European Commission

JRC SCIENCE FOR POLICY REPORT

Towards a better exploitation of the technical potential of waste-to-energy

Hans Saveyn, Peter Eder, Mark Ramsay, Grégoire Thonier, Kathryn Warren, Mathieu Hestin

2016





Joint Research Centre

EUR 28230 EN

Contact information
Name: Hans Saveyn
Address: European Commission, JRC, Edificio Expo, Calle Inca Garcilaso 3, E-41092 Sevilla, SPAIN
Email: Hans.Saveyn@ec.europa.eu
Tel.: +34 954 488 470

JRC Science Hub
https://ec.europa.eu/jrc

JRC104013

EUR 28230 EN

PDF ISBN 978-92-79-63778-0 ISSN 1831-9424 doi:10.2791/870953

Seville: European Commission, 2016

How to cite this report: Saveyn[1], H., Eder[1], P., Ramsay[2], M., Thonier[3], G., Warren[2], K., Hestin[3], M. (2016). Towards a better exploitation of the technical potential of waste-to-energy. EUR 28230 EN. DOI:10.2791/870953

a. European Commission, Joint Research Centre, Seville, Spain
b. Ricardo AEA Ltd., Shoreham-by-Sea, UK
c. Bio by Deloitte, Neuilly-sur-Seine, France

Title Towards a better exploitation of the technical potential of waste-to-energy

Abstract
In the EU, merely six types of wastes cover the lion's share of all the energy in waste going to incineration or landfill. They include in particular household and similar waste as well as sorting residues, which jointly account for nearly four fifths of the energy contained in all landfilled waste, and which together with wood waste comprise almost two thirds of the energy contained in all waste sent for incineration. A wider application of state-of-the-art techniques could improve the energy currently recovered from waste by more than a quarter. A better application of the waste hierarchy is expected to cause important changes in the waste-to-energy landscape in the coming years.

Abstract

The present study describes the state-of-play of incineration and other waste management options for different wastes in the EU, provides an assessment of proven and emerging techniques for increased energy recovery in waste-to-energy processes and concludes with an outlook of possible evolutions in the EU's waste-to-energy landscape.

An analysis of statistical data from Eurostat, enhanced with input from various industrial federations, revealed that just six types of wastes are responsible for the lion's share of the energy embedded in all the waste currently sent to incineration and/or landfill. They include in particular household and similar waste as well as sorting residues, which jointly account for nearly four fifths of the energy contained in all landfilled waste, and which together with wood waste comprise almost two thirds of the energy contained in all waste sent for incineration.

Techniques for improving energy recovery were discussed for each of the five main categories of waste-to-energy processes: combustion plants, waste incineration plants, cement and lime kilns, anaerobic digestion plants and others. Figures from 2013/2014 showed that the three middle categories together accounted for an estimated total annual mixed energy outputs from waste of 676 PJ. Using the technical options available today, and without taking into account any possible changes to the types and amounts of waste currently sent for energy recovery, this value could be increased by more than a quarter. However, future developments in waste generation and waste management may possibly lead to an increase in energy recovery by incineration for household and similar waste as well as for sorting residues, an increase in energy recovery by anaerobic digestion for animal and vegetal wastes and a decrease in the amounts sent for energy recovery for several other wastes, including source-separated wastes such as wood waste.

Executive Summary

Policy background and study objectives

The Energy Union strategy, launched by the European Commission in 2015, aims to bring greater energy security, sustainability and competitiveness to the European energy market. As part of the initiatives outlined in the Energy Union Package (COM (2015) 80 final), the Commission states its intention to further establish synergies between energy efficiency policies, resource efficiency policies and the circular economy. This will include providing information on the options for exploiting the potential of "waste-to-energy" in a Communication.

When waste cannot be prevented or recycled, recovering its energy content is in most cases preferable to landfilling it, in both environmental and economic terms. Waste-to-energy can therefore play a role and create synergies with EU energy and climate policy, but must always be guided by the principles of the EU waste hierarchy. The Commission will examine how this role can be optimised, without compromising the achievement of higher reuse and recycling rates, and how the corresponding energy potential can best be exploited.

The present study, initiated by the Joint Research Centre of the European Commission at the end of 2015, aims to underpin the forthcoming Communication with a detailed techno-scientific assessment of the European waste-to-energy landscape. Three main objectives constitute the core of this assessment:

1. to provide an analysis of the current use of waste for energy recovery in the EU;
2. to provide an analysis of the technical improvement potential for waste-to-energy; and
3. to provide an outlook on possible future developments in the waste-to-energy landscape.

Current use of waste for energy recovery in the EU

For the analysis of the current use of waste for energy recovery in the EU, two sub-objectives were defined:

- to analyse what waste management practices are applied across the EU for wastes featuring substantial amounts of embedded energy recoverable through incineration or other waste-to-energy processes; and
- to analyse which amounts and what forms of energy are recovered in which processes for wastes sent for energy recovery.

For the analysis related to the first sub-objective, the main focus of the study was on incineration with or without energy recovery as well as landfill/disposal. The wastes considered comprised both regular waste streams (e.g. household and similar waste) and waste-derived fuels (e.g. biogas). A screening of annual production volumes of different wastes and their embedded energy content led to a final selection of 13 waste streams and 5 waste-derived fuels, which jointly account for about 96% of the embedded energy from all wastes sent for waste-to-energy processes. Eurostat data, complemented and corrected with input from Member State authorities and European industrial federations, was used for an in-depth analysis for each type of waste. Data was used from 2006 until the latest available year (2012).

No clear evolution over time could be discerned for a number of reasons, including the effects of the 2008 economic crisis and its aftermath as well as changes to the methodology over the years, both by Eurostat and individual Member States. Moreover, the study revealed large differences between Member States in per capita generation of certain wastes, due to differences in interpretation of waste definitions, as well as issues with double counting of certain waste types, which were addressed as much as possible.

Table 1 presents a summary overview of the amounts of waste-embedded energy going to either incineration or to landfill/disposal, for 15 out of the 18 waste types for which sufficient data was available (covering 93% of the embedded energy from all wastes sent for waste-to-energy processes). Analysis of the data presented for these wastes shows that:

- 6 types of waste (highlighted in blue in the table) together contain 83% of the total energy embedded in wastes sent to incineration and 93% of the total energy embedded in wastes sent to landfill;
- 3 waste streams only - household and similar wastes (HSW), sorting residues and wood waste – account for nearly two thirds of the energy contained in waste sent for incineration;
- 2 waste streams only - household and similar wastes (HSW) and sorting residues - account for more than three quarters of the energy contained in landfilled waste.

Therefore, any changes in waste management practices for the six waste types highlighted in blue in the table, and in particular for household and similar wastes (HSW) and sorting residues, would be likely to have the largest impacts on the waste-to-energy landscape in the EU-28.

Table 1 – Amounts of waste-embedded energy sent to incineration or to landfill/disposal in 2012 in the EU-28

	Incineration (D10+R1) (PJ[3])		Landfill/disposal (D1-D7-D12) (PJ[3])	
Wood wastes	375	21%	7	0%
Plastic wastes	61	3%	51	4%
Paper and cardboard wastes	6	0%	3	0%
Textile wastes	2	0%	3	0%
Waste tyres	35	2%	2	0%
Spent solvents	29	2%	0	0%
Waste oils	32	2%	0	0%
Chemical wastes	93	5%	31	2%
Household and similar wastes (HSW)	470	26%	616	44%
Mixed and undifferentiated materials	149	8%	120	9%
Sorting residues	334	18%	489	35%
Animal and vegetal wastes[1]	70	4%	80	6%
Dried municipal sewage sludge[1]	22	1%	7	0%
Waste-derived biogas[2]	108	6%	0	0%
Waste-derived biodiesel[2]	19	1%	0	0%

	Incineration (D10+R1) (PJ[3])		Landfill/disposal (D1-D7-D12) (PJ[3])	
Total	**1,805**	**100%**	**1,409**	**100%**

1- For "Animal and vegetal wastes" and "Municipal sewage sludge", energy recovered from anaerobic digestion is taken into account within "waste-derived biogas".
2- Biogas and biodiesel are used only for energy purposes, so data for "Incineration (D10+R1) – PJ" is the same as the amount of waste-derived biofuel produced.
3- Data in PJ is calculated by multiplying the amount of waste sent to incineration or landfill by its average lower heating value.

For the analysis related to the second sub-objective, energy recovery processes for waste were clustered into five groups: Combustion plants, Waste Incineration (WI) plants, Cement and Lime (CL) production plants, Anaerobic Digestion (AD) plants and other Waste-to-Energy (WtE) plants (including pyrolysis, gasification and plasma treatment). Data on the amounts and forms of energy recovered from waste was only available for the three middle groups (see Table 2). The combined amounts of energy recovered in these three groups, 676 PJ, represents about 1.5% of the final energy consumption in the EU-28 (based on average Eurostat values for 2013 and 2014).

Table 2 – Estimation of energy recovery from waste in the EU-28 for the five groups of energy recovery processes studied

	Combustion plants	WI plants[1]		CL plants[2]	AD plants[3]			Other WtE plants
		Heat recovery (PJ)	Electricity recovery (PJ)	Thermal energy conversion (PJ)	Heat recovery (PJ)[4]	Electricity recovery (PJ)	Biomethane production (PJ)	
2006		180	81	127	n.a. (not available)			
2013	n.a.	275	110	176				n.a.
2014		n.a.	n.a.	n.a.	33	70	12	

1- Source: CEWEP.
2- No information for lime production plants. Information for cement kilns from CEMBUREAU.
3- Source: Deloitte calculation based on Eurostat Energy Statistics and EBA data.
4- Heat recovery after exclusion of internal use.

Table 2 shows that, in the period 2006-2013, the amount of energy recovered from waste increased by 39% for CL plants, by 36% for electricity from WI plants and by 53% for heat from WI plants. The latter can be explained by the significant increase in the number of WI plants providing combined heat and power (CHP).

Technical improvement potential for waste-to-energy

For the analysis of the technical improvement potential for waste-to-energy, techniques were evaluated in each of the five waste-to-energy process groups. The main evaluation criteria were the net annual energy efficiency and the applicability. The former criterion accounts for any seasonal energy demands (e.g. for heating or cooling). The latter criterion takes into account the location dependence of any technique, the number of waste streams and their combined embedded energy that can benefit from a given technique as well as the possibility to retrofit a technique in existing installations.

Both proven and emerging techniques were studied and the following proven techniques were selected for their technical improvement potential:

- For combustion plants:
  - high-efficiency circulating fluidised bed gasification and co-firing of syngas in the combustion plant: direct incineration of cleaned waste-derived syngas instead of waste;
  - feeding of secondary fuels into a fluidised bed combustion plant: use of waste-derived Solid Recovered Fuel (SRF) to replace (virgin) biomass.
- For waste incineration plants:
  - High steam parameters for boilers and superheaters: a set of different work-arounds to minimise any corrosive effects of waste that may limit energy recovery efficiency;
  - flue-gas condensation and component cooling: recovery of low-grade heat from flue-gases and cooling water;
  - heat pumps: used to upgrade low-temperature waste heat to useful high-temperature heat;
  - district cooling (100% load): using low-grade heat with an absorption refrigeration system to provide cold liquid for cooling;
  - 4th generation heat networks: using low-temperature heat, with low heat losses.
- For cement and lime producing plants:
  - conversion of waste heat to power: to partially cover on-site power demands.
- For anaerobic digestion plants:
  - sewage sludge advanced AD and thermal hydrolysis process (THP): hydrothermal destruction of sludge biomass to increase the biogas yield during the subsequent AD process;
  - AD with biomethane injection to grid (Gas-to-Grid): upgrading of biogas to biomethane for distribution via the existing natural gas grid.
- For other plants:
  - biodiesel from the hydro treatment of waste edible oils and fats: an alternative process to fatty methyl esterification, using hydrogen and steam.

Moreover, an analysis was made of the current energy efficiencies encountered for the different forms of energy recovered in each of the five waste-to-energy process groups. A summary overview is provided in Table 3 of what may be considered the current average and optimised efficiencies in each group.

Table 3 – Summary table of the current average (Av) and optimised (Opt) energy efficiency for each of the five waste-to-energy process groups

<table>
<tr><th></th><th colspan="2">Energy recovered as electricity, efficiency [1]</th><th colspan="2">Energy recovered as heat, efficiency [2]</th><th colspan="4">CHP recovery efficiency [3]</th><th colspan="2">Energy recovery to fuel, efficiency</th></tr>
<tr><td></td><td>Av %</td><td>Opt %</td><td>Av %</td><td>Opt %</td><td colspan="2">Av %</td><td colspan="2">Opt %</td><td>Av %</td><td>Opt %</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td>Electric</td><td>Heat</td><td>Electric</td><td>Heat</td><td></td><td></td></tr>
<tr><td>Combustion plants [4]</td><td>36</td><td>40</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td rowspan="2">WI plants</td><td rowspan="2">22 [5]</td><td rowspan="2">33 [6]</td><td rowspan="2">72 [7]</td><td rowspan="2">80 [8]</td><td>17 [9]</td><td>51 [9]</td><td>27 [10]</td><td>66 [10]</td><td rowspan="2">-</td><td rowspan="2">-</td></tr>
<tr><td colspan="2">Total 68</td><td colspan="2">Total 93</td></tr>
<tr><td>CL plants [11]</td><td>-</td><td>-</td><td>75</td><td>80</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td rowspan="2">AD plants</td><td rowspan="2">18 [12]</td><td rowspan="2">23 [13]</td><td rowspan="2">-</td><td rowspan="2">-</td><td>18 [14]</td><td>18 [14]</td><td rowspan="2">-</td><td rowspan="2">-</td><td rowspan="2">-</td><td rowspan="2">41 [15]</td></tr>
<tr><td colspan="2">Total 36</td></tr>
<tr><td>Others</td><td>20 [16]</td><td>35 [17]</td><td>75 [16]</td><td>80 [8]</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>40 [18]</td></tr>
</table>

Net annual average efficiency:

[1] 100% electrical load.
[2] 100% heat load.
[3] CHP - 80% of heat sold annually, 100% electrical load.

References:

[4] LCP BREF, coal / lignite pulverised combustion
[5] ISWA CE report 2015, gross existing plant efficiency corrected to net efficiency
[6] AEB Amsterdam / Martin GmBH statistics, refer also *High Steam Parameters for Boilers and Superheaters* proven technique
[7] CEWEP
[8] Ricardo estimate based on known boiler efficiencies
[9] Annual average efficiency based on ISWA CE report 2015 existing CHP plant gross efficiencies, corrected to net efficiency with annual average heat load
[10] Annual average efficiency based on optimised AEB / Martin GmBH net electrical efficiency and ISWA CE report 2015 high efficiency CHP plant gross efficiencies, corrected to net efficiency with annual average heat load
[11] CEMBUREAU
[12] ISWA CE report 2015, AD plant net efficiency
[13] UK Department of Energy and Climate Change, Advanced AD net efficiency
[14] ISWA CE report 2015, net efficiency with annual average heat load
[15] ISWA CE report 2015, net efficiency of biomethane production at 100% annual load
[16] Typical net power / heat only efficiency of a gasification system as an emerging technique
[17] High efficiency claimed by optimised emerging techniques such as *Two Stage Combustion with Plasma* with energy recovery through an internal combustion engine
[18] Typical net efficiency of an emerging technique producing a fuel product

Outlook on possible future developments in the waste-to-energy landscape

Due to the issues with statistical data quality outlined in the study and uncertainties on future developments in waste management in the different Member States, a detailed forecast of the evolutions in the waste-to-energy landscape could not be made. Hence a simple approach was followed, using a number of basic assumptions:

- Landfill is likely to further decrease in favour of incineration and/or other options higher up the waste hierarchy. Member States with low landfill rates can provide an indication of what is already practically achievable.
- More and better source-separated collection will reduce the generated amounts of mixed streams.
- The energy efficiency of WtE plants is expected to shift towards best performing plants.

The outlook was further split into two parts: one part focused on the possible future role of WtE for the different waste streams, whereas the other part focused on possible technical improvements to increase energy recovery.

The first part of the outlook assessment led to the following possible evolutions for the different waste streams:

- Household and similar wastes as well as sorting residues: while these streams may be composed of many materials that individually feature a high recycling potential, only limited possibilities for high-quality recycling remain once these materials end up in these mixed streams. Hence, despite the existing potential for waste prevention and reduced generation of these streams through better and more widespread source-separated collection, energy recovery is likely to increase to support the necessary massive diversion from landfill. Moreover, higher recycling rates for other waste types may lead to a further increase in the generation of sorting residues, unless the quality of the materials collected separately at source improves.
- Wood, plastic, textile, tyre, solvents, chemical and municipal sewage sludge wastes: energy recovery could see a reduced role in future, primarily due to the better application of the waste hierarchy.
- Organic waste such as animal and vegetal wastes: energy recovery through anaerobic digestion may increase rather than incineration, providing both energy and material recovery.
- Mixed and undifferentiated materials: the highly diverse nature of this waste category makes it difficult to forecast how energy recovery may evolve in the future.
- Paper waste: the high recyclability of this material already results in low incineration rates today, which are unlikely to rise.

The second part of the outlook assessment demonstrated that implementation of proven technical solutions to improve energy efficiency for waste incinerators and cement and lime plants, as well as AD installations, could lead to an increase in the combined forms of recovered energy of about 29%.

Disclaimer

The information and views set out in this report are those of the author(s) and do not necessarily reflect the official opinion of the Commission. The Commission does not guarantee the accuracy of the data included in this study. Neither the Commission nor any person acting on the Commission's behalf may be held responsible for the use which may be made of the information contained therein.

Table of Contents

Abstract 3
Executive Summary 4
Policy background and study objectives 4
Current use of waste for energy recovery in the EU 4
Technical improvement potential for waste-to-energy 6
Outlook on possible future developments in the waste-to-energy landscape 9
Disclaimer 10
Table of Contents 11
Glossary 14
Preface 17
1 Introduction 18
2 Purpose of the Study 19
2.1 Purpose of the study in relation to ongoing BREF work 20
2.2 Study constraints 20
3 Task 1 - Analysis of the current use of waste for energy recovery in the EU-28 ... 21
3.1 Scope of the study 21
3.1.1 Scope of combustible wastes studied 21
3.1.2 Note on terminology 23
3.1.3 Comparison of the energy contained in several combustible wastes sent to incineration 24
3.1.4 Scope of the data 26
3.1.5 Risk of double counting 27
3.2 Methodology for Task 1 27
3.2.1 Methodology for creation of the database 27
3.2.2 Analysis of the trends at European and national levels 28
3.3 Results of waste streams data collection and analysis 28
3.3.1 Wood wastes 28
3.3.2 Plastic wastes 33
3.3.3 Paper wastes 39
3.3.4 Textile wastes 44
3.3.5 Waste tyres and waste rubber 49
3.3.6 Waste solvents 54
3.3.7 Waste oils (mineral and synthetic) 59
3.3.8 Chemical waste 64
3.3.9 Household and similar wastes 69
3.3.10 Mixed and undifferentiated materials 74
3.3.11 Sorting residues 79
3.3.12 Animal and vegetal wastes 85
3.3.13 Dried municipal sewage sludge 90
3.4 Results of waste-derived fuels data collection and analysis 95
3.4.1 Waste-derived biogas 95
3.4.2 Waste-derived bioethanol 100
3.4.3 Waste-derived biodiesel 101
3.4.4 Gaseous output from gasification 105
3.4.5 Gaseous, liquid and solid output from pyrolysis 105
3.5 Discussion on data collection and trend analysis 105
3.5.1 Eurostat methodology for data collection 105
3.5.2 Quality of the Eurostat data and resulting limitations in data interpretation 107
3.6 Identification of combustible waste containing high overall amounts of energy 109

3.7 Main pathways for waste-to-energy 111
3.7.1 Identification of the main pathways for waste-to-energy 111
3.7.2 Waste-derived energy recovery for each main pathway......................112
4 Task 2 - Analysis of the technical improvement potential for waste-to-energy ..116
4.1 Identification of techniques..116
4.1.1 Summary of WtE pathways..117
4.2 Technique evaluation methodology 120
4.2.1 Evaluation definitions...120
Combining the applicability subcriteria 122
4.2.2 Approach and Technology Readiness Level 124
4.3 Task 2 - Technique dashboard 125
4.4 Combustion plants (other than CL plants) co-incinerating wastes 126
4.4.1 Overview of waste as a secondary fuel in large combustion plants......126
4.4.2 Combustion plants co-incinerating wastes - Proven improvement techniques 127
4.4.3 Large combustion plant techniques evaluation 129
4.5 Waste incineration plants 135
4.5.1 Overview of waste incineration..135
4.5.2 Energy efficiency 137
4.5.3 Waste incineration - Proven energy efficiency improvement techniques 138
4.5.4 Waste incineration techniques evaluation 139
4.5.5 Waste incineration plant techniques - Technology to watch................152
4.5.6 Waste incineration techniques evaluation 153
4.6 CL plants: Cement and lime production plants 159
4.6.1 Overview of waste in CL applications 159
4.6.2 Energy efficiency 159
4.6.3 CL plants - Proven improvement techniques and evaluation...............160
4.6.4 CL plant techniques - Technology to watch 162
4.6.5 Cement kiln emerging energy efficiency improvement techniques evaluation 162
4.7 Anaerobic digestion plants 164
4.7.1 Overview of anaerobic digestion..164
4.7.2 Energy efficiency 164
4.7.3 Anaerobic digestion - Proven improvement techniques 166
4.7.4 Anaerobic digestion techniques evaluation......................................167
4.7.5 Anaerobic digestion and biological techniques - Technology to watch ..174
4.7.6 AD and biological emerging techniques evaluation 175
4.8 Other waste-to-energy plants 180
4.8.1 Overview of other waste-to-energy plants 180
4.8.2 Other WtE plants - Proven improvement techniques and evaluation....181
4.8.3 Other WtE plants - Technology to watch..182
4.8.4 Other WtE emerging techniques evaluation 185
4.9 Detailed analysis of selected techniques 202
4.10 Discussion 243
4.10.1 Threats and opportunities for full deployment of proven techniques 243
4.10.2 Threats and opportunities for full deployment of emerging techniques 244
4.10.3 Ancillary WtE techniques to help address threats and opportunities to WtE 245
4.11 Task 2 - Conclusions on technical improvement potential of WtE 246
4.11.1 Combustion plants co-incinerating waste...247
4.11.2 Waste incineration..247
4.11.3 Cement and lime production 247
4.11.4 Anaerobic digestion 248
4.11.5 Other WtE processes 248

