	21.7	19.5	0.01	0.02
2018	2401	9.4	770	6.3	22.3	3.1	19.2	17.3	0.01	0.02
2019	2712	7.5	746	5.0	21.5	3.0	18.5	16.6	0.01	0.02
2020	2748	5.5	720	3.7	20.6	2.4	18.2	16.4	0.01	0.02
2021	2572	11.2	702	7.5	19.8	2.6	17.2	15.5	0.01	0.02

The total waste amount in the second column of Table 5.1.1 is the sum of the amounts of the 20 different waste types (Table 4.3.2).

The implied emission factors (IEFs) in the second last column in Table 5.1.1 reflects an aggregated emission factor calculated as the net methane emission divided by the total amount of waste deposited in the current year. This factor is highly affected by the amount of inert waste being reported. Therefore, a significant decrease in IEF is seen in the years 2009-2011 because of the transition from ISAG to ADS waste registration systems. As previously mentioned, ADS registers large amounts of soil, sand and stone from large building sites like e.g. bridge/tunnel construction, which was not reported under ADS. The IEF values in the last column in Table 5.1.1 represents more appropriate IEF values, i.e. calculated as the net methane emission divided by the total accumulated amount of decomposable degradable organic matter, D*DOCm*. The D*DOCm* are provided in the fourth column in Table 5.1.1.

The trend in the total amount of decomposable DOC accumulated at the Danish landfills and amount annual degraded organic matter, provided in the third and fourth column in Table 5.1.1, shows that the percent degraded decreases from 6.3 % in 1990 to 1.6 % in 2021.

Figure 5.1.3 visualises the trend in the annual deposited methane potential, the annual gross emission, the annual amount of recovered methane and the net methane emission with and without methane oxidation.

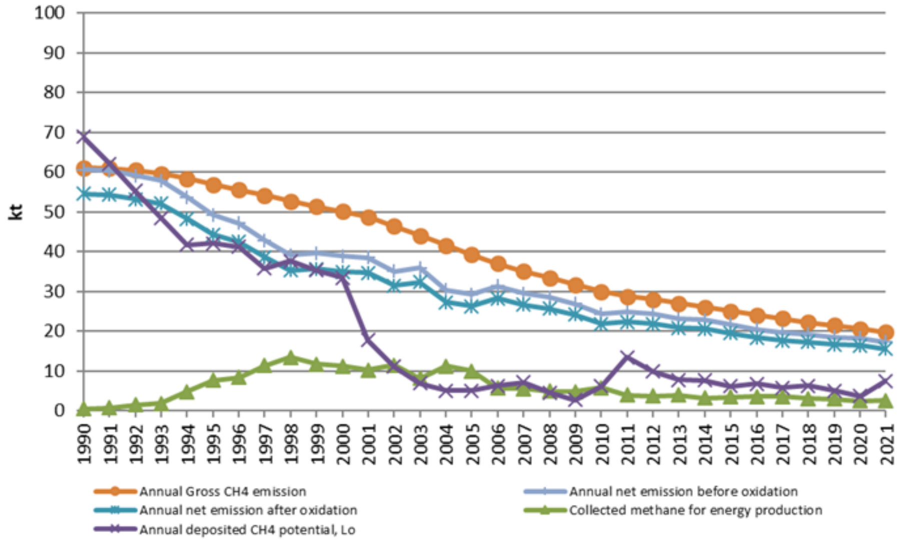

Figure 5.1.3 Time trend in the annual deposited methane potential, gross methane emission, recovered methane, annual net methane emission before and after oxidation.

In total, a reduction in the net methane emission after oxidation from 1990 to 2021 of 72 % is observed. This reduction in the methane emission is accompanied by a decrease in the accumulated amount of decomposable degradable organic matter (*DDOCma*) of 57 % and in the annual amount of deposited methane potential, which is reduced by 89 % in 2021 compared with 1990. The fluctuation in the net methane emission is explained by the fluctuations in the annual amount of deposited methane potential and the amount of recovered methane.

Figure 5.1.4 presents the timeseries of the generated methane, divided into four groups describing when the waste was deposited. Of the 19.8 kt CH_4 generated in 2021, 51 % originates from waste deposited in 1940-1989, 25 % from waste deposited in 1990-1999, 8 % from waste deposited in 2000-2009 and 16 % from waste deposited in 2010-2020. Recovered and oxidised methane are not included in these calculations.