5 Task 3 - Outlook on developments in the waste-to-energy landscape 250
5.1 Possible future role of waste-to-energy for the different waste streams 251
5.1.1 Wood waste 251
5.1.2 Plastic waste 252
5.1.3 Paper waste 252
5.1.4 Textile waste 252
5.1.5 Waste tyres 252
5.1.6 Waste solvents 253
5.1.7 Waste oils 253
5.1.8 Chemical waste 253
5.1.9 Household and similar waste (HSW) 253
5.1.10 Mixed and undifferentiated materials (M&UM) 254
5.1.11 Sorting residues 255
5.1.12 Animal and vegetal waste (A&VW) 255
5.1.13 Dried municipal sewage sludge 256
5.1.14 Summary overview for the various waste streams 256
5.1.15 Waste-derived fuels 258
5.2 What will be the expected changes in energy recovered from waste sent to waste-to-energy? 258
5.2.1 Calculation summary 262
6 Annexes 263
6.1 Annex 1- List of conversion factors 263
6.1.1 Lower calorific values of wastes 263
6.1.2 Conversion factors for units 264
6.2 Annex 2 - Detailed list of waste treatment methods according to the Waste Statistics Regulation 265
6.3 Annex 3 - Mass balance between waste generation and treatment 266
6.3.1 Mass balance for household and similar wastes 266
6.3.2 Mass balance for mixed and undifferentiated materials 266
6.3.3 Mass balance for sorting residues 267
6.4 Annex 4 - Calculation of improvement technique ratings 269
6.5 Annex 5 - Subscoring for technique applicability 270
6.6 Annex 6 – Eurostat EU-28 calculation data for the construction of the two energy recovery scenarios 272

Glossary

Abbreviation	Terminology
ABP	Animal By-Products
ACT	"Accelerated Carbonation Technology" or "Advanced Conversion Technologies"
AD	Anaerobic Digestion
ADR	Advanced Dry Recovery
Al_2O_3	Aluminium Oxide
APC	Air Pollution Control
APCr	Air Pollution Control Residues
ASR	Auto Shredder Residue
ATT	Advanced Treatment Technology
BFB	Bubbling Fluidised Bed
CaO	Calcium Oxide
CBM	Compressed Biomethane
CCU	Carbon Capture and Utilisation
C&IW	Commercial and Industrial Waste
CFB	Circulating Fluidised Bed
CHP	Combined Heat and Power
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CoP	Coefficient of Performance
CV	Calorific Value
DHN	District Heating Network
DMS	Direct Melting System
DS	Dry Solids
ECS	Eddy Current Separation
EfW	Energy from Waste (combustion)
ELP	End-of-Life Plastic
Fe_2O_3	Iron Oxide
FGC	Flue-Gas Condensation
FGT	Flue-Gas Treatment
FGR	Flue-Gas Recirculation
GHG	Greenhouse Gas
GtG	Gas-to-Grid

Abbreviation	Terminology
H2	Hydrogen
H_2S	Hydrogen Sulphide
HCl	Hydrogen Chloride
HF	Hydrogen Fluoride
IBA	Incinerator Bottom Ash
IED	Industrial Emissions Directive
IGCC	Integrated Gasification Combined Cycle
ISWA	International Solid Waste Association
ITHP	Intermediate Thermal Hydrolysis Process
LBM	Liquefied Biomethane
LTDH	Low-Temperature District Heating
MBT	Mechanical and Biological Pretreatment
MCA	Multi-Criterion Analysis
MHT	Mechanical Heat Treatment
MSW	Municipal Solid Waste
MTHW	Medium-Temperature Hot Water
NCV	Net Calorific Value
NO	Nitrogen Oxide
NO_X	Nitrogen Oxides
NO_2	Nitrous Oxide
NTP	Non-Thermal Plasma
PCDD/F	Polychlorobenzodioxins and Furans
PE	Polyethylene
PET	Polyethylene terephthalate
PP	Polypropylene
PVC	Polyvinylchloride
PWN	Private Wire Network
RED	Renewable Energy Directive
RDF	Refuse-Derived Fuel
RFB	Revolving Fluidised Bed
ROCs	Renewable Obligation Certificates
SCR	Selective Catalytic Reduction
SiO_2	Silicon Dioxide
SNCR	Selective Non-Catalytic Reduction
SO_X	Sulphur Oxides
SO_2	Sulphur Dioxide

Abbreviation	Terminology
SRF	Solid Recovered Fuel
TDP	Thermal Depolymerisation
THP	Thermal Hydrolysis Process
TIF	Twin Interchanging Fluidised Bed
TOC	Total Organic Carbon
TRL	Technology Readiness Level
UCO	Used Cooking Oil
WDF	Waste-Derived Fuel
WFD	Waste Framework Directive
WHPG	Waste Heat Power Generation
WID	Waste Incineration Directive
WtE	Waste-to-Energy

Preface

Policy background

The Energy Union strategy, launched by the European Commission in 2015, aims to bring greater energy security, sustainability and competitiveness to the European energy market. As part of the initiatives outlined in the Energy Union Package (COM (2015) 80 final), the Commission states its intention to further establish synergies between energy efficiency policies, resource efficiency policies and the circular economy. This will include providing information on the options for exploiting the potential of "waste-to-energy" in a Communication.

When waste cannot be prevented or recycled, recovering its energy content is in most cases preferable to landfilling it, in both environmental and economic terms. Waste-to-energy can therefore play a role and create synergies with EU energy and climate policy, but must always be guided by the principles of the EU waste hierarchy. The Commission will examine how this role can be optimised, without compromising the achievement of higher reuse and recycling rates, and how the corresponding energy potential can best be exploited.

Study objectives

The present study, initiated by the Joint Research Centre of the European Commission at the end of 2015, aims to underpin the forthcoming Communication with a detailed techno-scientific assessment of the European waste-to-energy landscape. Three main objectives constitute the core of this assessment:

1. to provide an analysis of the current use of waste for energy recovery in the EU;
2. to provide an analysis of the technical improvement potential for waste-to-energy and;
3. to provide an outlook on possible future developments in the waste-to-energy landscape

Study methodology and scope

The study methodology, centred on the three main objectives, is detailed in the initial sections of each main chapter of this document (Chapters 3, 4 and 5).
The scope of the study is clarified in section 3.1, which also elaborates on the different definitions used in this study and provides a note on terminology.

Acknowledgements

The Joint Research Centre would like to express its gratitude to all stakeholder organisations that have contributed to this study by providing data and information as well as suggestions for corrections during the two consultation rounds. These stakeholders include several Member State authorities as well as industrial federations at national and European level. In addition, the JRC would like to thank Commission experts who have contributed to this study, in particular from DG Environment and Eurostat. The JRC is also grateful to Ms Anna Atkinson for proofreading the final manuscript. Last but not least, contracted consultant companies Ricardo AEA and Bio by Deloitte are greatly acknowledged for their invaluable contribution to this study.

JRC, Seville, December 2016

1 Introduction

As part of the Energy Union Package, the European Commission committed to issuing a Communication on Waste-to-Energy (WtE). The aim of the Communication is to maximise the potential of WtE, by facilitating a joined-up approach in both energy and resource efficiency policies, and the transition to a Circular Economy.

Member States are obliged under the EU's revised Waste Framework Directive (Directive 2008/98/EC) to apply as a priority the waste hierarchy, which ranks waste management options in order of environmental preference. Energy recovery can represent a sustainable option for the type of waste that cannot be reused or recycled, by diverting it from landfill, which could ultimately result in lower greenhouse gas emissions and in economic, social and environmental benefits (e.g. avoided methane emissions).

It is also recognised that efficient energy recovery from residual waste can enhance environmental benefits compared to landfill disposal, make an important contribution to the EU's renewable energy targets[1], and help provide energy security throughout Member States. However, there is currently a gap between the potential for, and delivery of, WtE which is resulting in valuable resources going to landfill.

The waste hierarchy options of prevention, reuse, recycling and recovery are not mutually exclusive and recovering energy from waste is not incompatible with increasing recycling rates. However, a wide range of pretreatment and thermal treatment technologies exist that are technically proven to be effective and are also commercially available in the EU and around the world, and many others are available at different stages of their development cycle around the world. The selection of the most environmentally and commercially sustainable technologies for a defined set of circumstances can be challenging and represent a perceived barrier to investment.

Energy recovery technologies include conventional technologies (both direct combustion and the combustion of waste-derived fuel) and advanced conversion technologies (ACT). ACT are broadly categorised into:

- pyrolysis;
- gasification processes (including emerging waste treatment technologies such as plasma arc gasification and a combination of pyrolysis and gasification);
- liquefaction processes to produce fuels.

Whilst energy recovery from municipal solid waste (MSW) is well established, there is currently an increasing range of commercial and industrial waste streams for which energy recovery is being considered as an alternative to landfill. Developments in WtE technologies have also led to an increased flexibility in how the intermediate products of energy recovery can be used (i.e. the conversion of biogas into a vehicle fuel or injection to a gas grid, or the conversion of products of pyrolysis into chemical commodities.)

Previous work has provided extensive data for the production and use of waste-derived fuels within the European Union, mainly for the year 2008. However, a more dynamic approach is now required to provide up-to-date data (up to either 2012 or

[1] Insofar as the feedstock used for energy recovery is renewable in nature.

2014), to identify trends in the development of WtE in each Member State. Such a study could provide an outlook on the future of WtE techniques and present a more comprehensive analysis on the generation of different forms of energy and other outputs from WtE.

Whilst WtE is prevalent in some Member States, less than 5% of all waste was used for energy recovery across the EU-28 in 2012. Landfill still dominates waste management in many EU countries.

2 Purpose of the Study

This study is aimed at supporting the forthcoming Communication on Waste-to-Energy by delivering a robust and up-to-date examination of the current landscape of WtE in the EU, whilst also investigating how proven and innovative technologies may play a role in increasing the potential of WtE operations. To this effect, the work was split into three main tasks:

- Task 1: Provide an analysis of the current use of waste streams for energy recovery in the EU-28:
    - Sub-task 1.1: Produce a comprehensive database for the generation, use and energy recovery from 20 waste streams for the EU-28 over the period 2009 to the most recent year for which reliable data are available; and
    - Sub-task 1.2: Identify the main trends in the deployment of WtE in each Member State and provide an explanation as to why WtE has evolved differently across the EU-28.
- Task 2: Provide an analysis of the technical improvement potential for waste-to-energy.
    - Sub-task 2.1: Identify techniques that demonstrate the greatest potential to improve current WtE operations, without resulting in a negative impact on the environment or human health when compared to existing WtE operations.
    - Sub-task 2.2: For each of the techniques identified in Task 2.1, evaluate two key criteria: net annual average energy efficiency and applicability. This process identifies the WtE techniques with the highest potential, which are subject to a more detailed analysis in a next phase of the study.
    - Sub-task 2.3: Detailed analysis of WtE techniques.
- Expert Workshop: An expert workshop was held on 9 March, 2016 to obtain input for the study from key stakeholders. The feedback from the workshop and subsequent written feedback from stakeholders was incorporated into the methodology and content of this report.
- Task 3: The objective of this final task was to draw together the current status and use of waste streams which could be appropriate for the recovery of energy (from Task 1) with the WtE technical improvement potential identified in Task 2.

This report and its conclusions should help to highlight how industry and authorities can improve the WtE landscape by providing guidance and improving knowledge and understanding. Such advances will help to remove barriers to WtE technologies by ensuring that all related information is readily available.

2.1 Purpose of the study in relation to ongoing BREF work

At the time of writing, the JRC was reviewing the Best Available Techniques (BAT) REFerence document for Waste Incineration (the WI BREF) which was first published in 2006. The review of the WI BREF is expected to be finalised around 2018. The objective of the WI BREF review is to establish new benchmarks for the environmental performance of waste incineration plants over the next decade, including a consideration of energy performance.

However, it should be stressed that this report is not intended to overlap with the WI BREF review, or the development or review of any other BREF by the JRC's services. The approach, timeline and objectives of the study presented in this report were also completely different from those of the widely known "Sevilla Process" that forms the basis for developing and reviewing BREF documents.

2.2 Study constraints

This study is solely focused on identifying opportunities to better exploit the technical potential of WtE when a waste cannot be prevented, recycled or reused. Therefore, the study does not include the following:

- Analysis of non-waste fuels (e.g. virgin biomass).
- Analysis of techniques for landfill gas capture to produce biogas for power generation, since this relates to waste already disposed by landfilling.
- Techniques focused on recycling.
- A consideration of commercial aspects which may restrict the implementation of the technical potential of WtE.
- A detailed analysis of the mass/energy balance for each technique or for any pretreatment which is required to implement a technique. In Section 4.2.1.3, the study provides an estimation of the energy input required for waste pretreatment in order to produce Solid Recovered Fuel (SRF).

Finally, it should be mentioned that the current study had to be performed in a very short timeframe (from November 2015 to October 2016), which did not allow for a more in-depth analysis of certain issues highlighted in this document.

3 Task 1 - Analysis of the current use of waste for energy recovery in the EU-28

Task 1 aims at providing an analysis of the current use of combustible wastes in waste-to-energy operations in the EU-28.

3.1 Scope of the study

3.1.1 Scope of combustible wastes studied

Definition of waste as part of this study

For the purpose of this study, waste is defined based on the Waste Framework Directive (WFD) (2008/98/EC) as any substance or object which the holder discards or intends to or is required to discard.

Substances and materials which are residues of production or consumption processes may or may not be waste, and a distinction between residue and waste should be made.

In particular, the WFD includes in Article 5 a definition of by-products and the main conditions which must be met by a substance or object in order to be classified as a by-product. A substance or object resulting from a production process, the primary aim of which is not the production of that item, may not be regarded at waste, but as being a by-product only if the following conditions are met:

(a) further use of the substance or object is certain;

(b) the substance or object can be used directly without any further processing other than normal industrial practice;

(c) the substance or object is produced as an integral part of a production process; and

(d) further use is lawful, i.e. the substance or object fulfils all relevant product, environmental and health protection requirements for the specific purpose and will not lead to overall adverse environmental or human health impacts.

Type of wastes included in the scope of the study

The scope of the study includes solid, liquid and gaseous combustible wastes that can be used as energy sources. They can be divided into two categories:

- Combustible wastes that are always waste-derived but not necessarily transformed into fuels (e.g. wood waste, waste oil, sorted residues), called “**waste streams**” in this report.
- Combustible wastes that are always used as fuels, called “**waste-derived fuels**” in this report. It should be noted that such fuels, e.g. biodiesel, bioethanol or biogas, can also be derived from non-waste feedstock. Therefore, for this category the scope of the study is limited to the share of fuel that is waste-derived. It should be noted as well that waste-derived fuels such as biodiesel and biogas can be produced from waste streams that fall into the previous category, leading to a possible risk of double counting. This problem is further discussed in Section 3.1.5.

In conclusion, in this study, “**combustible wastes**” is a generic expression used to refer to “waste streams” **and** “waste-derived fuels”.

In contrast, the energy from combustible waste that has already been subjected to treatment and disposal is outside the scope of the present study. Therefore, landfill gas capture and urban mining are not discussed in this study.

Scope of the study in relation to the hierarchy for waste management

The scope of the study is in line with the hierarchy for waste management as defined by the Waste Framework Directive. Therefore, it focuses on combustible wastes that are not able to be prevented, reused or recycled in an economically and environmentally sound way. As a consequence, it should not be seen as a stimulus for more energy recovery when options are available that are ranked higher in the waste hierarchy. In other words, the treatment option which is highest in the waste hierarchy should always be considered first before descending to less environmentally favourable options, even for waste streams representing a high calorific value.

However, considering that the technical, economic and environmental feasibility of waste material recovery changes with time and geography, the scope of the study also includes combustible wastes that are currently recycled in some parts of Europe, such as plastic wastes, waste oil, etc.

List of combustible wastes studied

The list of combustible wastes studied is partially based on the scope of the Waste Framework Directive. According to the provisions of WFD Article 2[2], this excludes in particular straw and woodchips. In addition, this study also includes animal faeces and sludge that are not considered in the WFD.

The constitution of this list is based on two main sources of information (see Table 1.1):

1) The list of the main combustible wastes sent for incineration (with and without energy recovery). This information comes from Eurostat Waste Statistics.
2) The list of 18 combustible wastes studied in the 2011 second interim report from Umweltbundesamt (UBA) called "Waste-derived fuels: Characterisation and suitability for end-of-waste" (henceforth referred to as "UBA 2011 report").

The list of 18 combustible wastes studied in this report:

- Waste streams:
  1. Wood waste
  2. Plastic waste
  3. Paper waste
  4. Textile waste
  5. Tyres and rubber waste
  6. Waste solvents
  7. Oil waste (used oils)
  8. Chemical waste
  9. Household and similar waste
  10. Mixed and undifferentiated materials
  11. Sorting residues

[2] http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32008L0098.

12. Animal and vegetal waste[3]
13. Dried municipal sewage sludge

- Waste-derived fuels:
  14. Biogas
  15. Bioethanol
  16. Biodiesel
  17. Gaseous output from gasification
  18. Gaseous, liquid and solid output from pyrolysis

The production and treatment of Solid Recovered Fuels (SRF) is addressed in Section 3.3.11 on sorting residues.

According to Table 1.1, the 18 studied combustible wastes account for 96% of the total theoretically available energy contained in all combustible wastes sent for incineration (with and without energy recovery) in the EU-28 in 2012.

3.1.2 Note on terminology

The definition of the 13 aforementioned waste streams is provided in Section 3.3. In addition, Figure 1.1 shows the scope of these waste streams according to their origin (municipal waste, and commercial and industrial waste) and method of collection. It should be noted that even though construction and demolition waste (C&DW) is not included in Figure 1.1, it is included in the scope of the study.

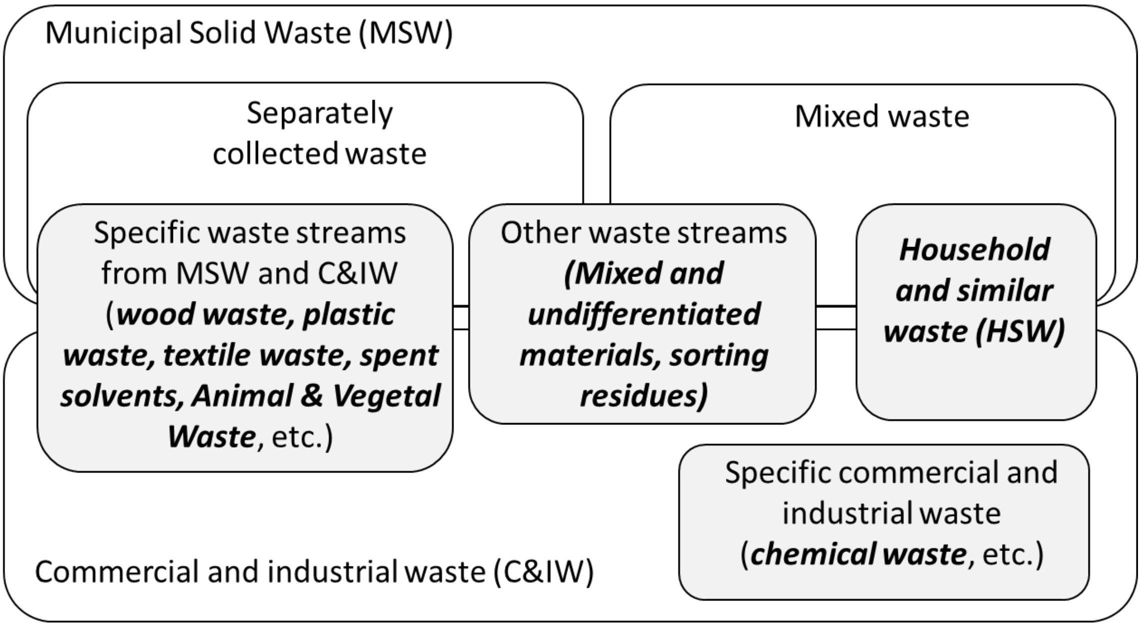


Figure 1.1: Scope of the waste streams considered in the study (source: Deloitte/JRC).

Looking at Figure 1.1, there is a clear distinction between household and similar wastes (HSW) and municipal solid waste (MSW): in principle, HSW does not cover source-separated materials (e.g. glass or paper), whereas MSW does cover such materials. The amount of total MSW produced per capita is roughly double the amount of HSW produced.

[3] Composed of three waste sub-streams: "Animal and mixed food waste", "Animal faeces, urine and manure" and "vegetal waste'.

3.1.3 Comparison of the energy contained in several combustible wastes sent to incineration

In Table 1.1, the total theoretically available energy contained in waste is calculated by multiplying the amount of combustible wastes sent for (co)incineration[4] by their average lower heating values (based on various sources detailed in Annex 1). This calculated data does not take into account technological advances in terms of energy efficiencies. Therefore, it does not provide an estimate of the current energy recovered from waste, but it can be used to compare the theoretically available energy for recovery from various combustible wastes.

Table 1.1: Total theoretically available energy contained in waste sent to incineration (D10 +R1) in the EU-28 in 2012 (Source: Eurostat Energy Statistics and Deloitte calculations) – in blue, waste categories included in the list of 18 combustible wastes

		Total incinerated (R1 + D10)	Lower Heating Value	Total energy amount contained in incinerated waste		Related combustible wastes category(4)
		Thousand tonnes or million Nm^3	MJ/kg or MJ/Nm^3	PJ	% (7)	
Waste streams						
Animal and vegetal wastes (1)						
	Animal and mixed food waste	2,080	17	35	2%	12
	Animal faeces, urine and manure	1,030	6	6	0%	
	Vegetal wastes	1,750	16	28	1%	
Chemical and medical wastes (1)						
	Acid, alkaline or saline wastes	130	n.a.(6)	0	0%	
	Chemical wastes	3,740	25	93	5%	8
	Health care and biological wastes	1,150	24	28	1%	
	Industrial effluent sludges	2,700	10	26	1%	
	Sludges and liquid wastes from waste treatment	370	10	4	0%	
	Spent solvents	1,070	28	29	2%	7
	Used oils	1,060	31	32	2%	6
Dried municipal sewage sludges (3)						
	Municipal sludges	2,306	10	22	1%	14
Equipment (1)						
	Batteries and accumulators wastes	0	n.a.	0	0%	
	Discarded equipment	40	15	1	0%	
	Discarded vehicles	0	n.a.	0	0%	
	Waste containing PCB	10	15	0	0%	
Mineral and solidified wastes (1)						
	Combustion wastes	630	15	9	0%	
	Dredging spoils	0	n.a.	0	0%	
	Mineral waste from construction and	1,460	n.a.	0	0%	

[4] Based on Eurostat Waste Statistics, Eurostat Water Statistics and Eurostat Energy Statistics databases, and other information provided by European experts and federations.