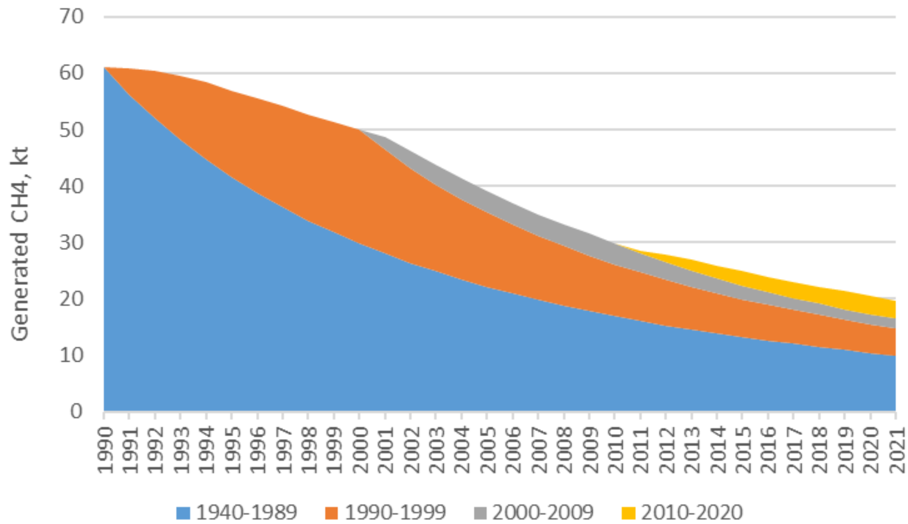

Figure 5.1.4 Time series for generated methane showing when the waste, from which the methane originates, was deposited.

5.2 Air pollutant emissions

Table 5.2.1 shows the total national emissions from waste handling at solid waste disposal sites. The full time series is shown in Annex 8.

Table 5.2.1 National emissions from waste handling at solid waste disposal sites.

	1985	1990	1995	2000	2005	2010	2015	2018	2019	2020	2021
NMVOC, kt	2.50	1.76	1.17	0.95	0.33	0.16	0.18	0.22	0.18	0.15	0.19
TSP, kg	-	321.20	197.98	160.29	98.58	167.87	218.24	216.07	244.10	247.30	231.51
PM_{10}, kg	-	142.76	87.99	71.24	43.81	74.61	97.00	96.03	108.49	109.91	102.89
$PM_{2.5}$, kg	-	24.98	15.40	12.47	7.67	13.06	16.97	16.81	18.99	19.23	18.01

The NMVOC emissions are decreasing through the time series due to the reduced amount of organic waste being deposited at Danish landfills. For particulate emissions, the emissions fluctuate with the total amount of waste landfilled, a big part of which is soil and stone that varies greatly from year to year.

6 Recalculations

6.1 Overview

Recalculations presented in this chapter relates to the difference between the 2022 and 2023 submissions to the UNFCCC, EU and to the UNECE CLRTAP.

Recalculations have occurred for the Solid waste disposal on land sector in the whole time series 1985 to 2020 due to a thorough assessment of both activity data and emission factors applied in the sector.

Table 6.1.1 presents an overview of the recalculations for a number of selected years in the time series.

Table 6.1.1 Changes in emissions from the Solid waste disposal sector.

	Unit	1990	1995	2000	2005	2010	2015	2017	2018	2019	2020
CH_4											
Previous inventory	kt	61.5	53.2	42.9	36.4	30.9	26.1	23.7	23.1	21.4	21.5
Recalculated	kt	54.5	44.3	34.9	26.3	21.8	19.5	17.7	17.3	16.6	16.4
Change	kt CO_2 eqv.	-194.4	-250.2	-223.3	-281.3	-253.2	-185.6	-169.1	-162.2	-133.2	-142.8
Change	-	-11.3%	-16.8%	-18.6%	-27.6%	-29.3%	-25.4%	-25.5%	-25.1%	-22.3%	-23.8%
NMVOC											
Previous inventory	kt	1.76	1.21	0.94	0.23	0.28	0.35	0.40	0.38	0.33	0.31
Recalculated	kt	1.76	1.17	0.95	0.33	0.16	0.18	0.21	0.22	0.18	0.15
Change	t	0.21	-35.5	10.9	95.4	-119.6	-163.6	-183.1	-163.6	-145.6	-159.3
Change	-	0.01%	-2.9%	1.2%	41.5%	-42.0%	-47.1%	-46.3%	-42.6%	-44.7%	-51.2%
$PM_{2.5}$											
Previous inventory	t	0.02	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02
Recalculated	t	0.02	0.02	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02
Change	kg	2.7	1.6	2.0	0.8	-4.4	-0.1	-0.1	-0.1	-0.1	0.2
Change	-	11.9%	11.7%	19.6%	11.4%	-25.0%	-0.5%	-0.5%	-0.3%	-0.3%	1.1%

6.2 Changes made

All aspects of the Solid waste disposal on land sector has gone through a thorough assessment. Among the changes made are:

- Extrapolation of activity data for 1940-1969 is now based on population and GDP, rather than kept constant.
- The number of waste fractions in the FOD model (DCE categories) was changed from 18 to 20. Among the new categories are "Degradable chemicals". Some categories have been divided into two new ones, this is the case for "Textile, fur & leather" that was divided into "Textiles" and "Rubber & leather" and "Sludge, degradable" that was divided into "Domestic sludge, degradable" and "Industrial sludge, degradable". The category "Scrap vehicles" was removed.
- Historical data for 1970 and 1985 were revised, resulting in increased degradable waste; +0.4 % in 1970 and +4.7 % in 1985.
- The link between waste types reported in the ISAG waste database (1994-2009) and DCE categories was revised and updated. The distribution of e.g. "combustible waste" into DCE categories is now the same in all years covered by ISAG (i.e. 1994-2009).
- The link between EWCs and DCE categories was revised and updated, resulting in changes for 2010-2020.

- Revision of several half-life times and content of degradable organic matter, e.g. the changing of DOC for degradable sludge from 15 % to 5 % and 9 % for degradable domestic sludge and degradable industrial sludge respectively.
- Updated activity data from DEPA on deposited waste for 2010-2020.
- Inclusion of the inert secondary waste from the ISAG database 1994-2009.

As mentioned above, two specific changes were made to the waste data collected from the ISAG database. The effects of these changes are elaborated in Chapter 6.2.1 below.

6.2.1 ISAG data

The recalculations made for the ISAG data (i.e. 1994-2009) are presented graphically in the following four figures.

The emission calculations include 20 waste categories, of which 10 are degradable. However, to increase the transparency of the recalculations made to the ISAG data, some of the new waste categories are stacked in the figures below for easier comparison with the previous submission. This is the case for the two new categories for degradable sludge and "Textiles"/"Rubber & leather".

The figures show (as previously mentioned) that inert waste amounts have increased while degradable waste fractions have decreased.

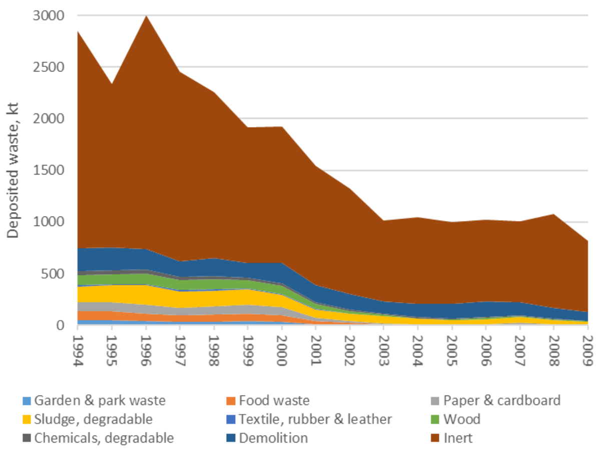

Figure 6.2.1a: New dataset from ISAG.

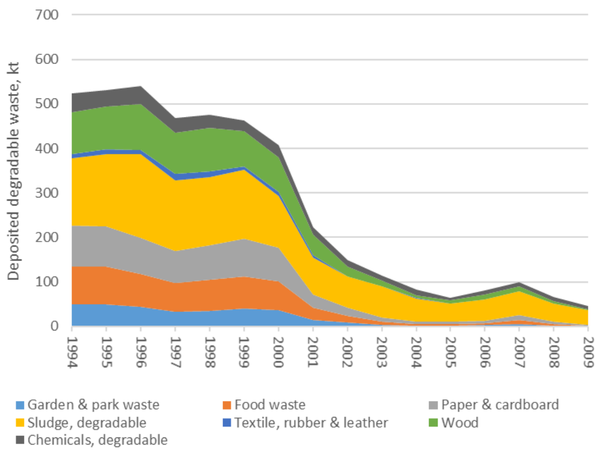

Figure 6.2.1b: New dataset from ISAG, degradable waste fractions (excl. demolition) only.

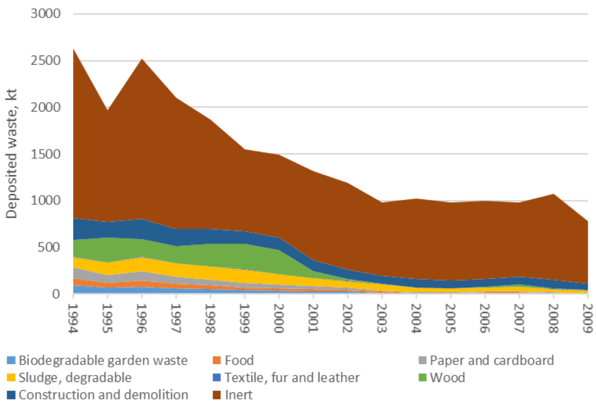

Figure 6.2.1c: Old dataset from ISAG.