	Total incinerated (R1 + D10)	Lower Heating Value	Total energy amount contained in incinerated waste		Related combustible wastes category(4)
	Thousand tonnes or million Nm^3	MJ/kg or MJ/Nm^3	PJ	% (7)	
demolition					
Mineral wastes from waste treatment and stabilised wastes	220	n.a.	0	0%	
Other mineral wastes	230	n.a.	0	0%	
Soils	50	n.a.	0	0%	
Mixed ordinary wastes (1)					
Household and similar wastes	52,180	9	470	25%	9
Mixed and undifferentiated materials	11,480	13	149	8%	10
Sorting residues	22,280	15	334	18%	11
Recyclable wastes (1)					
Glass wastes	0	n.a.	0	0%	
Metal wastes, ferrous	40	n.a.	0	0%	
Metal wastes, mixed ferrous and non-ferrous	0	n.a.	0	0%	
Metal wastes, non-ferrous	10	n.a.	0	0%	
Paper and cardboard wastes	340	17	6	0%	3
Plastic wastes	1,700	36	61	3%	2
Wastes tyres	1,195	29	35	2%	5
Textile wastes	140	17	2	0%	4
Wood wastes	27,960	13	375	20%	1
Waste-derived fuels (2)					
Waste-derived biogas	4,225	26	108	6%	15
Waste-derived biodiesel	520	37	19	1%	16
Waste-derived bioethanol	~0	n.a.	~0	0%	17
Gaseous output from gasification	~0	n.a.	~0	0%	18
Gaseous, liquid and solid output from pyrolysis	~0	n.a.	~0	0%	19
Total	137,871 (5)		1,873	100%	

(1) Categories used in Eurostat Waste Statistics (see descriptions in following paragraphs).
(2) Categories not included in Eurostat Waste Statistics, but used in the UBA 2011 report (see descriptions in following paragraphs).
(3) Category used in Eurostat Water Statistics (see descriptions in following paragraphs).
(4) The numbers refer to the above list of 18 combustible wastes.
(5) Total in thousand tonnes excluding biogas.
(6) n.a. = not applicable.
(7) The % values are rounded to the nearest whole number which explains why the total % seems different to 100%.

3.1.4 Scope of the data

3.1.4.1 Period for data collection

The data collection targeted the period 2006-2016. The Eurostat Waste Statistics database was the main source of information and it provides information at two-year intervals. The 2014 waste statistics were not available at the time of writing, so 2012 is the most recent year for which waste statistics data could be used.

3.1.4.2 Type of data collected

For each EU-28 country, the data collection focused on the following criteria:

- Amount of combustible waste generated.
- Import/export into/outside the EU-28 is also studied whenever relevant.
- Amount of waste treated, for the following categories[5]:
    - Incineration / energy recovery (R1);
    - Incineration on land / Disposal (D10);
    - Disposal (D1, D2, D3, D4, D5, D6, D7, D12);
    - Recovery other than energy recovery (R2 to R11).
- Amount of energy recovered, for the following categories:
    - Conversion into heat with direct use: mostly relevant for cement kilns;
    - Conversion into heat for steam production;
    - Conversion into electricity;
    - Biogas conversion into biomethane.

Conversion into liquid biofuel is studied separately as part of waste-derived ethanol and waste-derived biodiesel production (see Sections 3.4.2 and 3.4.3 respectively).

Waste treatment categories should be understood as follows[5]:

- *Recovery other than energy recovery* means any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy.

  Note that recycling is a subset of recovery and means any recovery operation by which waste materials are reprocessed into products, materials or substances, whether for the original or other purposes. It includes the reprocessing of organic material (e.g. composting, anaerobic digestion) but excludes its use as fuel and its use for backfilling operations.

  In this report, "material recovery" refers to "recovery other than energy recovery".

- *Disposal* means any operation which is not recovery even where the operation has as a secondary consequence the reclamation of substances or energy.

Annex 2 also provides the definition of all treatment methods for recovery (R1 to R10) and for disposal (D1 to D12).

[5] Definitions of waste treatment methods and related categories (R1, D10, etc.) are provided in the Eurostat Manual on waste statistics.

3.1.5 Risk of double counting

To provide an overview of combustible waste generation and treatment in the EU-28, it is necessary to add up the figures for the 18 combustible wastes studied (see Table 1.1). However, the result is not correct as some wastes are counted more than once. As part of the present study, double counting mostly occurs in the following situations:

- Eurostat data on waste generation: for consistency reasons, the current methodology for the estimation of combustible waste generation uses - when possible - data from the Eurostat Waste Statistics database. As explained in further detail in Section 3.5.1, Eurostat data on waste generation shall cover all waste (primary and secondary) generated by the statistical units, which means that double counting of waste is part of the concept. This also means that "sorting residues" are already accounted for as part of other waste streams.
- Eurostat data on waste treatment: only waste sent to final treatment should be reported to Eurostat; treated waste should thus be counted only once. However, there is also evidence of double counting for HSW sent to MBT (Mechanical Biological Treatment) plants.
- Waste-derived biogas production: in the Eurostat Waste Statistics database, the fermentation of biodegradable wastes for biogas production is not accounted for under the categories "incineration" or "energy recovery", but instead under the category "recovery other than energy recovery" along with other treatment methods (such as composting). Therefore, it is not possible to estimate the production of waste-derived biogas for each organic waste stream studied (in particular for "Animal and vegetal waste" (A&VW) and "Municipal sewage sludge" (MSS)). Waste-derived biogas is studied separately, which represents double counting. However, waste-derived biogas is expressed in Nm^3 (whereas other waste-derived biogas feedstocks (A&VW, MSS) are in tonnes), and energy recovery from these feedstocks is only accounted for once, because the Eurostat Waste Statistics database does not provide it.
- Waste-derived biodiesel: most of the waste-derived biodiesel production in the EU-28 comes from waste edible oil and fat, which are also included in the waste category "Animal and vegetal wastes". However, data on edible oil and fat generation and treatment are difficult to find and most data provided by Member States to Eurostat do not account for it. Considering that waste-derived biodiesel represents a growing market for energy recovery, it was decided to study it as a separate combustible waste.

3.2 Methodology for Task 1

3.2.1 Methodology for creation of the database

The figure below shows the four-step methodology used to create the database.

Step 1: draft database

In order to ensure results that are harmonised and comparable with the 2011 study from UBA, for combustible wastes that are common to both studies, the data collection started with the methodology and key assumptions used by UBA for combustible wastes that are common to both studies. The construction of the draft database was completed with up-to-date bibliographic research.

Step 2: discussion with European federations
Key EU federations were contacted to discuss the main assumptions of the draft methodology. The draft database was then updated according to their feedback.

Step 3: workshop with national and European experts
The updated database and first elements of the data analysis were presented in a background document. This document was sent to national and European experts, who were invited to attend a one-day stakeholder workshop organised in Seville. Following this workshop, numerous inputs were received (assumptions, ratios used, other existing databases) and implemented. Inputs related to specific national data were not used in the calculations for consistency reasons. However, they were taken into account to analyse the robustness of the results.

Step 4: final database
The final database was compiled using the latest feedbacks that stakeholders provided after reading the draft final report.

3.2.2 Analysis of the trends at European and national levels

The analysis is based on compiled databases for the years 2006 to 2012 (or later whenever available). For trends related to the waste treatment method, a specific focus was on the waste hierarchy. In addition, Member States were asked to provide inputs to explain unexpected past evolutions or their outlook for developments of waste management practices. Whenever provided, these explanations are included in the analysis of the trends.

3.3 Results of waste streams data collection and analysis

3.3.1 Wood wastes

Generation of wood wastes
Data on the generation of wood wastes comes from Eurostat Waste Statistics. Eurostat's EWC-Stat category "07.5 Wood wastes" contains hazardous and non-hazardous wastes.

The category and main NACE sectors that produce wood wastes are described as follows by the Eurostat Manual on waste statistics[6]:

"Wood wastes (07.5): These wastes are wooden packaging, sawdust, shavings, cuttings, waste bark, cork and wood from the production of pulp and paper; wood from the construction and demolition of buildings; and separately collected wood waste. They mainly originate from wood processing, the pulp and paper industry and the demolition of buildings but can occur in all sectors in lower quantities due to wooden packaging. Wood wastes are hazardous when containing hazardous substances like mercury or tar-based wood preservatives."

Copper, chromium and arsenic (CCA) are also used for wood treatment and found in hazardous wood waste.

[6] Additional information can be found in the "Guidance on classification of waste according to EWC-Stat categories" document.

Table 1.2: Evolution of the generation of wood wastes by Member State (Source: Eurostat Waste Statistics)

	Wood waste generation (thousand tonnes/yr)			
	2006	2008	2010	2012
Austria	6,300	6,232	1,295	888
Belgium	1,797	1,573	2,779	4,193
Bulgaria	161	327	115	201
Croatia	199	195	174	97
Cyprus	33	17	24	14
Czech Republic	638	248	303	238
Denmark	864	892	304	232
Estonia	1,791	1,288	871	816
Finland[7]	13,338	12,477	12,281	11,941
France	7,478	8,682	8,945	6,051
Germany	8,835	10,271	10,812	11,713
Greece	745	830	350	121
Hungary	482	336	287	242
Ireland	401	147	508	201
Italy	2,469	3,448	3,760	3,901
Latvia	240	87	87	56
Lithuania	220	231	300	182
Luxembourg	85	74	111	87
Malta	1.0	0.4	8.2	13.3
Netherlands	1,944	2,272	2,561	2,572
Poland	2,808	3,367	3,508	3,949
Portugal	1,233	736	905	824
Romania	1,466	1,806	2,340	2,058
Slovakia	768	629	239	401
Slovenia	1,154	470	334	339
Spain	1,909	1,932	1,624	1,247
Sweden	4,689	4,508	1,863	1,171
United Kingdom	7,607	4,398	2,827	3,742
Total EU-28	69,656	67,476	59,515	57,489

Table 1.2 shows that the EU-28 wood waste production has been consistently decreasing between 2006 and 2012, with a very significant decrease (of 13%) between 2010 and 2008.

Based on data from Table 1.2, Figure 1.2 shows the evolution of the generation of wood wastes for the 14 Member States that were responsible for more than 96% of the overall generation in 2012.

[7] Since 2013, Finland has changed its methodology for the reporting of wood wastes to Eurostat and data for 2013 will be around 3 million tonnes compared to 12 million tonnes for 2012.

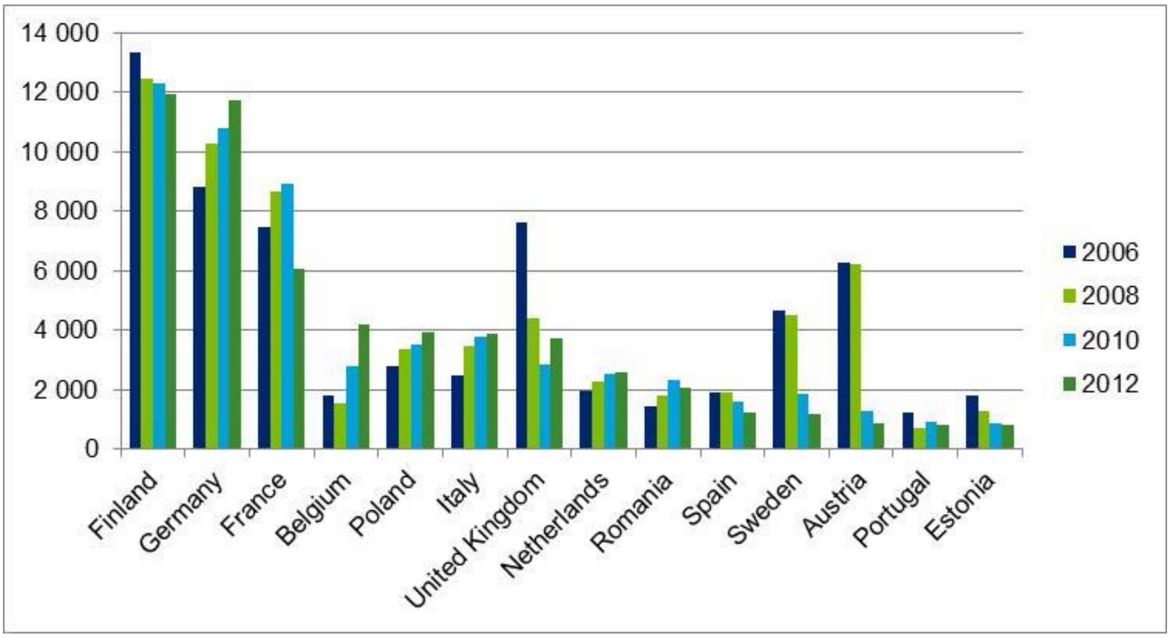


Figure 1.2: Evolution of the generation of wood wastes for the 14 main EU-28 producers in 2012 (Source: Eurostat Waste Statistics – in thousand tonnes/yr)

Looking at the main EU-28 producers, we can see different trends among countries from 2006 until 2012. While it appears that wood waste generation is decreasing in Finland, Sweden and Austria, it is increasing in Germany and Belgium.

In the case of Spain the decrease in wood waste generation may be due to the collapse of the construction sector since 2008, which previously demanded a significant amount of wood-based products. No further information was provided by Member States that might explain the figures.

It should be noted that reporting on wood waste is extremely difficult, subject to interpretation and sometimes changes due to evolution in the reporting methodology (see Finland in Table 1.2). Indeed, it is difficult to distinguish between virgin and pretreated wood, wood waste used in production processes and wood waste used for energy recovery. Further difficulties may arise due to the fact that wood waste is often recovered internally. Therefore, Eurostat data for wood waste generation should be used carefully.

Import/export into/outside the EU-28

Quantities of imported and exported wood waste into/outside the EU-28 were collected from the Eurostat COMEXT Database. Quantities are available on a monthly and yearly basis from 1988 to 2008. For the purpose of the study, yearly imported and exported quantities from 2006 to 2008 were considered. Relevant data were identified based on their CN8 code. According to the methodology used in the UBA 2011 study, the following CN8 codes were used for wood wastes:

WDF	CN8 Code	Description
Waste wood	44013090	Wood waste and scrap, whether or not agglomerated in logs, briquettes, pellets or similar forms (excl. sawdust)
	45019000	Cork waste; crushed, powdered or ground cork

Table 1.3 shows that the EU-28 has a growing negative trade balance which represented 2% of the wood wastes generated in the EU-28 in 2006 and 3% in 2008.

Table 1.3: Evolution of wood wastes trade outside the EU-28 (Source: Eurostat COMEXT Database)

	Import/export into/outside the EU-28 (thousand tonnes/yr)		
	Import	Export	Trade balance
2006	1,390	137	-1,252
2008	1,917	168	-1,748
2010	NA	NA	NA
2012	NA	NA	NA
2014	NA	NA	NA

Unfortunately no data are available for the years after 2008.

Treatment of wood waste

Wood waste treatment data comes from Eurostat Waste Statistics. Eurostat provides data on material recovery for the years 2006, 2008, 2010 and 2012, but data on other methods of treatment (energy recovery, incineration on land, and landfill) is only available for the years 2010 and 2012.

Table 1.4: Evolution of the wood wastes sent for energy recovery by Member State (Source: Eurostat Waste Statistics)

	2010 (thousand tonnes/yr)		2012 (thousand tonnes/yr)	
	Energy recovery (R1)	Incineration/ Disposal (D10)	Energy recovery (R1)	Incineration/ Disposal (D10)
Austria	330	3.8	446	0.0
Belgium	732	314.6	136	785.9
Bulgaria	89	0.2	79	0.1
Croatia	71	1.0	21	0.0
Cyprus	2	2.5	0	0.0
Czech Republic	36	0.4	26	1.3
Denmark	25	0.0	30	0.0
Estonia	265	0.0	289	0.0
Finland	7,649	15.5	8,426	44.4
France	1,601	266.5	1,614	92.5
Germany	6,915	158.5	8,260	5.2
Greece	39	0.0	11	0.0
Hungary	36	0.9	29	0.3
Ireland	73	17.0	18	0.0
Italy	867	44.8	776	12.8
Latvia	4	0.0	6	0.5
Lithuania	101	0.0	85	0.1
Luxembourg	0	0.0	0	0.0
Malta	0	0.0	0	0.0
Netherlands	904	17.5	1,043	10.8
Poland	2,582	2.8	2,286	1.6
Portugal	490	1.1	585	0.8
Romania	1,173	0.2	1,039	0.2
Slovakia	67	0.3	56	5.0

	2010 (thousand tonnes/yr)		2012 (thousand tonnes/yr)	
	Energy recovery (R1)	Incineration/ Disposal (D10)	Energy recovery (R1)	Incineration/ Disposal (D10)
Slovenia	172	0.8	202	0.1
Spain	3	0.3	3	0.0
Sweden	1,373	1.6	1,191	2.5
United Kingdom	248	0.0	347	0.0
Total EU-28	25,840	850.0	27,000	960.0

Between 2010 and 2012 the amount of wood wastes sent for energy recovery increased by 4% at the EU-28 level. While in most EU-28 countries this amount was stable or slightly decreasing, Finland and Germany, the two countries sending the most wood waste for energy recovery, increased the amount they sent for energy recovery by 10% and 19% respectively.

Figure 1.3 shows the repartition of wood waste treatment methods for the 14 EU-28 countries representing 99% of wood wastes sent to incineration and energy recovery in 2012.

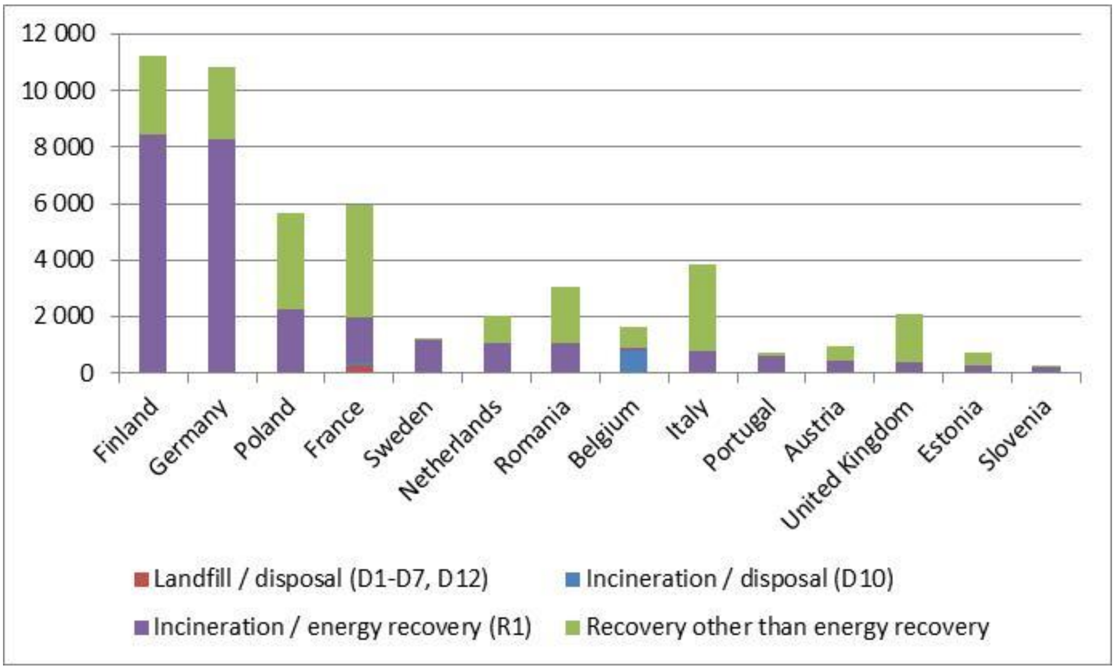


Figure 1.3: Treatment of wood wastes for the 14 EU-28 main contributors to energy recovery from wood waste in 2012 (Source: Eurostat Waste Statistics – in thousand tonnes/yr)

Figure 1.4 gives an overview of the repartition of wood waste treatment methods in the EU-28 and its evolution between 2010 and 2012. While at the EU-28 level similar amounts of wood wastes were sent for energy recovery and material disposal, Figure 1.3 shows that some Member States focused their treatment strategy on energy recovery while other countries sent more wood wastes to material recovery.

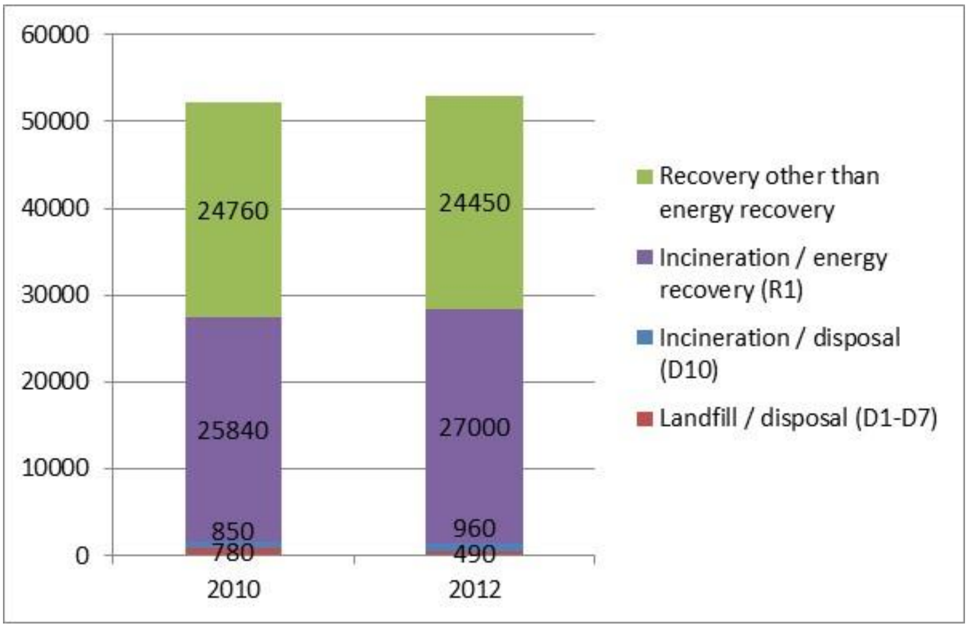


Figure 1.4: Evolution of wood waste treatment methods in the EU-28 (Source: Eurostat Waste Statistics – in thousand tonnes/yr)

It is important to highlight that, according to Eurostat, around 2 million tonnes of wood waste is considered hazardous waste. Hazardous waste may contain impurities and hazardous compounds which may not be suitable to be used in co-incineration plants or additional energy consumption may be required for pretreatment of waste and emission abatement systems.