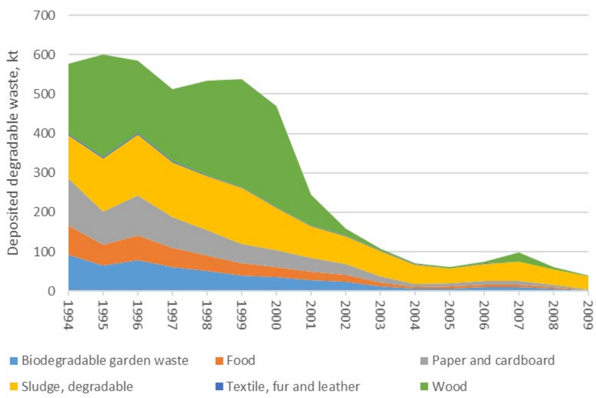

Figure 6.2.1d: Old dataset from ISAG, degradable waste fractions (excl. demolition) only.

6.3 Effects

The resulting overall methane recalculation for the sector is between -4.8 kt CH_4 (-22 %) in 2019 and -10.2 kt CH_4 (-24 %) in 2003.

There are no updates to the emission factors applied in the calculations of NMVOC and particle emissions. Recalculations for these pollutants are therefore solely caused by recalculations in the activity data; i.e. both total deposited waste and total deposited organic waste. As the activity data are updated for the entire time series, so are the NMVOC and particle emissions.

Resulting recalculations are between -183 tonnes NMVOC (in 2017) and +101 tonnes NMVOC (in 2006) for 1990-2020; i.e. -51 % to +42 %.

NMVOC emissions for 1985-1989 were not previously reported, resulting in increases of 1.9-2.5 kt NMVOC for these years.

For particle emissions, recalculations are between -4.4 kg $PM_{2.5}$ and +2.7 kg $PM_{2.5}$; i.e. -25 % to +23 %.

7 Uncertainties

7.1 Uncertainties

The uncertainty models follow the methodology in the IPCC Guidelines (IPCC, 2006). Approach 1 is based on the simplified uncertainty analysis.

7.1.1 Input data

The waste amounts for solid waste disposal are registered in a national database held by the Danish EPA and assessed to be of high quality resulting in the adoption of an uncertainty for reported waste amounts of 10 %.

FOD model input parameter uncertainties for SWDS considered in the Approach 1 uncertainty analysis are based on the IPCC (IPCC 2006, Vol. 5, Chap. 3, Table 3.5) default values and provided in Table 7.1.1.

Table 7.1.1 also lists the uncertainties for activity data and emission factors in the SWDS sub-sector at the present level of available information. The uncertainties are assumed valid for all years 1990-2021.

Table 7.1.1 Approach 1 input uncertainty rates for activity data, emission factors and model parameters.

Parameter	Parameter ID	Uncertainty, %
The waste amount sent to SWDS	*W*	10
Degradable organic carbon	DOC_i	20
Fraction of DOC dissimilated	DOC_f	20
Methane correction factor	*MCF*	10
Fraction of CH_4 in landfill gas		**5**
Methane generation rate constant	*k*	100
Non methane volatile organic carbon	NMVOC	200
Total suspended particulate matter	TSP	500
Particles, less than 10 µm	PM_{10}	500
Particles, less than 2.5 µm	$PM_{2.5}$	500

Based on the uncertain range provided in IPCC (2016, Vol. 5, Chap. 3, Table 3.4), a simple standard deviation assuming normal probability distribution of the half-live times was calculated. The standard deviation of $t_{½}$ was transformed into k-values using eq. 4.3.3, resulting in an uncertainty range for the methane generation constants, k, of -71 % to +166 %. For the Approach 1 uncertainty calculation the uncertainty of k was kept at 100 %. For the remaining parameters, default uncertainties are used. The uncertainty on the implied CH_4 emission factor, U_{ief}, is based on uncertainty estimates in Table 7.1.1 and is approximated with IPCC (2006, Vol. 3, Chap. 3, Equation 3.1) equals

$$U_{ief}\ \% = \sqrt{20^2 + 20^2 + 10^2 + 5^2 + 100^2} = 104.5\ \%$$

These uncertainties give the combined Approach 1 uncertainty on the emission from SWDS of:

$$U_{total} = \sqrt{10^2 + 104.5^2} = 105\ \%$$

In addition, the average and standard deviation of the half-life times and DOC values and remaining input parameters in Table 7.1.1 (except for the deposited amounts of waste and air pollutants) were derived from the 2006 IPCC guidelines (Chap. 3, Table 3.4 and Chap. 2, Table 2.4) assuming a normal distribution. A Monte Carlo calculation based on random selected values for each of the input parameters within defined 95 % confidence interval uncertainty ranges were run 1000 times returning resulting implied emission factor- and net CH_4 emission values for 1990 and 2017 (Nielsen et al, 2019). The resulting uncertainty of the implied emission factor is 24 % in 1990 and 26 % in 2017 indicating that the Approach 1 uncertainty of the implied emission factor is rather conservative.

7.1.2 Uncertainty results

The Approach 1 uncertainty estimates for the SWDS sub-sector are calculated from 95 % confidence interval uncertainties, results are shown in Table 7.1.2.

Table 7.1.2 Approach 1 uncertainty estimates for the SWDS sub-sector.

Pollutant	2021 emission,		2021 emission uncertainty, %	Trend* 1990-2021, %	Trend uncertainty, %
CH_4	433.5	kt CO_2 eqv.	±105.0	-71.6	±4.0
NMVOC	194.6	t	±200.2	-88.9	±1.6
TSP	0.23	t	±500.1	-27.9	±10.2
PM_{10}	0.10	t	±500.1	-27.9	±10.2
$PM_{2.5}$	0.02	t	±500.1	-27.9	±10.2

*Per cent change in emission in 2021 with respect to the base year 1990.

7.2 Sensitivity analysis

The two main assumptions/alterations introduced to the emission inventory on deposited waste in this report are:

1. The extrapolation of total waste amounts deposited in 1940-1969.
2. The allocation of “combustible waste” from the ISAG database (1994-2009) and of EWCs from the ADS database (2010-2021) to the 20 DCE waste classifications.

These two points have therefore been selected for a sensitivity analysis.

For point 1, the FOD model has been run on two scenarios, where the historical waste amounts for 1940-1969 were decreased and increased by 10 % respectively. The resulting CH_4 emission from this analysis is presented in Figure 7.2.1.

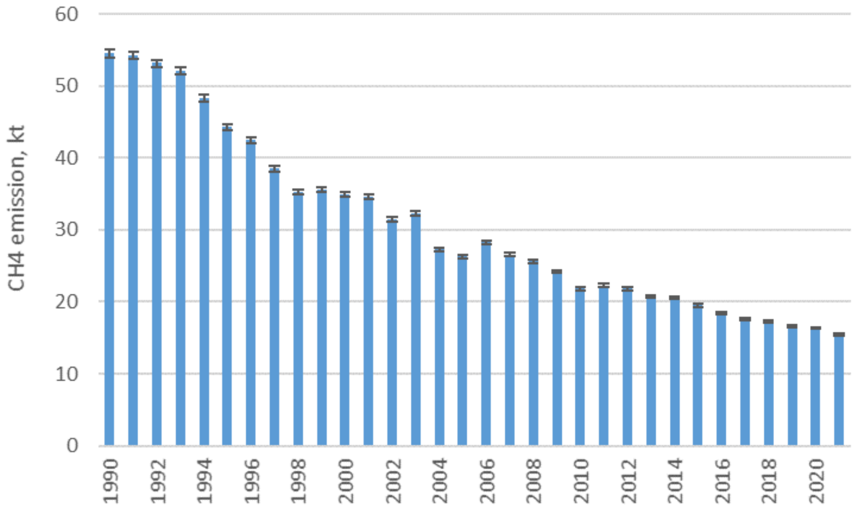

Figure 7.2.1 Methane emissions from SWDS, including the sensitivity analysis of the applied historical waste amounts for 1940-1969.

Figure 7.2.1 shows that the effect in the 1990-2021 CH_4 emission from increasing or decreasing the historical waste amounts being deposited in 1940-1969 is very limited. The effect is highest in 1990, where the calculated emission is 54.5 kt CH_4 (53.9-55.0 kt CH_4).

For point 2, both ISAG data (1994-2009) and ADS data (2010-2021) have been altered for the sensitivity analysis. For the emission inventory calculations, the ISAG data category "Other combustible" is allocated between the DCE categories food waste, paper/cardboard, wood, textiles, rubber/leather, GPW and plastics as believed to be the best estimate. For the sensitivity analysis, other combustible waste from ISAG is allocated 100 % to plastics (i.e. max inert) and 0 % to plastic (i.e. max organic) respectively.

Similarly, for the emission inventory calculations, the ADS data EWCs are allocated between the DCE categories as believed to be the best estimate. But for the sensitivity analysis, this allocation was altered in a max inert and a max organic scenario. Adjustments were only made for EWCs such as "02 01 99 Other, not otherwise specified", where waste amounts were originally divided between both inert and organic DCE waste fractions; e.g. paper/cardboard and glass. For these EWCs, allocations to DCE classifications was altered to remove all organic fractions (i.e. max inert) and remove all inert waste fractions (i.e. max organic) respectively.

The resulting CH_4 emission from this analysis is presented in Figure 7.2.2.