3.3.2 Plastic wastes

Generation of plastic wastes

Data on the generation of plastic wastes comes from Eurostat Waste Statistics. PlasticsEurope, the European Association of Plastic Manufacturers, provides annual data on plastic production, consumption and plastic wastes management in the EU-28. However, it is difficult to compare it with Eurostat data because the scope is not the same: the scope of PlasticsEurope's data is broader as it represents all post-consumer plastics generated. For instance, in 2012 in the EU-28, collected post-consumer plastic wastes reached 25 million tonnes[8], while 17 million tonnes of plastic wastes were reported by Member States to Eurostat (see Table 1.5). Plastic waste data reported by PlasticsEurope is probably included in other Eurostat categories besides the category "plastic waste (07.4)", in particular "household and similar wastes". PlasticsEurope's data is however useful to comment on plastic waste trends in the EU-28.

Eurostat's EWC-Stat category "07.4 plastic wastes" contains only non-hazardous wastes. The category and main NACE sectors that produce plastic wastes are described as follows by the Eurostat Manual on waste statistics[9]:

"*Plastic wastes (07.4): These are plastic packaging; plastic waste from plastic production and machining of plastics; plastic waste from sorting and preparation processes; and separately collected plastic waste. They originate from all sectors as packaging waste, from sectors producing plastic products and from separate sorting by businesses and households. All plastic wastes are non-hazardous. A distinction*

[8] http://www.plasticseurope.org/Document/plastics-the-facts-2012.aspx.
[9] Additional information can be found in the "Guidance on classification of waste according to EWC-Stat categories" document.

should be made between plastic wastes and mixed packaging that belongs to the category 'mixed and undifferentiated materials'."

Table 1.5: Evolution of the generation of plastic wastes by Member State (Source: Eurostat Waste Statistics)

	Plastic waste generation (thousand tonnes/yr)			
	2006	2008	2010	2012
Austria	350	641	565	358
Belgium	632	1,075	698	611
Bulgaria	26	73	60	100
Croatia	186	30	25	39
Cyprus	57	68	84	74
Czech Republic	214	232	254	326
Denmark	54	73	79	107
Estonia	90	94	25	23
Finland	125	87	71	91
France	1,166	1,551	1,437	1,647
Germany	1,414	1,936	2,288	2,530
Greece	755	673	227	133
Hungary	147	150	151	186
Ireland	358	39	335	126
Italy	1,564	1,609	2,141	2,733
Latvia	12	9	8	22
Lithuania	30	31	40	51
Luxembourg	32	20	27	26
Malta	1	2	4	4
Netherlands	378	410	518	610
Poland	325	407	863	970
Portugal	996	193	224	214
Romania	580	419	564	649
Slovakia	75	94	111	108
Slovenia	43	47	56	48
Spain	1,617	1,904	1,465	1,143
Sweden	188	223	219	176
United Kingdom	3,447	2,489	3,660	3,986
Total EU-28	**14,863**	**14,578**	**16,201**	**17,091**

Table 1.5 shows that EU-28 plastic waste production has been increasing since 2008, after a small decrease from 2006 to 2008.

PlasticsEurope's data for 2012 to 2014 is in line with the small increase shown in Table 1.5: the five countries (Germany, Italy, France, the UK and Spain) representing two thirds of the plastics demand show a small upward trend over the period[10]. This increase is, however, much smaller than the evolution presented in Figure 1.5.

[10] http://www.plasticseurope.org/Document/plastics---the-facts-2015.aspx.

Based on data from Eurostat in Table 1.5, Figure 1.5 shows the evolution of the generation of plastic wastes for the 14 Member States responsible for more than 94% of the overall generation in 2012.

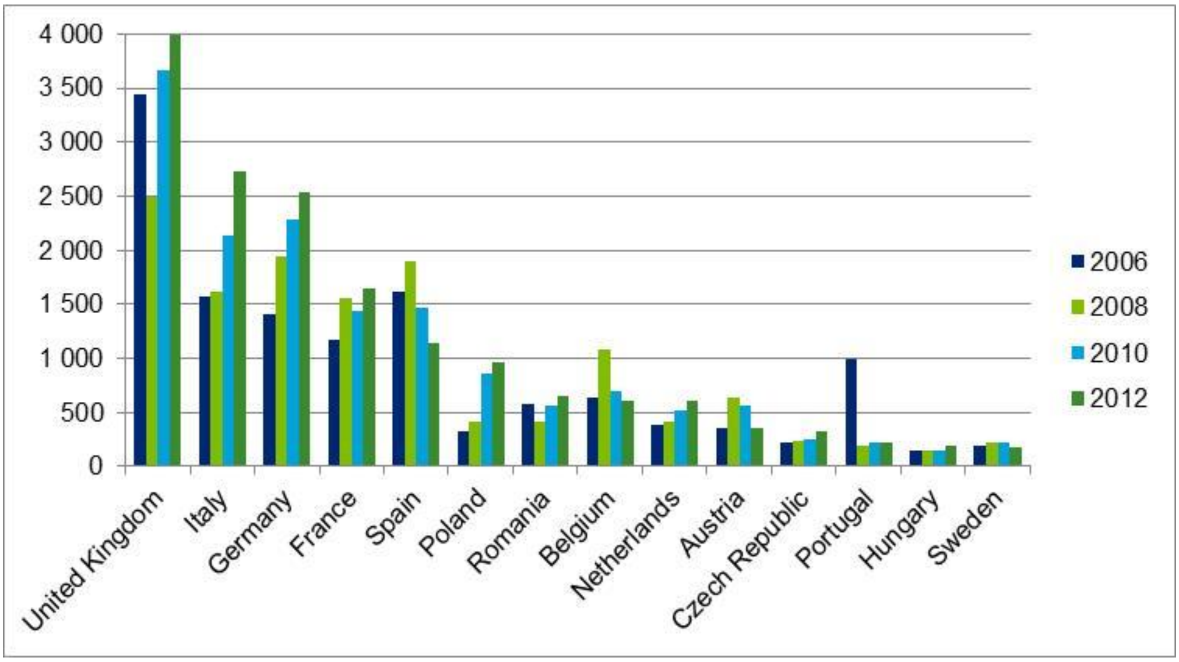


Figure 1.5: Evolution of the generation of plastic wastes for the 14 main EU-28 producers in 2012 (Source: Eurostat Waste Statistics – in thousand tonnes/yr)

The three biggest producers (the UK, Italy and Germany) represent 54% of the total plastic wastes generated. According to Figure 1.5, the amount of plastic wastes generated increased by 60% in the UK from 2008 to 2012 and by 75% and 79% in Italy and Germany from 2006 to 2012 respectively.

In contrast, Greece ranks as the fifteenth biggest EU-28 producer in 2012 with around 130,000 tonnes of plastic wastes, while it ranked as the seventh biggest producer in 2006 with more than 750,000 tonnes of plastic wastes.

In the case of Spain, the decrease may be due to both the effect of the economic crisis on consumption and a change in methodology in order to avoid double counting. No further information was provided by Member States that might explain the figures.

PlasticsEurope's data for plastic packaging waste generation in countries presented in Figure 1.5 shows similar figures for the UK, Italy and France, but higher figures for Germany. Eurostat data should be considered with caution because no explanation could be found for the fact that the UK reports much more plastic waste than Italy, Germany or France.

Import/export into/outside the EU-28

Quantities of imported and exported plastic wastes into/outside the EU-28 were collected from the Eurostat COMEXT Database. Quantities are available on a monthly and yearly basis from 1988 to 2014. For the purpose of the study, yearly imported and exported quantities from 2006 to 2014 were considered. Relevant data were identified based on their CN8 code. According to the methodology used in the UBA 2011 report, the following CN8 codes were used for plastic wastes:

WDF	CN8 Code	Description
Waste plastics (production residues)	39151000	Waste, parings and scrap of polymers of ethylene
	39152000	Waste, parings and scrap of polymers of styrene
	39153000	Waste, parings and scrap of polymers of vinyl chloride
	39159011	Waste, parings and scrap of polymers of propylene
	39159018	Waste, parings and scrap, of addition polymerization products (excl. that of polymers of ethylene, styrene and vinyl chloride and propylene)
	39159090	Waste, parings and scrap, of plastics (excl. that of additional polymerization products)

Table 1.6 shows that the EU-28 has a positive trade balance, which represented around 13% of EU-28 plastic waste generation in 2010 and 12% in 2012. This trade balance increased slightly between 2010 and 2012, then decreased over the year 2012 and increased significantly again from the year 2013 until 2014.

Table 1.6: Evolution of plastic wastes trade outside the EU-28 (Source: Eurostat COMEXT Database)

	Import/export outside the EU-28 (thousand tonnes/yr)		
	Import	Export	Trade balance
2006	252	2,105	1,853
2008	238	2,243	2,005
2010	75	2,129	2,053
2012	79	2,191	2,111
2014	108	2,194	2,086

Treatment of plastic wastes

Plastic waste treatment data comes from Eurostat Waste Statistics. Eurostat provides data on material recovery for the years 2006, 2008, 2010 and 2012, but data on other methods of treatment (energy recovery, incineration on land, and landfill) are only available for the years 2010 and 2012.

Table 1.7: Evolution of the plastic wastes sent for energy recovery and incineration by Member State (Source: Eurostat Waste Statistics)

	2010 (tonnes/yr)		2012 (tonnes/yr)	
	Energy recovery (R1)	Incineration/ Disposal (D10)	Energy recovery (R1)	Incineration/ Disposal (D10)
Austria	126,192	338	39,845	0
Belgium	10,259	4,487	17,028	3,497
Bulgaria	585	40	3,388	76
Croatia	652	132	0	0
Cyprus	3	5	0	0
Czech Republic	44,676	118	28,248	253
Denmark	1,275	0	4,343	0
Estonia	719	0	0	0
Finland	19,724	15,381	32,047	10,031
France	750,000	0	776,211	0
Germany	304,122	44,996	435,955	30,659
Greece	0	0	601	0

	2010 (tonnes/yr)		2012 (tonnes/yr)	
	Energy recovery (R1)	Incineration/ Disposal (D10)	Energy recovery (R1)	Incineration/ Disposal (D10)
Hungary	5,496	3,121	7,526	2,815
Ireland	0	0	13	0
Italy	12,034	23,372	44,405	31,624
Latvia	0	0	0	0
Lithuania	0	0	72	0
Luxembourg	22,225	0	6,000	0
Malta	0	0	0	0
Netherlands	86,610	8,969	86,900	2,994
Poland	17,675	116	9,312	236
Portugal	4,050	23	3,347	40
Romania	16,414	1,856	18,837	538
Slovakia	2,756	65	1,010	22
Slovenia	3,998	1,043	117	1,643
Spain[11]	0	15,238	0	0
Sweden	84,718	0	105,011	0
United Kingdom	0	0	0	0
Total EU-28	1,514,183	119,300	1,620,216	84,428

Between 2010 and 2012 the amount of plastic wastes sent for energy recovery increased by 7% at the EU-28 level. Looking at Table 1.7, it appears that plastic wastes sent to incineration decreased by 35,000 tonnes while during the same period plastics sent for energy recovery increased by 100,000 tonnes.

Figure 1.6 shows the repartition of plastic waste treatment methods for the 14 EU-28 countries representing 99% of plastic wastes sent to incineration and energy recovery in 2012. France is both the main producer of energy from plastic wastes and the country which sends the most plastics for landfilling.

[11] "Plastic waste Management in European countries 2012-Facts and Figures. Consultic" provides complementary data for post-consumer plastic waste treatment in 2012 in Spain: generation (2 065kt)/ recycling (584-28%)/ energy recovery (345-17%)/ landfill (1136-55%).

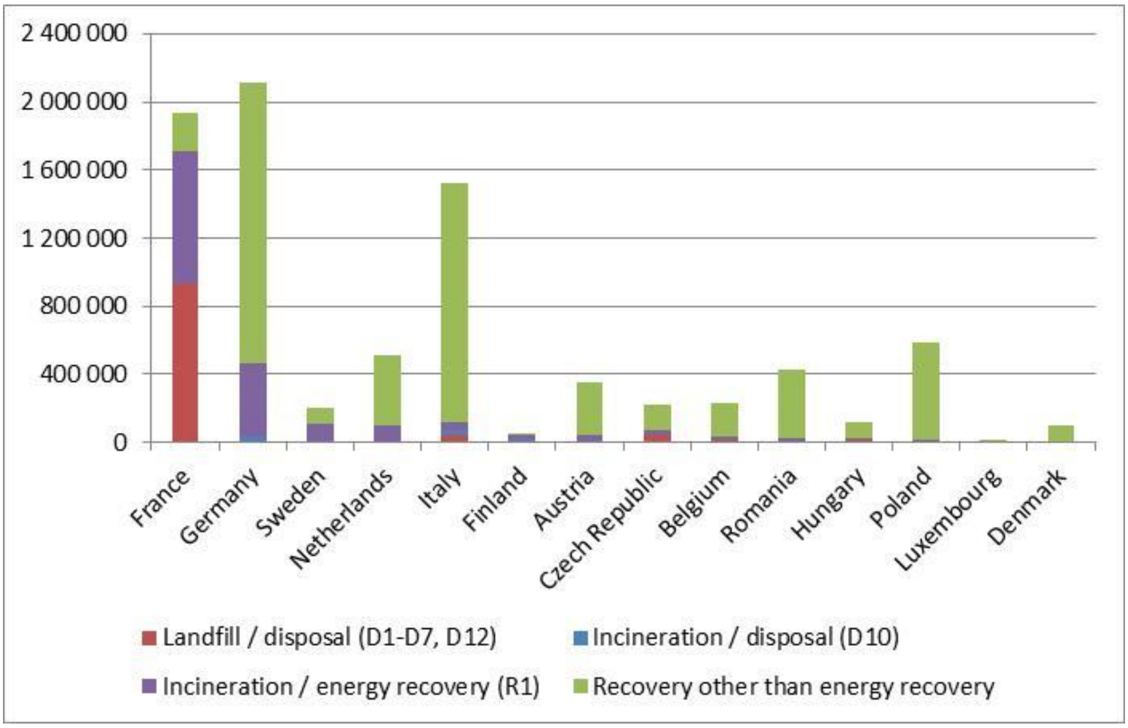


Figure 1.6: Treatment of plastic wastes for the 14 EU-28 main contributors to energy recovery from plastic waste in 2012 (Source: Eurostat Waste Statistics – in tonnes/yr)

Figure 1.7 gives an overview of the repartition of plastic waste treatment methods in the EU-28 and its evolution between 2010 and 2012. Looking at Figure 1.7, it appears that the European hierarchy for waste treatment was not applied in the EU-28 globally because plastic wastes sent for landfilling increased the most between 2010 and 2012.

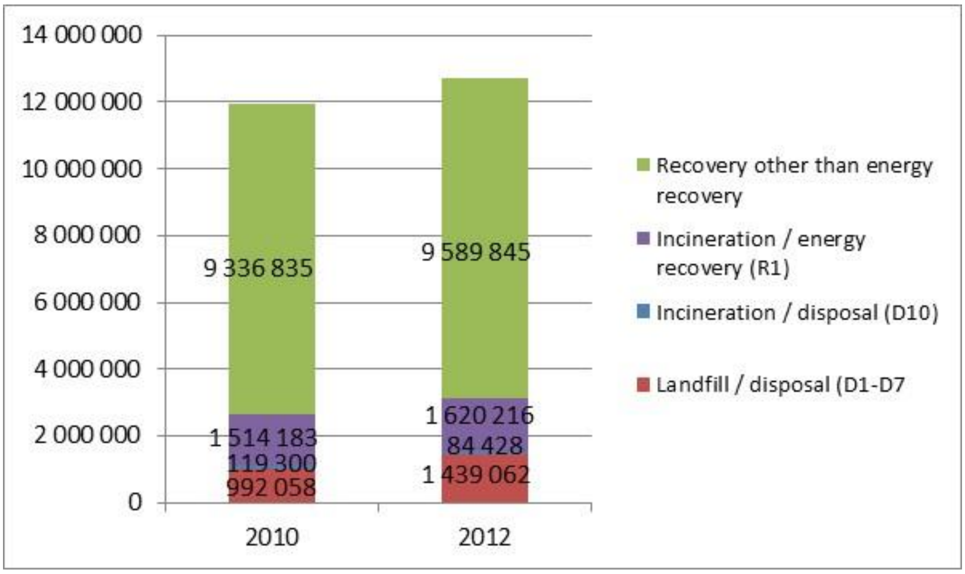


Figure 1.7: Evolution of plastic waste treatment methods in the EU-28 (Source: Eurostat Waste Statistics – in tonnes/yr)

According to PlasticsEurope, the evolution of the waste management for the 25 million tonnes of post-consumer plastics produced annually in the EU-28 is in line with the waste hierarchy: from 2006 to 2014, a decrease of landfill by 38%, and an increase of wastes sent for energy recovery and recycling by 46% and 64% respectively[12].

The possibility of using plastics as an energy source depends on several factors: the polymer (HDPE, PET, PP), the source (packaging, agriculture, EEE, vehicles), the existence of pollutants such as metals and their method of collection and treatment (separated, mixed, crushing the product, etc.).

3.3.3 Paper wastes

Generation of paper wastes

Data on the generation of paper wastes comes from Eurostat Waste Statistics. Eurostat's EWC-Stat category "07.2 Paper and cardboard wastes" contains only non-hazardous wastes.

The category and main NACE sectors that produce paper wastes are described as follows by the Eurostat Manual on waste statistics[13]:

"*Paper and cardboard wastes (07.2): These wastes are paper and cardboard from sorting and separate sorting by businesses and households. This category includes fibre, filler and coating rejects from pulp, paper and cardboard production. These wastes are largely generated by three activities: source separate collection, mechanical treatment of waste and pulp, and paper and cardboard production and processing. All paper and cardboard wastes are non-hazardous*."

Table 1.8: Evolution of the generation of paper wastes by Member State (Source: Eurostat Waste Statistics)

	Paper waste generation (thousand tonnes/yr)			
	2006	2008	2010	2012
Austria	2,020	1,525	1,937	1,841
Belgium	4,524	3,543	4,214	3,870
Bulgaria	317	110	160	202
Croatia	703	103	144	200
Cyprus	173	153	146	137
Czech Republic	637	698	690	702
Denmark	788	782	1,038	1,025
Estonia	439	159	80	95
Finland	1,231	806	767	649
France	7,611	6,899	7,005	7,348
Germany	9,334	9,982	8,062	8,184
Greece	474	729	652	522
Hungary	574	591	585	538
Ireland	1,101	34	746	396
Italy	5,612	5,161	5,352	5,148
Latvia	28	10	45	106
Lithuania	95	109	105	124
Luxembourg	97	105	125	109
Malta	4	4	12	11

[12] http://www.plasticseurope.org/Document/plastics---the-facts-2015.aspx.

[13] Additional information can be found in the "Guidance on classification of waste according to EWC-Stat categories" document.

	Paper waste generation (thousand tonnes/yr)			
	2006	2008	2010	2012
Netherlands	2,691	2,940	2,652	2,313
Poland	769	1,134	1,009	1,135
Portugal	2,380	1,150	1,249	987
Romania	1,099	548	585	928
Slovakia	199	219	192	222
Slovenia	175	200	134	130
Spain	4,648	4,733	3,843	3,599
Sweden	2,405	2,292	1,280	744
United Kingdom	14,242	12,803	5,760	5,680
Total EU-28	**64,370**	**57,518**	**48,567**	**46,945**

According to the Eurostat Manual on waste statistics, between 2008 and 2010, the significant decrease in paper wastes generation shown in Table 1.8 was mainly due to the evolution of waste categories. Indeed, two codes on production waste and unspecified wastes were removed from this category during that period.

This downward trend also results from a structural evolution due to a more general trend of reduced material use, which impacts mostly paper consumption and, to a lesser extent, the cardboard industry.

Based on data from Eurostat in Table 1.8, Figure 1.8 presents the evolution of the generation of paper wastes for the 14 Member States that were responsible for more than 93% of the overall generation in 2012.

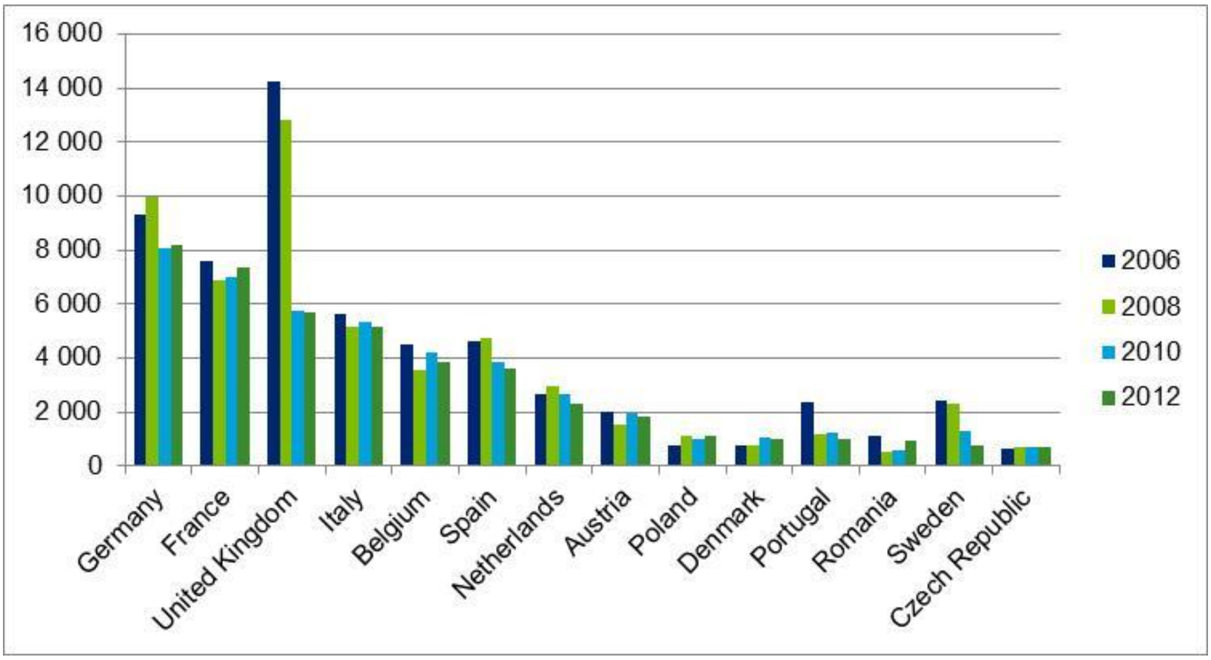


Figure 1.8: Evolution of the generation paper wastes for the 14 main EU-28 producers in 2012 (Source: Eurostat Waste Statistics – in thousand tonnes/yr)

Figure 1.8 shows that most of the main EU-28 paper waste producers display a generally downward trend in generation.

The sudden drop observed for the UK in Figure 1.8 between 2008 and 2010 is due to the adoption in 2012 of improved methodology for collecting data on paper wastes. The data for 2010 was revisited using the new methodology as a basis; however, the figures for year 2008 reflect the original methodology that was previously applied.

Import/export into/outside the EU-28

The data concerning the quantities of exported and imported paper wastes from/to the EU-28 were collected from Eurostat COMEXT Database. Quantities are available on a monthly and yearly basis from 1988 to 2014. For the purpose of the study, yearly imported and exported quantities from 2006 to 2014 were considered. Relevant data were identified based on their CN8 code. According to the methodology used in the UBA 2011 report, the following CN8 codes were used for paper wastes:

WDF	CN8 Code	Description
Waste paper	47071000	Unbleached craft paper or paperboard or corrugated paper or paperboard
	47072000	Other paper or paperboard made mainly of bleached chemical pulp, not coloured in the mass
	47073010	Old and unsold newspapers and magazines, telephone directories, brochures and printed advertising material
	47073090	Other paper or paperboard made mainly of mechanical pulp (for example, newspapers, journals and similar printed matter)
	47079010	Other, including unsorted waste and scrap paper
	47079090	Other, including sorted waste and scrap paper

Table 1.9 shows that the EU-28 has a positive trade balance which represented 20% of EU-28 waste generation in 2010 and 18% in 2012.

Table 1.9: Evolution of paper wastes trade outside the EU-28 (Source: Eurostat COMEXT Database)

	Import/export into/outside the EU-28 (tonnes/yr)		
	Import	Export	Trade balance
2006	1,007,054	8,628,412	7,621,358
2008	1,164,381	11,575,483	10,411,101
2010	1,362,876	10,183,107	8,820,230
2012	1,456,710	11,201,506	9,744,796
2014	1,293,907	9,913,960	8,620,052

Treatment of paper wastes

Paper waste treatment data comes from Eurostat Waste Statistics. Eurostat provides data on material recovery for the years 2006, 2008, 2010 and 2012, but data on other methods of treatment (energy recovery, incineration on land, and landfill) is only available for the years 2010 and 2012.

Table 1.10: Evolution of the paper wastes sent for energy recovery and incineration by Member State (Source: Eurostat Waste Statistics)

	2010 (tonnes/yr)		2012 (tonnes/yr)	
	Energy recovery (R1)	Incineration/ Disposal (D10)	Energy recovery (R1)	Incineration/ Disposal (D10)
Austria	13,709	570	10,546	0
Belgium	2,785	1,218	0	155
Bulgaria	24	213	10	15
Croatia	56	86	6	0
Cyprus	0	48	0	0

	2010 (tonnes/yr)		2012 (tonnes/yr)	
	Energy recovery (R1)	Incineration/ Disposal (D10)	Energy recovery (R1)	Incineration/ Disposal (D10)
Czech Republic	9,450	377	9,324	368
Denmark	3,351	0	4,012	0
Estonia	3	3	13	0
Finland	34,702	15,069	34,053	13,062
France	345,000	0	203,732	0
Germany	47,646	19,235	38,223	4,434
Greece	0	0	0	0
Hungary	952	501	846	282
Ireland	6	0	0	0
Italy	748	1,373	54	1,828
Latvia	13	0	30	0
Lithuania	101	0	73	0
Luxembourg	0	0	0	0
Malta	0	84	0	4
Netherlands	44,943	136	9	0
Poland	2,962	93	2,561	89
Portugal	429	89	166	254
Romania	19,056	2,244	10,349	58
Slovakia	2,050	92	395	145
Slovenia	21	40	17	26
Spain	0	0	0	0
Sweden	12,228	0	5,956	0
United Kingdom	74	468	0	334
Total EU-28	540,309	41,939	320,375	21,054

Between 2010 and 2012 the amount of paper wastes sent for energy recovery decreased by 40% at the EU-28 level. France is one of the main countries responsible for this evolution because the amount of paper wastes sent for energy recovery dropped from 345,000 tonnes in 2010 to 204,000 tonnes in 2012. The Netherlands are also responsible for this evolution but to a lesser extent.

Figure 1.9 shows the repartition of paper waste treatment methods for the 14 EU-28 countries representing nearly 100% of paper wastes sent to incineration and energy recovery in 2012. Material recovery is not included in this figure because it represents 99% of the paper wastes treated (see Figure 1.10 below). Looking at Figure 1.9, we can see that France alone represents 60% of the paper wastes sent for energy recovery.

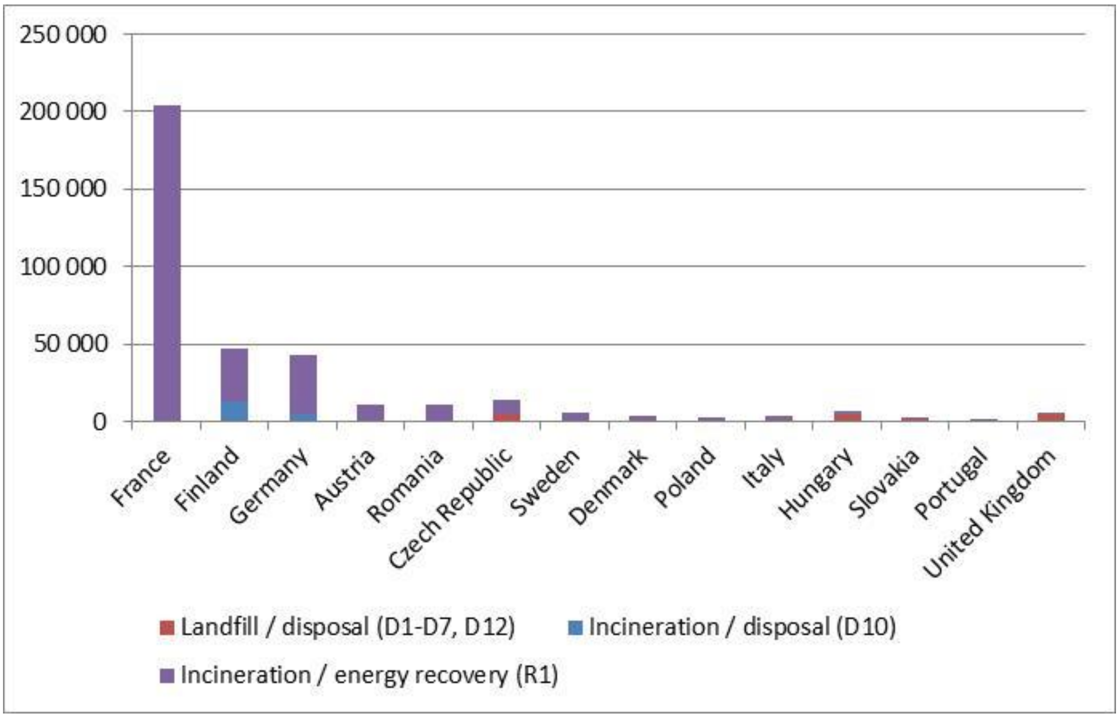


Figure 1.9: Treatment (excl. material recovery) of paper wastes for the 14 EU-28 main contributors to energy recovery from paper wastes in 2012 (Source: Eurostat Waste Statistics – in tonnes/yr)

Figure 1.10 gives an overview of the repartition of paper waste treatment methods in the EU-28 and its evolution between 2010 and 2012. The waste management system in the EU-28 is in line with the waste hierarchy because more than 99% of wastes are recovered.

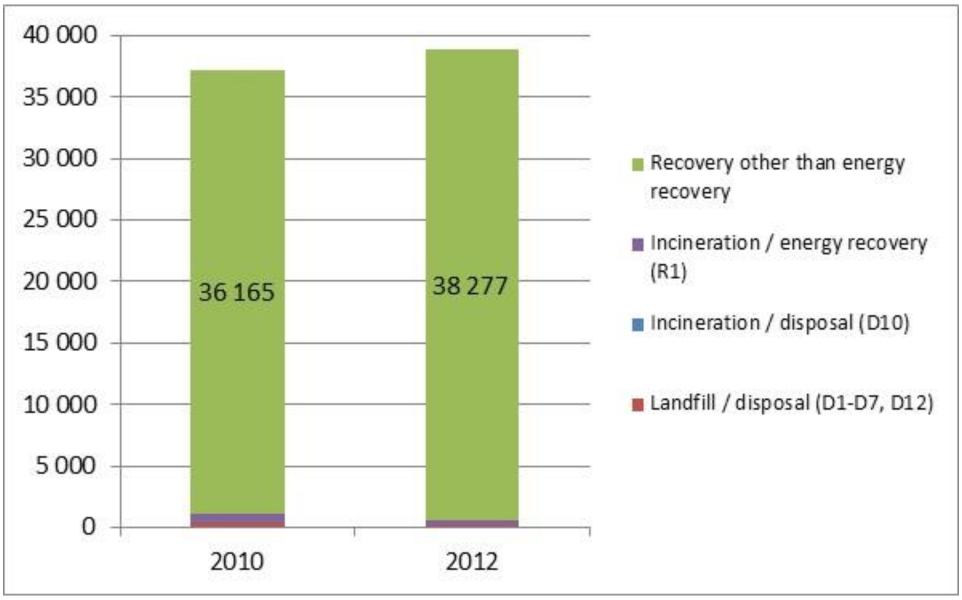


Figure 1.10: Evolution of paper waste treatment methods in the EU-28 (Source: Eurostat Waste Statistics – in tonnes/yr)

With the exception of heavily contaminated wastes, in compliance with the waste hierarchy, paper and cardboard wastes should be recycled.

3.3.4 Textile wastes

Generation of textile wastes

Data on the generation of textile wastes comes from Eurostat Waste Statistics. Eurostat's EWC-Stat category "07.6 textile wastes" contains only non-hazardous wastes.

The category and main NACE sectors that produce textile wastes are described as follows by the Eurostat Manual on waste statistics[14]:

"*Textile wastes (07.6): These wastes are textile and leather waste; textile packaging; worn clothes and used textiles; waste from fibre preparation and processing; waste tanned leather; and separately collected textile and leather waste. They originate from only a small number of activities: the leather and fur industry, the textile industry, the mechanical treatment of waste and source separate collection. All textile wastes are non-hazardous*."

According to this definition, textile waste generation only takes into account the wastes that are collected.

Table 1.11: Evolution of the generation of textile wastes by Member State (Source: Eurostat Waste Statistics)

	Textile waste generation (thousand tonnes/yr)			
	2006	2008	2010	2012
Austria	35	142	54	46
Belgium	627	166	246	173
Bulgaria	13	11	6	7
Croatia	21	9	17	3
Cyprus	24	42	31	28
Czech Republic	78	77	62	63
Denmark	0	0	1	3
Estonia	7	5	2	2
Finland	7	8	8	16
France	432	391	380	440
Germany	182	213	238	310
Greece	16	5	5	2
Hungary	50	13	27	20
Ireland	182	5	5	19
Italy	823	541	434	396
Latvia	0	0	0	0
Lithuania	6	5	5	9
Luxembourg	6	5	6	6
Malta	0	0	0	0
Netherlands	125	129	107	114
Poland	73	84	83	94
Portugal	476	96	125	61
Romania	254	19	19	15

[14] Additional information can be found in the "Guidance on classification of waste according to EWC-Stat categories" document.

	Textile waste generation (thousand tonnes/yr)			
	2006	2008	2010	2012
Slovakia	19	15	8	9
Slovenia	13	10	7	7
Spain	92	138	100	77
Sweden	20	20	19	6
United Kingdom	247	275	1,101	1,182
Total EU-28	3,826	2,425	3,097	3,108

According to Table 1.11, the generation of textile wastes decreased by 37% from 2006 to 2008 and increased by 28% from 2008 to 2010.

Based on data from Eurostat in Table 1.11, Figure 1.11 shows the evolution of the generation of textile wastes for the 14 main EU-28 producers representing 97% of the total EU-28 generation in 2012.

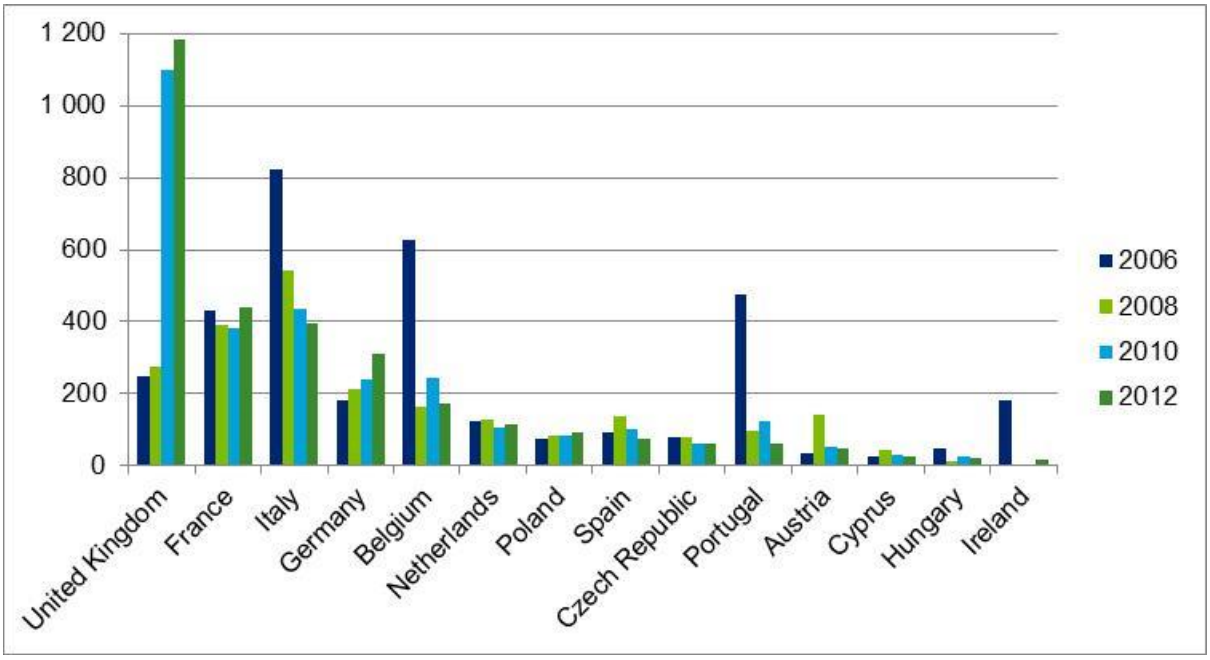


Figure 1.11: Evolution of the generation of textile wastes for the 14 main EU-28 producers in 2012 (Source: Eurostat Waste Statistics – in thousand tonnes/yr)

As shown in Figure 1.11, there was a sudden drop in textile wastes generation from 2006 to 2008 in four countries (Italy, Belgium, Portugal and Ireland). This decrease could be due to the evolution in the reporting methodology in these countries. No further information was provided by Member States that might explain this trend. In the same figure, it can be seen that between 2008 and 2010 the amount of textile waste generated in the UK increased by 400%. According to Defra, this is due to the adoption of an improved reporting methodology as of 2012 (2010 data being revisited using the new methodology).

Import/export into/outside the EU-28

Quantities of exported and imported textile wastes within the EU-28 were collected from the Eurostat COMEXT Database. Quantities are available on a monthly and yearly basis from 1988 to 2014. For the purpose of the study, yearly imported and exported quantities from 2006 to 2014 were considered. Relevant data were identified based on their CN8 code. According to the methodology used in the UBA 2011 report, the following CN8 codes were used for textile waste:

WDF	CN8 Code	Description
Waste textiles	41152000	Parings and other waste of leather or of composition leather, not suitable for the manufacture of leather articles; leather dust, powder and flour
	50030000	Silk waste (including cocoons unsuitable for reeling, yarn waste and garnetted stock)
	51031010	Wool or of fine animal hair, non-carbonised (excl. garnetted stock)
	51031090	Wool or of fine animal hair, carbonised (excl. garnetted stock)
	51032010	Yarn waste of wool or of fine animal hair
	51032091	Waste of wool or fine animal hair not carbonized
	51032099	Waste of wool or fine animal hair carbonized
	51033000	Waste of coarse animal hair
	52021000	Cotton waste (yarn waste)
	52029100	Cotton waste (garnetted stock)
	52029900	Other cotton waste
	53013090	Flax waste, incl. yarn waste and garnetted stock
	55051010	Waste (including yarn waste and garnetted stock) of manmade fibres of nylon or other polyamides
	55051030	Waste of polyesters
	55051050	Waste of acrylic or modacrylic
	55051070	Waste of polypropylene
	55051090	Waste of other synthetic fibres
	55052000	Waste off artificial fibres
	63090000	Worn clothing and other worn articles
	63101010	Used or new rags, scrap twine, cordage, rope and cables and worn out articles of twine, cordage, rope or cables, of wool or fine or coarse animal hair, sorted
	63101030	Rags of flax or cotton, sorted
	63101090	Rags of other textile materials, sorted
	63109000	Rags, unsorted

Table 1.12 shows that the EU-28 has a growing positive trade balance which represented 29% of the EU-28 textile waste generation in 2010 and 32% in 2012. This trade balance has been increasing since 2006.

Table 1.12: Evolution of textile wastes trade outside the EU-28 (Source: Eurostat COMEXT Database)

	Import/export into/outside the EU-28 (tonnes/yr)		
	Import	Export	Trade balance
2006	334,770	864,379	529,609
2008	295,794	1,006,198	710,404
2010	232,696	1,116,694	883,998
2012	239,730	1,228,421	988,691
2014	262,880	1,301,043	1,038,163

Treatment of textile wastes

Textile waste treatment data comes from Eurostat Waste Statistics. Eurostat provides data on material recovery for the years 2006, 2008, 2010 and 2012, but data on other methods of treatment (energy recovery, incineration on land, and landfill) is only available for the years 2010 and 2012.

For the years 2010 and 2012, not all countries provide data for all methods of treatment and for some countries like the UK and Portugal there are sudden increases and drops in the amount of wastes sent for material recovery.

Finally, it is important to consider that a significant amount of collected textile wastes are reused. Unfortunately there is no data available to estimate the share of collected textile wastes that are reused.

Table 1.13: Evolution of the textile wastes sent to incineration and energy recovery by Member State (Source: Eurostat Waste Statistics)

	2010 (tonnes/yr)		2012 (tonnes/yr)	
	Energy recovery (R1)	Incineration/ Disposal (D10)	Energy recovery (R1)	Incineration/ Disposal (D10)
Austria	20,334	61	22,767	0
Belgium	231	101	0	87
Bulgaria	80	1	117	0
Croatia	149	0	0	0
Cyprus	0	1	0	0
Czech Republic	14,156	147	20,701	74
Denmark	48	0	150	0
Estonia	0	0	0	0
Finland	60	1	12	0
France	4,984	192	0	0
Germany	36,122	5,482	41,489	5,452
Greece	0	0	0	0
Hungary	3,526	53	2,229	113
Ireland	0	0	17	0
Italy	0	1,252	1	1,509
Latvia	5	0	1,302	0
Lithuania	0	0	44	0
Luxembourg	0	0	0	0
Malta	0	0	0	0
Netherlands	6,599	3,472	20,193	151
Poland	1,946	21	1,957	48
Portugal	244	26	529	12
Romania	4,023	109	2,110	505
Slovakia	26	63	856	52
Slovenia	0	13	0	0
Spain	0	0	2,277	0
Sweden	0	0	0	0
United Kingdom	0	7,417	0	9,723

	2010 (tonnes/yr)		2012 (tonnes/yr)	
	Energy recovery (R1)	Incineration/ Disposal (D10)	Energy recovery (R1)	Incineration/ Disposal (D10)
Total EU-28	92,533	18,412	116,751	17,726

According to Table 1.13, the amount of textile wastes sent to incineration (D10) and energy recovery (R1) represents around 4% of the total textile wastes generated and collected. This estimate is in line with the estimated 5% of generated and collected textile wastes from the UBA report from 2011 (based on a literature review and interviews with experts).

Figure 1.12 shows the repartition of textile waste treatment methods for the 14 EU-28 countries representing nearly 100% of textile wastes sent to incineration and energy recovery in 2012. Recovery (other than energy recovery) is not included in this figure because it represents nearly 90% of the textile wastes treated (see Figure 1.13 below). As shown by Figure 1.12, Germany, Austria, the Czech Republic and the Netherlands represent 82% of the textile wastes sent to incineration (with and without energy recovery).