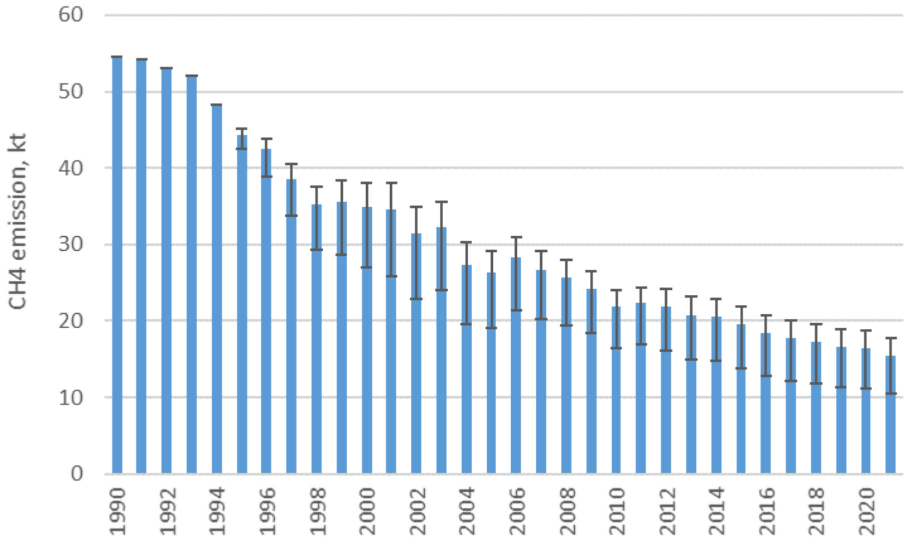

Figure 7.2.2 Methane emissions from SWDS, including the sensitivity analysis of the allocation of mixed waste types into DCE waste fractions for 2009-2021.

Figure 7.2.2 shows that the effect in the 1994-2021 CH_4 emission from increasing or decreasing the allocation of mixed waste categories to organic DCE waste fractions could have a significant impact. The effect is in absolute amount is highest in 2001, where the calculated emission is 34.6 kt CH_4 (25.9-38.1 kt CH_4).

8 Future improvements

The 2019 Refinement (IPCC, 2019) to the 2006 IPCC Guidebook (IPCC, 2006) presents improvements to the methodology that are not currently included in the Danish emission inventory for SWDS. The improvements that are potentially interesting in a Danish context are:

- Update of the fraction of degradable organic carbon which decomposes (DOC_f) from the universal IPCC (2006) default value of 0.5 to the waste type differentiated DOC_f values of 0.1-0.7 from IPCC (2019).
- IPCC (2019, V5, Ch3, page 3.12) states that average rainfall of 2-12 mm per day could reduce landfill gas production potential due to carbon washout by leachate. As mentioned in Chapter 4.3.2, Danish precipitation is measured to 2.03 mm per day. The potential effect of DOC leaching from SWDS should therefore be investigated further.
- The methodology for calculating the NMVOC emissions will be updated to one that refers to the CH_4 emission instead of the currently applied constant emission factor.

9 References

Danish Government, 1999: The Danish Government. Waste 21. Waste Management plan 1998-2004, 1999. Available at: http://www2.mst.dk/Udgiv/publications/1999/87-7909-571-2/pdf/87-7909-570-4.pdf (27/06-2022).

Danish Government, 2003: The Danish Government. Affaldsstrategi 2005-2008. Available at: http://www2.mst.dk/Udgiv/publikationer/2003/87-7972-971-1/pdf/87-7972-973-8.pdf (27/06-2022). (In Danish).

Danish Government, 2009: The Danish Government. Regeringens Affaldsstrategi 2009-2012, 1. Delstrategi, 18. marts 2009. Available at: http://mst.dk/media/mst/69997/Endelig%201%20%20del%20af%20Affaldsstrategi%202009-12.pdf (27/06-2022). (In Danish).

Danish Government, 2010: The Danish Government. Affaldsstrategi '10, 17. juni 2010. (Waste Strategy 2009-2012, Part II). Available at: https://mst.dk/media/mst/70153/Affaldsstrategi%2010.pdf (27/06-2022) (In Danish).

Danish Government, 2013: The Danish Government, Denmark without Waste, Recycle more – incinerate less, November 2013. Available at: http://mfvm.dk/fileadmin/user_upload/MFVM/Miljoe/Ressourcestrategi_UK_web.pdf (09/03-2023).

Danish Government, 2015: The Danish Government. Denmark without Waste II, A Waste Prevention Strategy, April 2015. Available at: http://eng.mst.dk/media/164923/denmark-without-waste-ii_wasteprevention.pdf (09/03-2023).

Danish Government, 2021: Handlingsplan for cirkulær økonomi. National plan for forebyggelse og håndtering af affald 2020-2032. Miljøministeriet, Juli 2021. Available at: https://mim.dk/media/224184/handlingsplan-for-cirkulaer-oekonomi.pdf (In Danish) (20/06-2023).