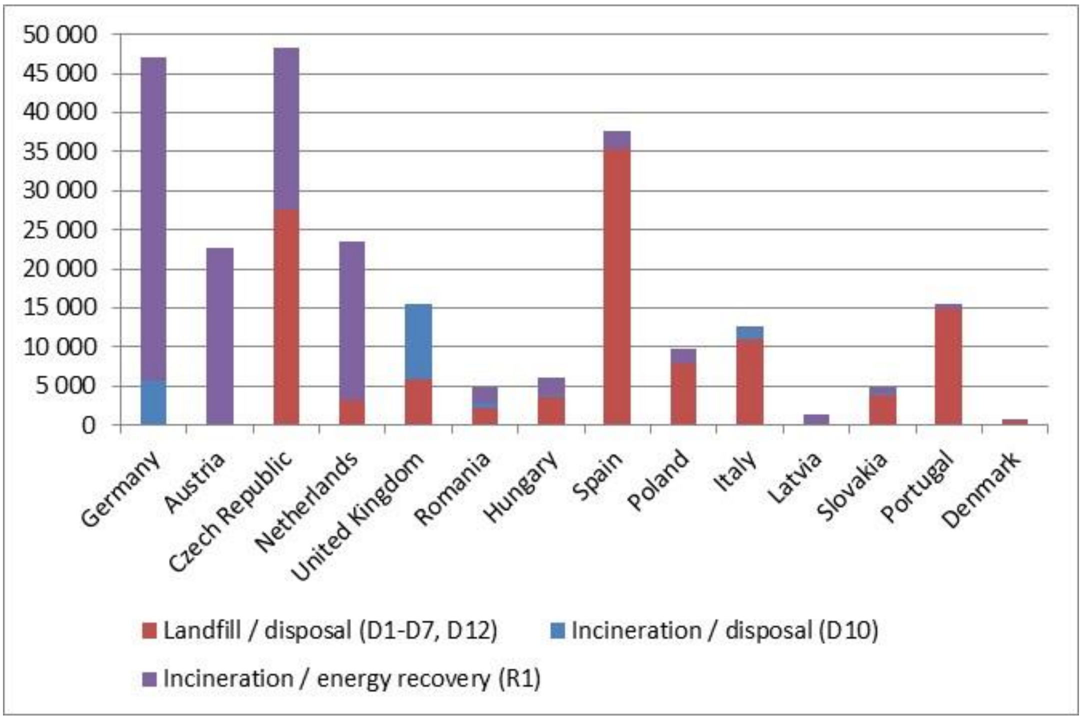


Figure 1.12: Treatment (excl. material recovery) of textile wastes for the 14 EU-28 main contributors to energy recovery from textile wastes in 2012 (Source: Eurostat Waste Statistics – in tonnes/yr)

Figure 1.13 provides an overview of the repartition of textile waste treatment methods in the EU-28 and its evolution between 2010 and 2012.

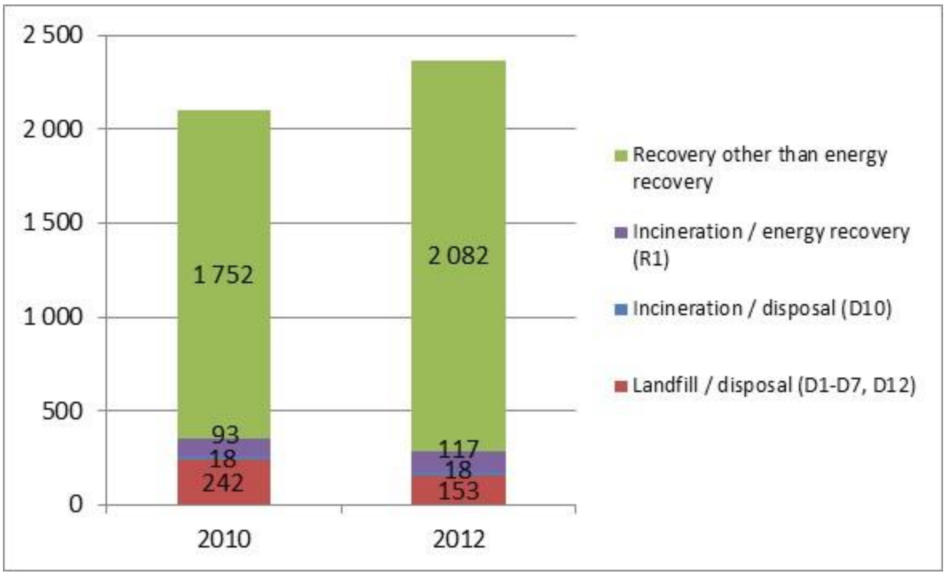


Figure 1.13: Evolution of textile waste treatment methods in the EU-28 (Source: Eurostat Waste Statistics – in thousand tonnes/yr)

The waste management system in the EU-28 is in line with the waste hierarchy because nearly 90% of wastes are recovered. However, considering the evolution in data reported by some Member States (including the UK), and the difficulty to estimate the share of textile wastes reused, these data should be used with caution.

At the time of writing this document, the European Textile Service Association was conducting a study on the end of life of textiles. It could provide useful information to explain the changes observed in the previous graphs, and to better understand the future trends in the EU-28 with regards to waste hierarchy.

3.3.5 Waste tyres and waste rubber

Generation of waste tyres and waste rubber

There are two main sources of information for the generation of waste tyres and waste rubber:

- Eurostat Waste Statistics collects data on the generation of the EWC-Stat category "07.3 Rubber wastes". It provides data every two years, 2012 being the latest available, for each EU-28 country. The category and main NACE sectors that produce textile wastes are described as follows by the Eurostat Manual on waste statistics: "*Rubber wastes (07.3): item 19. These wastes are only end-of-life tyres which come from the maintenance of vehicles, and end-of-life vehicles. All rubber wastes are non-hazardous. They can be generated in all sectors*. According to this definition, rubber production waste (hose, gloves, technical rubber goods) should not be included in the category "07.3 Rubber wastes". However, looking at the origin of the rubber waste, we see that 230,000 tonnes of the total rubber waste originates from NACE sectors C20-C22 "Manufacture of chemical, pharmaceutical, rubber and plastic products". This might indicate that a significant amount of rubber production waste is included in this category.
- ETRMA - the European Tyre & Rubber Manufacturers Association collects annual data from the industry on the amount of waste tyres generated. It provides annual data, 2013 being the latest available, for each EU-28 country.

This study uses the data from ETRMA because it seems to be more in line with real figures. For instance in 2009, Eurostat Statistics estimate that 3.75 million tonnes of wastes were produced, Portugal being responsible for generating 1 million tonnes of such wastes. According to the UBA 2011 report and the Portuguese collection scheme (Valorpneu), this figure should be around 90,000 tonnes. The same year, ETRMA estimates that 3.12 million tonnes of wastes were produced, of which 89,000 tonnes came from Portugal.

ETRMA has developed its own two-step methodology to estimate the share of waste tyres:

- Step 1: estimation of used tyres generation = new tyres (replacement market) + retreaded tyres (national market) + import of second-hand tyres;
- Step 2: estimation of waste tyres generation = used tyres generation – reuse – export – retreating.

In some counties like France and Italy, waste tyres generation also includes historical stocks that are collected and treated. Data collected by ETRMA comes from a wide range of sources including:

- national statistics reported to public authorities (e.g. ADEME in France, UK UTWG, DK, BG, SK, CZ);
- national statistics from other sources (Germany);
- end-of-life tyres management companies (14 operational; 16 created) in the ETRMA network;
- other end-of-life tyres management companies (such as FRP, TNU, EcoTyre);
- tyre industry.

Data for the generation of waste tyres are presented in Table 1.14 below.

Table 1.14: Evolution of the generation of wastes tyres by Member State (Source: ETRMA, n.a. = not available)

	Waste tyres generation (thousand tonnes/yr)			
	2008	2010	2012	2013
Austria	49	50	60	60
Belgium	73	69	66	55
Bulgaria	27	20	22	25
Croatia	n.a.	n.a.	n.a.	n.a.
Cyprus	8	8	5	5
Czech Republic	57	55	54	55
Denmark	41	37	36	38
Estonia	9	10	11	15
Finland	42	40	46	50
France	297	302	323	352
Germany	432	475	424	413
Greece	52	47	36	32
Hungary	43	29	36	36
Ireland	38	28	24	25
Italy	323	371	330	354
Latvia	9	10	11	9
Lithuania	11	11	13	23
Luxembourg	n.a.	n.a.	n.a.	n.a.
Malta	0	0	0	0
Netherlands	44	50	62	62
Poland	195	219	185	158
Portugal	72	71	64	66
Romania	53	33	46	34
Slovakia	23	22	23	23
Slovenia	15	11	10	15
Spain	250	234	219	228
Sweden	67	78	76	79
United Kingdom	368	335	282	419
Total EU-28	**2,598**	**2,615**	**2,464**	**2,631**

According to Table 1.14, the generation of wastes tyres was stable (+1.3%) from 2008 to 2013.

Based on data from ETRMA in Table 1.14, Figure 1.14 presents the evolution of the generation of waste tyres for the 14 main EU-28 producers representing 91% of the total EU-28 generation in 2013.

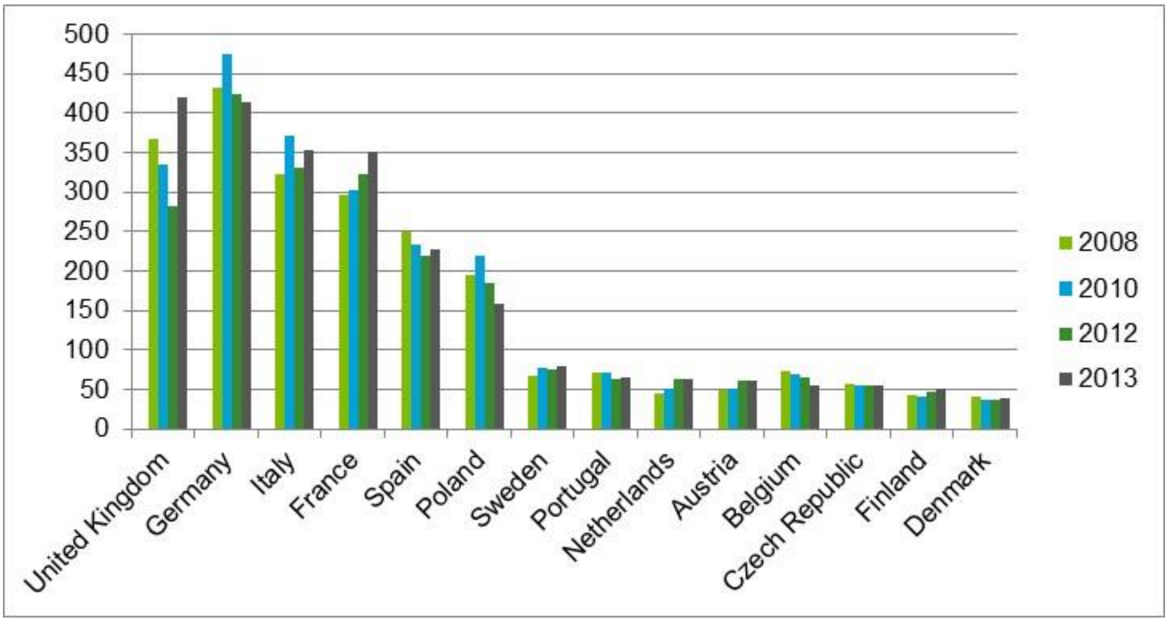


Figure 1.14: Evolution of the generation of waste tyres for the 14 main EU-28 producers in 2013 (Source: ETRMA – in thousand tonnes/yr)

In 2013, the six main EU-28 producers of waste tyres (the UK, Germany, Italy, France, Spain and Poland) represented 73% of the wastes generated. The global waste generation stability observed at European level (see Table 1.14) hides significant evolutions for some Member States: a decrease in Poland (-28%) and Germany (-13%) since 2010, and an increase in France (+17%) and the UK. In the UK, the increase by 48% of waste generation from 2012 to 2013 has not been explained and may be due to methodological changes in the estimation.

<u>Import/export into/outside the EU-28</u>

Quantities of imported and exported waste tyres and waste rubber into/outside the EU-28 were collected from the Eurostat COMEXT Database. Quantities are available on a monthly and yearly basis from 1988 to 2014. For the purpose of the study, yearly imported and exported quantities from 2006 to 2014 were considered. Relevant data were identified based on their CN8 code. According to the methodology used in UBA 2011 report, the following CN8 codes were used for waste tyres and waste rubber:

WDF	CN8 Code	Description
Waste tyres, waste rubber	40040000	Waste, parings and scrap of soft rubber and powders and granules obtained therefrom
	40170010	Hard rubber, e.g. ebonite, in all forms, incl. waste and scrap
	40122000	Used pneumatic tyres of rubber

Table 1.15 shows that the EU-28 has a positive trade balance that has been increasing since 2006.

Table 1.15: Evolution of waste tyres and waste rubber trade outside the EU-28 (Source: Eurostat COMEXT Database)

	Import/export into/outside the EU-28 (tonnes/yr)		
	Import	Export	Trade balance

	Import/export into/outside the EU-28 (tonnes/yr)		
	Import	Export	Trade balance
2006	94,578	212,749	118,171
2008	96,638	271,772	175,133
2010	96,836	322,782	225,945
2012	84,082	484,632	400,549
2014	79,594	611,467	531,872

Data in Table 1.15 includes waste tyres (CN8 Code 40122000) and other rubber waste (CN8 Codes 40040000 and 40170010). For comparison, Table 1.16 provides figures from ETRMA on the export of waste used tyres.

Table 1.16: Evolution of export of used tyres outside the EU-28 (Source: ETRMA)

	Export of used tyres (tonnes/yr)
2008	154,000
2010	179,000
2012	194,000
2013	244,000

<u>Treatment of waste tyres</u>

There are two main sources of information for treatment of waste tyres and waste rubber:

- Eurostat provides data on material recovery for the years 2006, 2008, 2010 and 2012 for EU-28 Member States. Data on other methods of treatment (energy recovery, incineration on land, and landfill) is only available for the years 2010 and 2012, and the quality of these data is uncertain because many countries have declared zero tonnes regarding quantities sent for landfill disposal and incineration on land.
- ETRMA possesses annual data (for EU-28 Member States and for the years 2006 to 2012) on the waste tyres treatment methods. According to ETRMA statistics, since 2008, at least 95% of the used tyres in Europe are recovered. This includes reuse of used tyres, recycling and energy recovery of end-of-life tyres. The management of the remaining 5% of wastes is uncertain. Some of it is lost to the ground and sent to landfill.

With regard to the treatment of end-of-life tyres (see Figure 1.15):

- 1.2 million tonnes are being sent to material recovery (latest data: 2013).
- About 1.3 million tonnes are sent annually for energy recovery (including co-incineration in cement kilns). On average, 92% of the tonnage of ELTs sent for energy recovery is sent to co-processing (cement kilns) and the remainder is used in district heating plants/boilers.

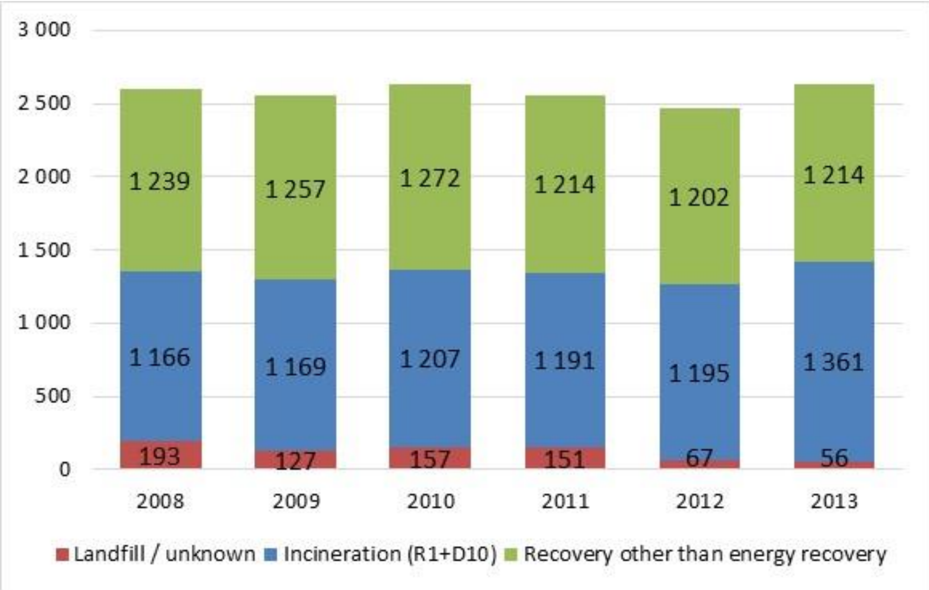


Figure 1.15: Evolution of waste tyres treatment methods in the EU-28 (Source: ETRMA – in thousand tonnes/yr)

According to ETRMA, under current market conditions the economic viability of pyrolysis, thermolysis and gasification has yet to be proved as there are few or no large-scale plants currently in operation. In 2013, the estimated quantity of ELT pyrolysis in Europe was about 11,000 tonnes in the EU-28.

3.3.6 Waste solvents

Generation of waste solvents

Data on the generation of waste solvents comes from Eurostat Waste Statistics. Eurostat's EWC-Stat category "01.1 spent solvents" contains only non-hazardous wastes.

The category and main NACE sectors that produce waste solvents are described as follows by the Eurostat Manual on waste statistics[15]:

"*Spent solvents (01.1): These are hydrocarbons, fluorocarbons, chlorinated carbons; organic halogenated, non-halogenated solvents, including organic washing liquids; and organic fluorinated refrigerants. They are used in chemical industries as reaction agent and in extraction processes, cleaning processes in mechanical engineering and surface treatment and appear almost exclusively in the manufacture of chemicals, chemical products, basic pharmaceutical products and preparations, and rubber and plastic products (item 9 of Section 8 of Annex I of the Waste Statistics Regulation). To a lesser extent, this type of waste can also be generated during the fabrication of metal products and during recycling. Separately collected fractions of spent solvents can be generated by almost all economic activities, including private households*."

[15] Additional information can be found in the "Guidance on classification of waste according to EWC-Stat categories" document.

Table 1.17: Evolution of the generation of waste solvents by Member State (Source: Eurostat Waste Statistics)

	Waste solvent generation (thousand tonnes/yr)			
	2006	2008	2010	2012
Austria	24	34	48	29
Belgium	208	75	176	302
Bulgaria	0	0	0	0
Croatia	5	1	0	1
Cyprus	0	0	0	0
Czech Republic	13	12	13	9
Denmark	15	14	19	22
Estonia	0	0	0	0
Finland	20	16	20	19
France	413	264	431	440
Germany	714	741	723	734
Greece	0	0	0	0
Hungary	36	29	22	36
Ireland	140	130	606	159
Italy	282	236	244	279
Latvia	0	0	1	1
Lithuania	0	0	0	0
Luxembourg	1	1	1	2
Malta	3	3	1	1
Netherlands	211	155	154	114
Poland	14	6	6	8
Portugal	61	12	10	9
Romania	1	2	3	1
Slovakia	9	3	3	3
Slovenia	10	12	21	19
Spain	218	257	182	190
Sweden	44	68	62	63
United Kingdom	417	308	206	251
Total EU-28	**2,863**	**2,382**	**2,952**	**2,694**

According to Table 1.17, the production of wastes solvents decreased by 17% from 2006 to 2008 and increased by 24% from 2008 to 2010.

Based on data from Eurostat in Table 1.17, Figure 1.16 shows the evolution of the generation of waste solvents for the 14 main EU-28 producers representing 99% of the total EU-28 generation in 2012.

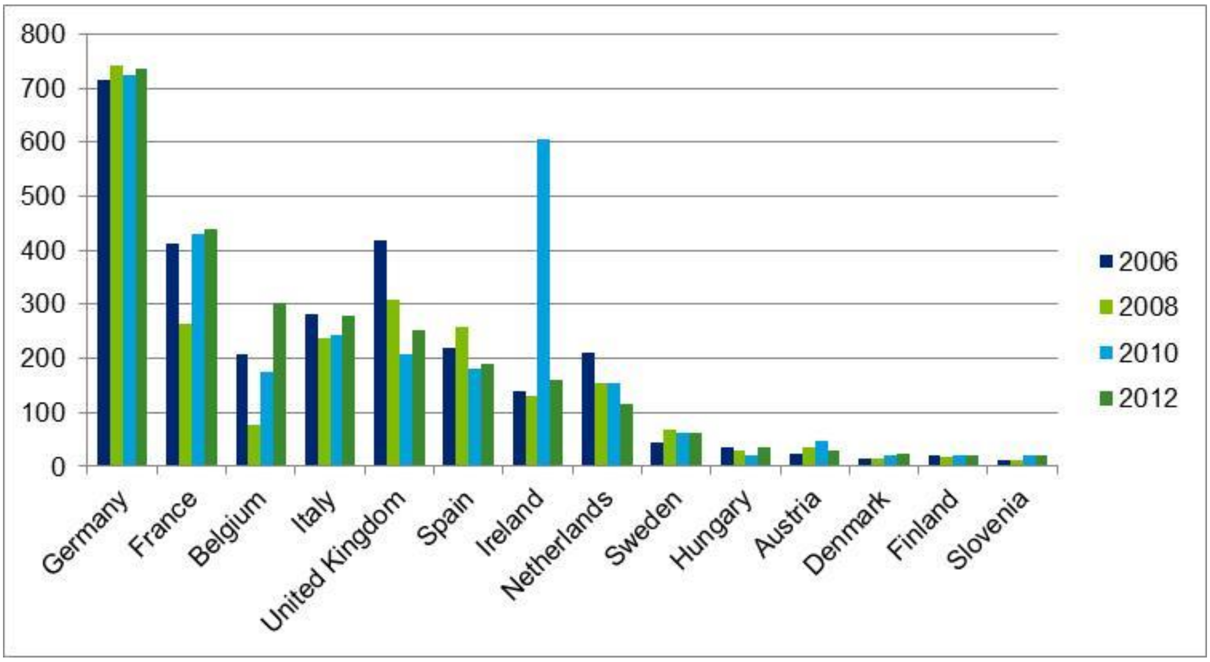


Figure 1.16: Evolution of the generation of waste solvents for the 14 main EU-28 producers in 2012 (Source: Eurostat Waste Statistics – in thousand tonnes/yr)

Several trends shown in Figure 1.16 are difficult to explain: the sudden drops in waste solvents generation in 2008 in France and Belgium and the sudden spike in Ireland in 2010, where generation was about 400% higher than in other years. No information was provided by Member States that might explain the figures.

Import/export into/outside the EU-28

Quantities of imported and exported waste solvents into/outside the EU-28 were collected from the Eurostat COMEXT Database. Quantities are available on a monthly and yearly basis from 1988 to 2014. For the purpose of the study, yearly imported and exported quantities from 2006 to 2014 were considered. Relevant data were identified based on their CN8 code. According to the methodology used in UBA 2011 report, the following CN8 codes were used for waste solvents:

WDF	CN8 Code	Description
Waste solvents	38254100	Waste organic solvents, halogenated
	38254900	Waste organic solvents, non-halogenated

Table 1.18 shows that the EU-28 has had a fluctuating and negative waste solvents trade balance since 2006, which reached a minimum in 2014. This trade balance represented around -0.12% of the EU-28 annual production of waste solvents in 2010 and -0.16% in 2012.

Table 1.18: Evolution of waste solvents trade outside the EU-28 (Source: Eurostat COMEXT Database)

	Import/export into/outside the EU-28 (tonnes/yr)		
	Import	Export	Trade balance
2006	6,065	1,782	-4,283
2008	5,933	253	-5,679
2010	8,322	4,926	-3,395

	Import/export into/outside the EU-28 (tonnes/yr)		
	Import	Export	Trade balance
2012	4,543	121	-4,421
2014	12,948	2,119	-10,829

<u>Treatment of waste solvents</u>

Waste solvent treatment data comes from Eurostat Waste Statistics. Eurostat provides data for all methods of treatment but only for the years 2010 and 2012.

Table 1.19: Evolution of the waste solvents sent for energy recovery and incineration by Member State (Source: Eurostat Waste Statistics)

	2010 (tonnes/yr)		2012 (tonnes/yr)	
	Energy recovery (R1)	Incineration/ Disposal (D10)	Energy recovery (R1)	Incineration/ Disposal (D10)
Austria	22,520	34,539	31,599	0
Belgium	42,212	34,700	3	37,994
Bulgaria	0	0	0	0
Croatia	32	0	0	0
Cyprus	0	4	0	2
Czech Republic	2,296	3,016	1,547	5,477
Denmark	14,261	0	14,277	0
Estonia	0	0	98	1
Finland	42	19,972	0	20,856
France	136,332	109,426	164,328	101,990
Germany	285,915	236,419	305,734	215,206
Greece	11	0	0	0
Hungary	72	14,728	0	18,042
Ireland	13,586	19,314	8,005	12,889
Italy	5,374	42,124	0	42,976
Latvia	0	200	0	0
Lithuania	0	12	0	49
Luxembourg	192	0	341	6
Malta	0	0	0	0
Netherlands	25,477	39,146	34,181	13,192
Poland	38	1,543	82	1,484
Portugal	3	2	13	0
Romania	57	2,330	15	106
Slovakia	12	189	11	150
Slovenia	2,000	10,933	917	6,645
Spain	44,796	836	30,103	0
Sweden	431	3,884	1,393	5,000
United Kingdom	8,581	0	0	0
Total EU-28	604,240	573,317	592,647	482,065

According to Table 1.19, almost the same amount of waste solvents is sent for incineration as for energy recovery, and the two treatment methods represented 40% of waste solvent generation in the EU-28 in 2010 and 2012.

According to a report from the JRC in 2010[16], energy recovery represented about 35% of the treatment and disposal pathways for waste solvents in the EU-28.

Figure 1.17 shows the repartition of waste solvent treatment methods for the 14 Member States responsible for nearly 100% of the waste solvent sent to incineration and energy recovery in the EU-28 in 2012.

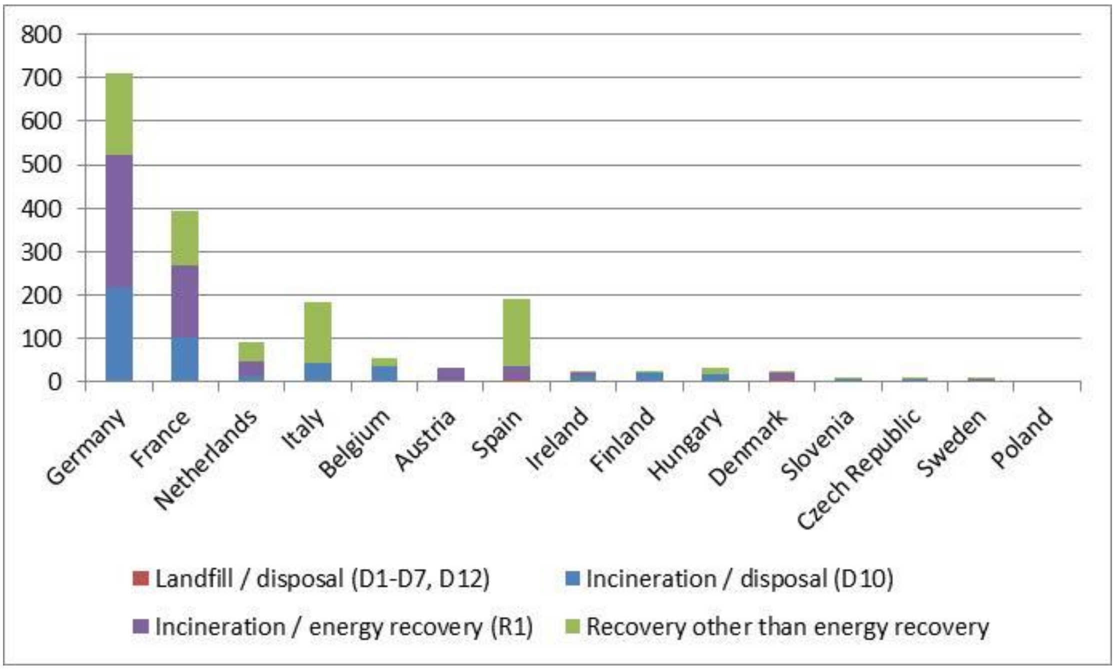


Figure 1.17: Treatment of waste solvents for the 14 EU-28 main contributors to energy recovery from waste solvents in 2012 (Source: Eurostat Waste Statistics – in thousand tonnes/yr)

According to Figure 1.17, Germany and France are by far the main contributors to energy recovery from waste solvents. Energy recovery could still increase because nearly a third of wastes are still sent to incinerators in these countries.

Figure 1.18 gives an overview of the repartition of waste solvent treatment methods in the EU-28 and its evolution between 2010 and 2012. Looking at Figure 1.18, it appears that, in accordance with the European hierarchy for waste treatment, wastes sent for material recovery are increasing by 15,000 tonnes while those sent for energy recovery and incineration without energy recovery are decreasing by 12,000 tonnes and 90,000 tonnes, respectively. Even though wastes sent for landfilling represent less than 1% of the total wastes, it is important to note that this amount doubled between 2010 and 2012.

[16] Source: JRC 2010: "Study on the selection of waste streams for end-of-waste assessment".

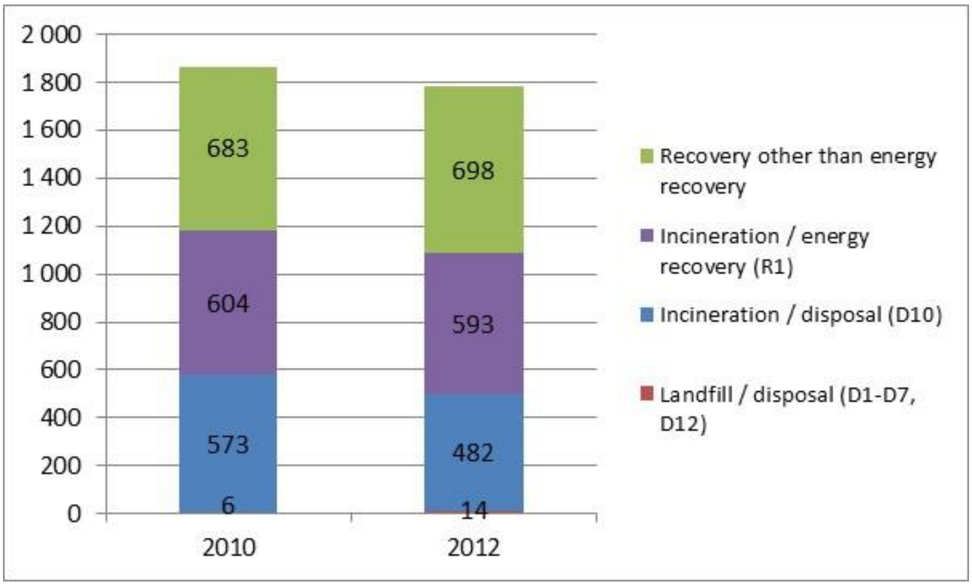


Figure 1.18: Evolution of waste solvent treatment methods in the EU-28 (Source: Eurostat Waste Statistics – in thousand tonnes/yr)

3.3.7 Waste oils (mineral and synthetic)

Generation of waste oils

The methodology used to estimate generation of waste oils is to make assumptions on the amount of collected used oils based on information on the consumption of lubricants.

The Eurostat Waste Statistics database has information on the consumption of used oils. However, this database is not employed because, according to the UBA 2011 report, the used oils waste category also contains waste types not suitable to be used as combustible waste (e.g. desalter sludge).

Data on the generation of waste oils comes from the United Nations Statistics Division. Assumptions on the amount of used oils collected come from GEIR (Groupement Européen de l'industrie de la Régénération). They estimate that 47% of the total used oils consumed are collected and that the rest is lost during the operation (e.g. lubricants used in car motors, lubricants on saw chains). This estimation is in line with the assumption used in the UBA 2011 report of 50%.

Table 1.20: Evolution of the generation of waste oils by Member State (Source: UN Database and assumptions from GEIR)

	Waste oils generation (thousand tonnes/yr)				
	2006	2008	2010	2012	2013
Austria	37	34	31	38	23
Belgium	49	43	25	24	20
Bulgaria	22	15	21	16	12
Croatia	18	18	16	14	14
Cyprus	3	3	3	2	2
Czech Republic	90	73	74	70	76
Denmark	29	26	24	24	24
Estonia	2	2	2	1	1

	Waste oils generation (thousand tonnes/yr)				
	2006	2008	2010	2012	2013
Finland	37	41	35	31	31
France	346	323	292	282	273
Germany	551	521	475	486	486
Greece	57	32	19	16	18
Hungary	46	43	37	25	8
Ireland	15	16	13	14	14
Italy	305	228	205	266	252
Latvia	12	12	7	10	10
Lithuania	12	11	9	9	10
Luxembourg	6	4	4	3	4
Malta	2	2	2	2	2
Netherlands	86	99	74	49	47
Poland	105	112	110	104	96
Portugal	39	36	31	23	22
Romania	37	30	34	45	42
Slovakia	32	21	14	21	25
Slovenia	14	8	6	10	9
Spain	236	228	207	169	171
Sweden	195	216	55	22	21
United Kingdom	336	242	273	194	196
Total EU-28	2,718	2 441	2,097	1,972	1,908

According to Table 1.20, the production of waste oils decreased on average by 10% every two years from 2006 to 2013.

Based on data from the UN in Table 1.20, Figure 1.19 presents the evolution of the generation of waste oils for the 14 main EU-28 producers representing 92% of the total EU-28 generation in 2013.

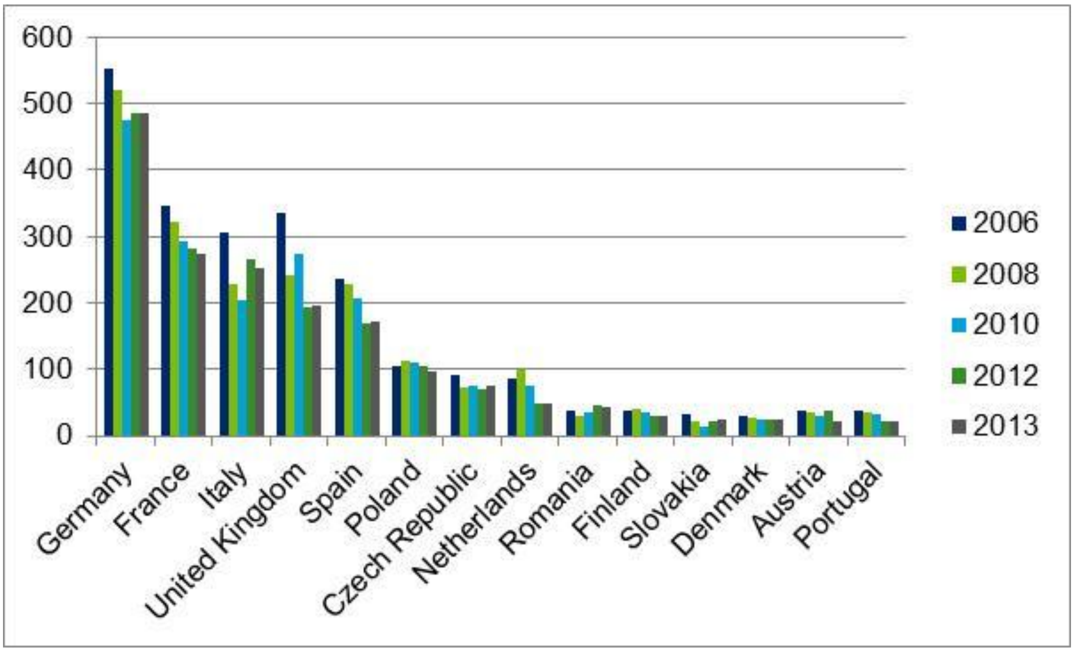


Figure 1.19: Evolution of the generation waste oil for the 14 main EU-28 producers in 2013 (Source: UN Database – in thousand tonnes/yr)

Most of the EU-28 main producers of waste oils also follow a downward trend from 2006 to 2013.

Import/export into/outside the EU-28

Quantities of imported and exported waste oils into/outside the EU-28 were collected from the Eurostat COMEXT Database. Quantities are available on a monthly and yearly basis from 1988 to 2014. For the purpose of this study, yearly imported and exported quantities from 2006 to 2014 were considered. Relevant data were identified based on their CN8 code. According to the methodology used in UBA 2011 report, the following CN8 codes were used for waste oil:

WDF	CN8 Code	Description
Waste oil	27109100	Waste oils containing polychlorinated biphenyls [PCBs], polychlorinated terphenyls [PCTs] or polybrominated biphenyls [PBBs]
	27109900	Waste oils containing mainly petroleum or bituminous minerals (excl. those containing polychlorinated biphenyls [PCBs], polychlorinated terphenyls [PCTs] or polybrominated biphenyls [PBBs])

Table 1.21 shows that the EU-28 has a negative oil waste trade balance but that it has been fluctuating since 2006. This trade balance represented around 1% of the EU-28 annual production of waste solvents in 2010 and -2% in 2012.

Table 1.21: Evolution of waste oil trade outside the EU-28 (Source: Eurostat COMEXT Database)

	Import/export into/outside the EU-28 (tonnes/yr)		
	Import	Export	Trade balance
2006	16,913	21,813	4,899
2008	45,054	3,585	-41,468
2010	47,573	65,381	17,808
2012	94,392	64,010	-30,382
2014	66,273	32,194	-34,078

Treatment of waste oils

There is no database available on the treatment of waste oils. In a previous report from 2011, UBA estimated the amount of used oils sent for energy recovery based on the following assumptions:

- in Western European countries, the share being combusted was assumed to be 45 % of the collected amount (cf. EC, 2006[17]);
- for the newest Member States, it is assumed that 95% of the amount collected is used as a waste-derived fuel.

Even though there is no publically available data, based on expert interviews, it is estimated that most waste oils that are not sent for energy recovery are recycled.

Table 1.22: Evolution of the waste oils sent for energy recovery by Member State (Source: calculations based on UN Database – in thousand tonnes/yr)

	Waste oils sent for energy recovery (thousand tonnes/yr)				
	2006	2008	2010	2012	2013
Austria	17	15	14	17	10
Belgium	22	19	11	11	9
Bulgaria	21	14	20	16	12
Croatia	17	17	15	13	13
Cyprus	1	1	1	1	1
Czech Republic	86	69	71	67	72
Denmark	13	12	11	11	11
Estonia	2	2	2	1	1
Finland	17	18	16	14	14
France	156	145	131	127	123
Germany	248	235	214	218	218
Greece	54	31	18	16	17
Hungary	43	41	35	24	7
Ireland	7	7	6	6	6
Italy	137	103	92	120	113
Latvia	12	11	6	10	9
Lithuania	11	11	9	9	9
Luxembourg	3	2	2	1	2

[17] Source: EC – European Commission (2006): Report from the Commission to the Council and the European Parliament on implementation of the community waste legislation Directive 75/442/EEC on waste, Directive 91/689/EEC on hazardous waste, Directive 75/439/EEC on waste oils, Directive 86/278/EEC on sewage sludge, Directive 94/62/EC on packaging and packaging waste and Directive 1999/31/EC on the landfill of waste for the period 2001–2003, SEC(2006)972.

	Waste oils sent for energy recovery (thousand tonnes/yr)				
	2006	2008	2010	2012	2013
Malta	1	1	1	1	1
Netherlands	38	45	33	22	21
Poland	100	106	105	99	91
Portugal	18	16	14	10	10
Romania	35	29	32	42	40
Slovakia	30	20	13	20	24
Slovenia	13	7	5	9	8
Spain	106	103	93	76	77
Sweden	88	97	25	10	9
United Kingdom	151	109	123	87	88
Total EU-28	**1,446**	**1,287**	**1,118**	**1,059**	**1,018**

According to Table 1.22, waste oils sent for energy recovery showed a downward trend from 2006 to 2013.

Even though no recent aggregated data on waste oil management in the EU-28 could be found, the results in Table 1.22 are deemed to represent high-range estimates. As an example, in 2014 in Spain[18], 32% of waste oils were sent for energy recovery and 68% was regenerated into lubricant oil bases. More recent data on waste oil treatment methods should soon be available from GEIR.

Figure 1.20 shows the repartition of waste oil treatment methods for the 14 EU-28 countries representing nearly 91% of the waste oils sent for energy recovery in 2013. According to European experts, the estimated amount of waste oils recycled in Figure 1.20 is considered a low-range estimate of the current situation. In addition, results from Figure 1.20 should be used with caution, because the 45% and 95% assumptions used to estimate the share of waste sent for energy recovery correspond to averages at European level and are not country-specific ratios.

[18] Source: SIGAUS (The Waste Oils Management System).

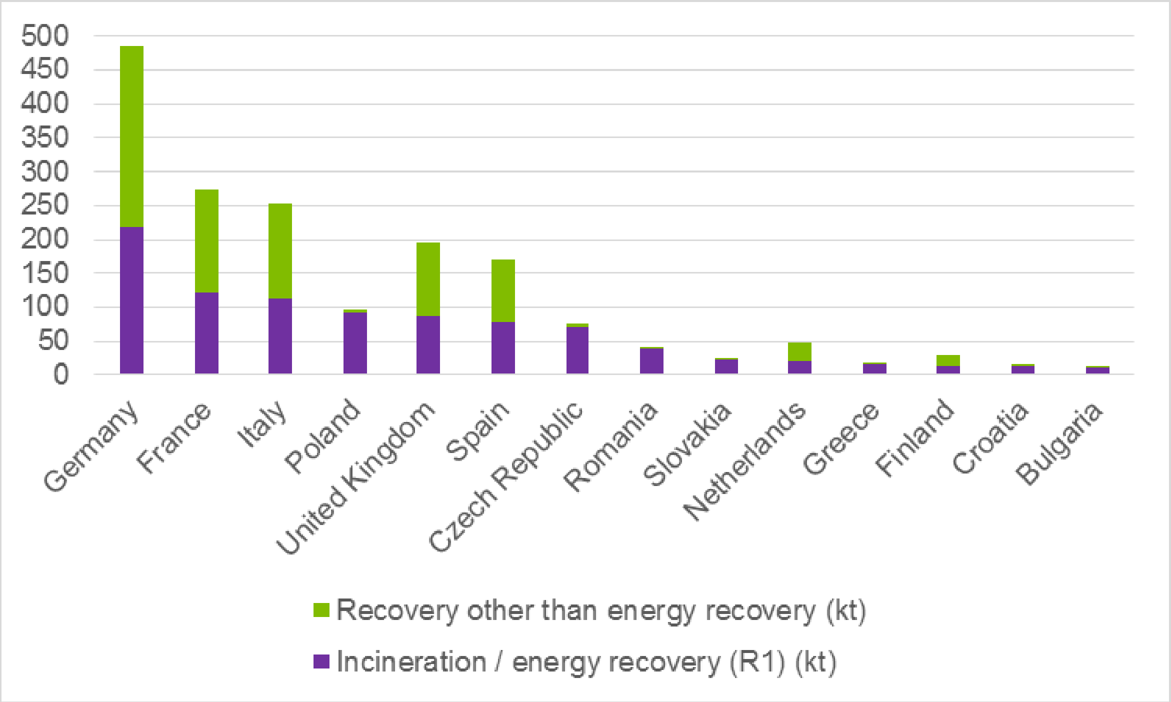


Figure 1.20: Treatment of waste oils for the 14 EU-28 main contributors to energy recovery in 2013 (Source: calculations based on UN Database – in thousand tonnes/yr)

Based on federation and expert input, it appears that waste oil is a 100% recyclable material. Following the waste hierarchy, waste management should therefore focus on reaching high quality recycling.

3.3.8 Chemical waste

Generation of chemical wastes

Data on the generation of chemical wastes comes from Eurostat Waste Statistics. Eurostat's EWC-Stat category "*Chemical wastes*" comes from the fusion of three categories after 2008:

- Spent chemical catalysts (01.4);
- Chemical preparation wastes (02);
- Chemical deposits and residues (03.1).

This category contains non-hazardous wastes.

The category and main NACE sectors that produce chemical wastes (HSW) are described as follows by the Eurostat Manual on waste statistics[19]:

"*Chemical wastes (01.4, 02, 03.1): These are solid or liquid spent chemical catalysts; off specification products and wastes like agro-chemicals, medicines, paint, dyestuff, pigments, varnish, inks and adhesives, including related sludges; chemical preparation waste like preservatives, brake and antifreeze fluids, waste chemicals; tars and carbonaceous waste like acid tars, bitumen, carbon anodes, tar and carbon waste; fuels, emulsions, sludges containing oil, like bilge oil, waste fuels oil, diesel, petrol, waste from oil water separator; aqueous rinsing and washing liquids, aqueous mother*

[19] Additional information can be found in the "Guidance on classification of waste according to EWC-Stat categories" document.

liquors; spent filtration and adsorbent material like activated carbon, filter cakes, ion exchangers. They mainly originate from the chemical industry and from various industrial branches producing and using chemical products. They are hazardous when containing toxic chemical compounds, oil, heavy metals or other dangerous substances."