DEPA, 1974: Danish Environmental Protection Agency, Vejledning for kontrollerede lossepladser. Placering, indretning og drift 1974. Vejleding fra Miljøstyrelsen. Vejledning nr. 1/74. Available at: https://www2.mst.dk/Udgiv/publikationer/1974/87-503-1633-8/pdf/87-503-1633-8.pdf (11-05-2022). (In Danish).

DEPA, 1993: Danish Environmental Protection Agency, Affaldsstrømmene i Danmark. Arbejdsrapport fra Miljøstyrelsen Nr. 15 1993. Available at: https://www2.mst.dk/Udgiv/publikationer/1993/87-7909-716-2/pdf/87-7909-716-2.pdf (10/05-2022). (In Danish).

DEPA, 2001: Danish Environmental Protection Agency, Metode til risikovurdering af gasproducerende lossepladser. Miljøprojekt nr. 648 2001. Available at: https://www2.mst.dk/Udgiv/publikationer/2001/87-7944-831-3/pdf/87-7944-832-1.pdf (24-06-2022). (In Danish).

DEPA, 2002: Danish Environmental Protection Agency, Vejledning om overgangsplaner – Udarbejdelse af overgangsplaner for bestående deponeringsanlæg. Nr. 5 2002. Available at: https://www2.mst.dk/udgiv/publikationer/2002/87-7972-231-8/pdf/87-7972-231-8.pdf (24/06-2022).

DEPA, 2013: Danish Environmental Protection Agency. Notat. Klimaplan Krav om og tilskud til biocover på visse lossepladser. 4. juni 2013. Available at: https://mst.dk/media/93663/ens_krav-om-og-tilskud-til-biocover-paa-visse-lossepladser.pdf (24-06-2022). (In Danish).

DEPA, 2022: Personal communication with Maja Hornung Thorndahl, 2. December 2022.

DGC, 2009: DGC målerapport 731-28-5 November 2009. Gasmotoranlæg. Jenbacher J 316. deponigas. Steen D. Andersen. Available at:
https://www.dgc.dk/sites/default/files/filer/publikationer/Report_Site5.pdf (25-08-2022).

DMI, 2021: Danish Climate Atlas. Data available through:
https://www.dmi.dk/klima-atlas/data-og-rapporter-klimaatlas/
Excel file available:
https://www.dmi.dk/fileadmin/klimaatlas/excel/DMI_Klimaatlas_Alle_kommuner_v2021a.xlsx (25-08-2022).

EEA, 2019: EMEP/EEA air pollutant emission inventory guidebook — 2019 https://www.eea.europa.eu/publications/emep-eea-guidebook-2019 (01/03-2023).

EU, 1999: European Parliament, Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste. Available at:
https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:1999L0031:20081211:ENG:PDF (24-06-2022).

European Commission, 2015: The European Commission. Commission decision 2000/532/EC, updated version from 01/06-2015. Available at:
https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02000D0532-20150601&from=EN (26/08-2022)

GEUS, 2020: Geological Survey of Denmark and Greenland (GEUS), Muligheder og udfordringer for landfill mining i Danmark. MiMa rapport 2020/1 og 2020/2. Available at:
http://mima.geus.dk/wp-content/uploads/MiMa_rapport_2020-1-Muligheder-og-udfordringer-for-landfill-mining-i-Danmark.pdf
and
http://mima.geus.dk/wp-content/uploads/Muligheder-og-udfordringer-for-landfill-mining-i-Danmark-2020.pdf (24-06-2022). (In Danish).

IPCC, 2006: 2006 IPCC Guidelines for National Greenhouse Gas Inventories

IPCC, 2019: 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories

ISAG, 2022: Waste statistics database 1994-2009. Available at: https://mst.dk/affald-jord/affald/affaldsdatasystemet/find-affaldsdata/isag-udtraek/ (17/10-2022) (In Danish).

MIM 1985: Miljøministeriet (Ministry of Environment of Denmark). Bekendtgørelse af Lov om miljøbeskyttelse (Miljøbeskyttelsesloven), LBK nr 85 af 08/03/1985. Bekendtgørelse af lov nr. 372 af 13. juni 1973 om miljøbeskyttelse, jfr. lovbekendtgørelse nr. 663 af 16. december 1982 med de ændringer, der følger af lov nr. 250 af 23. maj 1984. Available at: https://www.retsinformation.dk/eli/lta/1985/85 (24/06-2022). (In Danish).

MIM, 2001: Miljøministeriet (Ministry of Environment of Denmark). Bekendtgørelse om deponeringsanlæg (Executive Order on landfills). BEK nr. 650 af 29/06/2001. Available at:
https://www.retsinformation.dk/eli/lta/2001/650
(24/06-2022). (In Danish).

MIM, 2011: Miljøministeriet (Ministry of Environment of Denmark). Deponeringsbekendtgørelsen (Statutory order for Landfilling). BEK nr. 719 af 24/06/2011. Available at:
https://www.retsinformation.dk/forms/R0710.aspx?id=137791
(27/06-2022). (In Danish).

MIM, 2012: Miljøministeriet (Ministry of Environment of Denmark). Affaldsbekendtgørelsen (Statutory order for Waste). BEK nr. 1309 af 18/12/2012. Available at:
https://www.retsinformation.dk/Forms/R0710.aspx?id=144826
(27/06-2022). (In Danish).

MST, 2018: Kortlægning af sammensætningen af dagrenovation og kildesorteret organisk affald fra husholdninger, 2017. Miljø- of Fødevareministeriet, Miljøstyrelsen, Undgå affald, stop spild nr. 17. Marts 2018. Available at: https://www2.mst.dk/udgiv/publikationer/2018/03/978-87-93614-78-9.pdf (15/12-2022) (In Danish).

Nielsen, O.-K., Plejdrup, M.S., Winther, M., Nielsen, M., Gyldenkærne, S., Mikkelsen, M.H., Albrektsen, R., Thomsen, M., Hjelgaard, K., Fauser, P., Bruun, H.G., Johannsen, V.K., Nord-Larsen, T., Vesterdal, L., Callesen, I., Caspersen, O.H., Scott-Bentsen, N., Rasmussen, E., Petersen, S.B., Olsen, T. M. & Hansen, M.G., 2019: Denmark's National Inventory Report 2019. Emission Inventories 1990-2017 - Submitted under the United Nations Framework Convention on Climate Change and the Kyoto Protocol. Aarhus University, DCE – Danish Centre for Environment and Energy, 886 pp. Scientific Report No. 318. Available at: http://dce2.au.dk/pub/SR318.pdf
(20/01-2023).

Nielsen, O.-K., Plejdrup, M.S., Winther, M., Nielsen, M., Gyldenkærne, S., Mikkelsen, M.H., Albrektsen, R., Hjelgaard, K., Fauser, P., Bruun, H.G., Levin, L., Callisen, L.W., Andersen, T.A., Johannsen, V.K., Nord-Larsen, T., Vesterdal, L., Stupak, I., Scott-Bentsen, N., Rasmussen, E., Petersen, S.B., Baunbæk, L., & Hansen, M.G. 2023A: Denmark's National Inventory Report 2023. Emission Inventories 1990-2021 - Submitted under the United Nations Framework Convention on Climate Change. Aarhus University, DCE – Danish Centre for Environment and Energy, 933 pp. Scientific Report No. 541. Available at: http://dce2.au.dk/pub/SR541.pdf (20/06-2023).

Nielsen, O-K., Plejdrup, M.S., Winther, M., Mikkelsen, M.H., Nielsen, M., Gyldenkærne, S., Fauser, P., Albrektsen, R., Hjelgaard, K.H. & Bruun, H.G., 2023B: Annual Danish Informative Inventory Report to UNECE. Emission inventories from the base year of the protocols to year 2021. Aarhus University, DCE – Danish Centre for Environment and Energy, 603 pp. Scientific Report No. 540. Available at:
http://dce2.au.dk/pub/SR540.pdf (20/06-2023).

Nissen, 2017: Expert judgement by Ellen Lindholt Nissen on Number of active landfills in Denmark, DEPA, personal communication, 29. September 2017.

Pipatii, 2001: Pipatti, Riitta. Greenhouse gas emissions and removels in Finland. Espoo 2001. Technical Research Center of Finland, VTT Tiedotteita – Meddelanden – Research Notes 2094. 59 p. + app. 95 p. Available at:
https://publications.vtt.fi/pdf/tiedotteet/2001/T2094.pdf (05/01-2023).

Thejll, P., Boberg, F., Schmith, T., Christiansen, B., Christensen, O. B., Madsen, M.S., Su, J., Andree, E., Olsen, S., Langen, P.L., Madsen, K.S., Pedersen, R.A. and Payne, M.R., 2021: Methods used in the Danish Climate Atlas, 2021. DMI Report 21-41. ISBN 978-87-7478-690-0.

Vattenfall, 2011: EU ETS report for Fynsværket, 2010. Confidential.

Verdo, 2012: EU ETS report for Verdo Produktion, 2011. Confidential.

DANISH EMISSION INVENTORY FOR SOLID WASTE DISPOSAL ON LAND

Results of inventories up to 2021

This report forms part of the documentation for the emission inventories for solid waste disposal on land. The report includes both methodological descriptions for estimating emissions of greenhouse gases and air pollutants and presents the resulting emission data as reported to the United Nations Framework Convention on Climate Change and the United Nations Economic Commission for Europe Convention on Long-Range Transboundary Air Pollution. The results of inventories up to 2021 are included.

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