Table 1.23: Evolution of the generation of chemical wastes by Member State (Source: Eurostat Waste Statistics)

	Chemical waste generation (thousand tonnes/yr)			
	2006	2008	2010	2012
Austria	673	472	230	225
Belgium	960	722	708	888
Bulgaria	161	135	84	51
Croatia	547	456	26	20
Cyprus	0	0	0	0
Czech Republic	320	365	311	234
Denmark	30	35	125	109
Estonia	1,123	1,402	1,450	1,518
Finland	456	675	280	254
France	1,569	1,392	1,527	1,595
Germany	4,482	5,081	3,642	3,061
Greece	58	17	13	41
Hungary	186	184	156	184
Ireland	183	167	812	219
Italy	2,573	2,518	2,224	2,197
Latvia	13	10	8	10
Lithuania	2,026	1,963	43	37
Luxembourg	17	20	22	19
Malta	30	34	14	11
Netherlands	938	1,225	1,241	1,221
Poland	3,287	2,551	1,946	1,523
Portugal	2,795	230	230	214
Romania	360	209	140	61
Slovakia	133	113	91	100
Slovenia	63	75	27	50
Spain	1,541	1,536	1,012	861
Sweden	816	748	735	558
United Kingdom	3,144	2,342	1,285	1,786
Total EU-28	28,483	24,676	18,382	17,048

According to Table 1.23, the generation of chemical wastes decreased by 40% from 2006 to 2012.

Based on data from Eurostat in Table 1.23, Figure 1.21 presents the evolution of the generation of chemical waste for the 14 main EU-28 producers representing 95% of the total EU-28 generation in 2012.

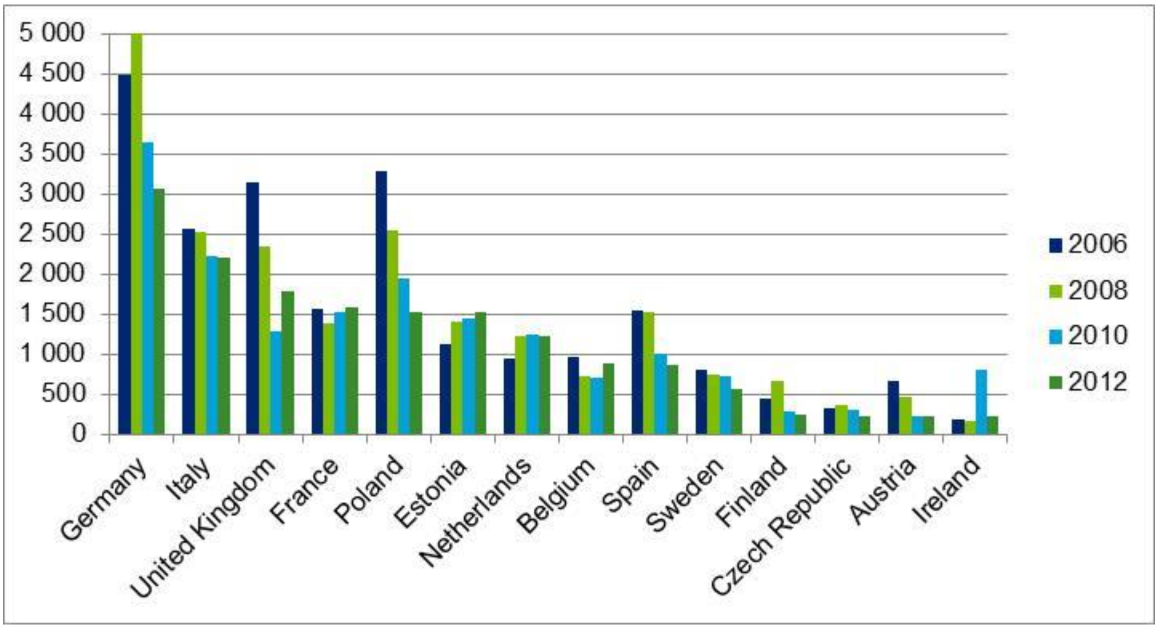


Figure 1.21: Evolution of the generation of chemical waste for the 14 main EU-28 producers in 2012 (Source: Eurostat Waste Statistics – in thousand tonnes/yr)

As shown by Figure 1.21, from 2006 to 2014, four of the five main EU-28 chemical waste producers follow a downward trend (Germany, Italy, the UK and Poland), while the generation of waste is stable in France over the same period. No information was provided by Member States that might explain the figures.

Import/export into/outside the EU-28

No information on the import/export of chemical waste outside the EU-28 has been identified.

Treatment of chemical waste

Chemical waste treatment data comes from Eurostat Waste Statistics. Eurostat provides data for all methods of treatment (energy recovery, incineration on land, landfill, and material recovery) but only for the years 2010 and 2012.

Table 1.24: Evolution of the chemical wastes sent for energy recovery and incineration by Member State (Source: Eurostat Waste Statistics)

	2010 (thousand tonnes/yr)		2012 (thousand tonnes/yr)	
	Energy recovery (R1)	Incineration/ Disposal (D10)	Energy recovery (R1)	Incineration/ Disposal (D10)
Austria	61	30	79	0
Belgium[20]	92	69	1	111
Bulgaria	0	0	0	0
Croatia	11	3	2	0
Cyprus	0	0	0	0
Czech Republic	28	21	11	31
Denmark	92	0	66	0
Estonia	5	0	3	0
Finland	6	59	2	55

[20] According to Belgian experts, some fluctuation in the data from Belgium is possible due to the evolution of the statistical approach of data gathering and processing.

	2010 (thousand tonnes/yr)		2012 (thousand tonnes/yr)	
	Energy recovery (R1)	Incineration/ Disposal (D10)	Energy recovery (R1)	Incineration/ Disposal (D10)
France	474	574	409	626
Germany	511	498	601	448
Greece	2	0	2	0
Hungary	22	39	26	41
Ireland	31	0	5	0
Italy	54	178	73	159
Latvia	0	0	0	0
Lithuania	0	1	0	0
Luxembourg	0	0	0	0
Malta	0	0	0	0
Netherlands	105	420	82	510
Poland	10	31	2	46
Portugal	3	12	1	14
Romania	35	50	10	8
Slovakia	1	2	1	4
Slovenia	0	3	11	3
Spain	120	5	65	0
Sweden	47	68	49	24
United Kingdom	0	8	0	131
Total EU-28	**1,710**	**2,070**	**1,500**	**2,213**

Between 2010 and 2012, the amount of chemical waste sent for energy recovery decreased by 12%, while over the same period the amount sent for incineration/disposal increased by 7%.

Figure 1.22 shows the repartition of chemical waste treatment methods for the 14 EU-28 countries representing 98% of chemical wastes sent to incineration and energy recovery in 2012. The repartition of chemical wastes is very different from one country to another. Some countries send most of their wastes to incineration/disposal (France and the Netherlands), while others send most of their wastes to material recovery (Germany, Spain and Poland).

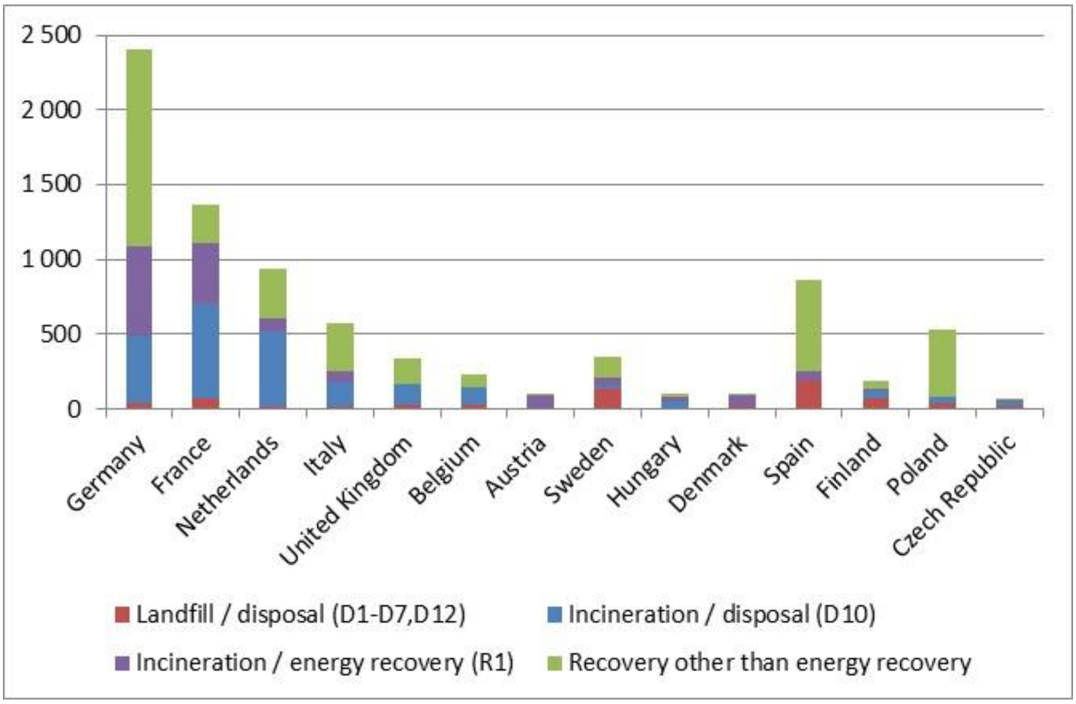


Figure 1.22: Treatment of chemical wastes for the 14 main EU-28 contributors to energy recovery from chemical waste in 2012 (Source: Eurostat Waste Statistics – in thousand tonnes/yr)

Figure 1.23 gives an overview of the repartition of chemical waste treatment methods in the EU-28 and its evolution between 2010 and 2012. Looking at Figure 1.23, it seems that EU-28 Member States tended to follow the European waste management hierarchy. Between 2010 and 2012, waste sent to landfill showed the biggest decrease while waste sent for incineration/disposal increased and those sent for material recovery were stable over the same period.

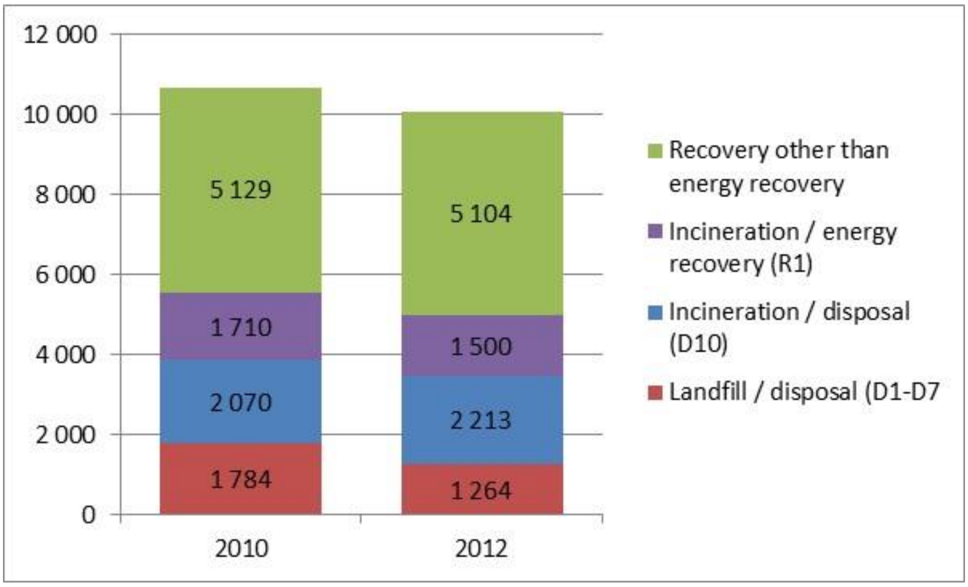


Figure 1.23: Evolution of chemical waste treatment methods in the EU-28 (Source: Eurostat Waste Statistics – in thousand tonnes/yr)

3.3.9 Household and similar wastes

Generation of household and similar wastes

Data on the generation of chemical wastes comes from Eurostat Waste Statistics.
The category and main NACE sectors that produce household and similar wastes (HSW) are described as follows by the Eurostat Manual on waste statistics[21]:

"*Household and similar wastes (10.1): These wastes are mixed municipal waste, bulky waste, street-cleaning waste like packaging, kitchen waste, and household equipment* ***except separately collected fractions****. They originate mainly from households but can also be generated by all sectors in canteens and offices as consumption residues. Household and similar wastes are non-hazardous*".

This definition reveals a clear distinction between household and similar wastes (HSW) and municipal solid waste (MSW): in principle, HSW does not cover source-separated materials (e.g. glass or paper), whereas MSW does cover such materials (see Figure 1.1). The amount of total MSW produced per capita is roughly double the amount of HSW produced.

In addition to the data collected by Eurostat every second year as required by the WStatR (Waste Statistics Regulation), Members States also provide Eurostat with annual information on municipal waste, as part of the Joint Questionnaire OECD/Eurostat. Even though the database on municipal waste is very reliable, it could not be used in this study because it is not possible to extract specific data for household and similar wastes.

Data on the generation of household and similar wastes (HSW) comes from Eurostat Waste Statistics. In Eurostat, the EWC-Stat category "10.1 Household and similar wastes" contains non-hazardous wastes.

Table 1.25: Evolution of the generation of household and similar wastes by Member State (Source: Eurostat Waste Statistics)

	Household and similar wastes generation (thousand tonnes/yr)			
	2006	2008	2010	2012
Austria	2,459	1,876	3,664	2,624
Belgium[22]	5,020	3,608	2,570	2,837
Bulgaria	4,102	3,747	3,107	3,110
Croatia	1,320	1,677	1,337	1,396
Cyprus	253	183	173	166
Czech Republic	3,189	3,281	3,309	3,100
Denmark	3,141	3,172	2,806	2,733
Estonia	655	466	305	294
Finland	1,931	1,705	2,031	1,594
France	25,527	23,921	22,179	22,371
Germany	20,933	20,806	21,376	20,955
Greece	4,927	5,077	4,771	4,305
Hungary	4,111	3,494	3,195	2,897

[21] Additional information can be found in the "Guidance on classification of waste according to EWC-Stat categories" document.
[22] Data for 2010 did not contain specific waste from households in Flanders at the time the report was written. Corrections have since been sent to Eurostat.

	Household and similar wastes generation (thousand tonnes/yr)			
	2006	2008	2010	2012
Ireland	342	145	3,265	2,737
Italy	25,063	26,190	21,378	18,043
Latvia	957	752	563	727
Lithuania	1,286	1,253	1,065	1,016
Luxembourg	198	212	210	208
Malta	241	261	218	206
Netherlands	8,208	7,878	7,432	7,185
Poland	7,195	6,784	8,638	8,774
Portugal	6,651	6,830	6,024	4,661
Romania	4,152	5,504	4,464	5,343
Slovakia	1,437	1,533	1,458	1,382
Slovenia	727	861	777	560
Spain	23,236	22,604	21,120	19,584
Sweden	2,671	2,523	2,511	2,587
United Kingdom	47,745	43,701	28,956	28,261
Total EU-28	207,675	200,044	178,896	169,655

According to Table 1.25, the production of household and similar wastes (HSW) decreased by 18% from 2006 to 2012.

Based on data from Eurostat in Table 1.25, Figure 1.24 presents the evolution of the generation of HSW for the 14 main EU-28 producers representing 89% of the total EU-28 generation in 2012.

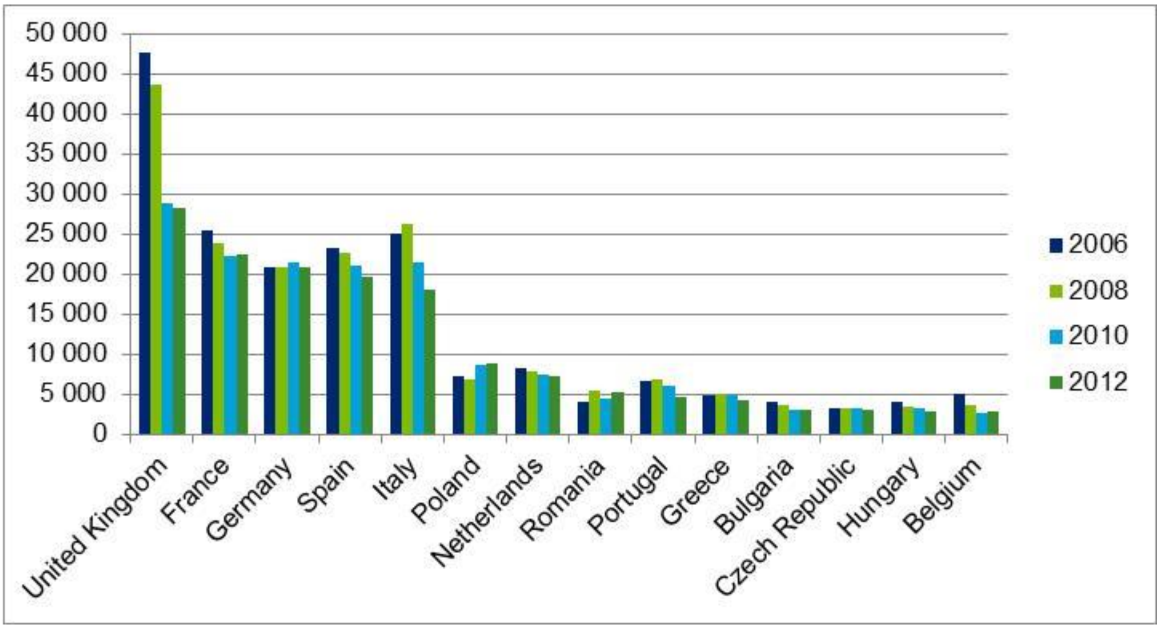


Figure 1.24: Evolution of the generation of household and similar wastes for the 14 main EU-28 producers in 2012 (Source: Eurostat Waste Statistics – in thousand tonnes/yr)

Figure 1.24 shows that the main EU-28 producers follow the general downward trend observed at European level. The sudden drop observed for the UK between 2008 and 2010 is due to the adoption in 2012 of an improved methodology for collecting data on paper wastes. The data for 2010 was revised using the new methodology as a basis, but the figures for 2008 and 2006 reflect the previous methodology.

Import/export into/outside EU-28

No information on the import/export of HSW outside the EU-28 has been identified.

Treatment of household and similar wastes

HSW treatment data comes from Eurostat Waste Statistics. Eurostat Waste Statistics provides data on material recovery only for the years 2010 and 2012, and data on other methods of treatment (energy recovery, incineration on land, and landfill) is available for the years 2006, 2008, 2010 and 2012.

Table 1.26 presents the mass balance between the generation and treatment of HSW. The detail of the mass balance per country is available in Annex 3.

Table 1.26: Mass balance between household and similar wastes generation and treatment in the EU-28 in 2010 and 2012 (Source: Eurostat Waste Statistics – in thousand tonnes/yr)

	2010	2012
Waste generation	178,896	169,655
Waste treatment	153,150	137,343
Difference[23]	-14%	-19%

There appears to be a discrepancy between the waste generation and the amount of waste treated in the EU-28. Import/export into/outside the EU-28 could be responsible for the observed difference of 14% to 19%. Some Member States indicated that the difference between HSW generation and treatment could be explained by different interpretations for complying with the Waste Framework Directive. For instance, in the Netherlands, HSW that is sorted will be given a new LoW (List of Waste) code, which might be as sorted waste and then it will be incinerated or recycled. Only HSW that is directly incinerated will keep the LoW code as HSW.

Table 1.27 presents the evolution of the amount of household and similar wastes sent for energy recovery and incineration by Member State in 2010 and 2012.

Table 1.27: Evolution of the household and similar wastes sent for energy recovery and incineration by Member State (Source: Eurostat Waste Statistics)[24]

	2010 (thousand tonnes/yr)		2012 (thousand tonnes/yr)	
	Energy recovery (R1)	Incineration/ Disposal (D10)	Energy recovery (R1)	Incineration/ Disposal (D10)
Austria	0	1,191	1,069	0
Belgium	1,294	372	1,479	569
Bulgaria	0	0	0	0
Croatia	2	4	0	0
Cyprus	0	0	0	0
Czech Republic	452	0	586	0
Denmark	2,299	0	2,232	0
Estonia	0	0	0	0
Finland	340	101	902	2
France	6,333	5,388	6,728	5,058

[23] Difference (%) = (Treatment-Generation)/Generation.

[24] Section 3.5.2.3 provides further information on Eurostat data on R1 and D10.

	2010 (thousand tonnes/yr)		2012 (thousand tonnes/yr)	
	Energy recovery (R1)	Incineration/ Disposal (D10)	Energy recovery (R1)	Incineration/ Disposal (D10)
Germany	6,580	8,286	7,474	6,905
Greece	0	0	0	0
Hungary	408	0	366	0
Ireland	0	0	134	0
Italy	18	3,028	33	2,595
Latvia	0	0	0	0
Lithuania	0	0	0	0
Luxembourg	0	116	0	122
Malta	0	0	0	0
Netherlands	3,208	2,091	5,705	25
Poland	0	102	17	51
Portugal	1,053	46	923	42
Romania	2	0	6	0
Slovakia	167	2	163	4
Slovenia	0	0	0	0
Spain	1,567	9	1,496	7
Sweden	2,268	0	2,296	0
United Kingdom	16	4,107	0	5,190
Total EU-28	**26,007**	**24,845**	**31,610**	**20,570**

According to Table 1.27, between 2010 and 2012 the amount of HSW sent for energy recovery increased by 22% at the EU-28 level, while over the same period the amount that was sent for incineration/disposal decreased by 17%. According to Eurostat Waste Statistics, wastes sent for energy recovery represented about 20% of HSW generation in the EU-28.

Figure 1.25 shows the repartition of HSW treatment methods for the 14 EU-28 countries representing 99% of the HSW sent to incineration and energy recovery in 2012. The repartition of HSW is very different across Member States:

- Italy was the only country where material recovery was the main treatment pathway;
- four countries (France, the UK, Italy and Spain) sent more than 5 million tonnes of wastes to landfill;
- Germany and France were the only countries sending significant amounts of wastes to both incineration disposal and energy recovery.

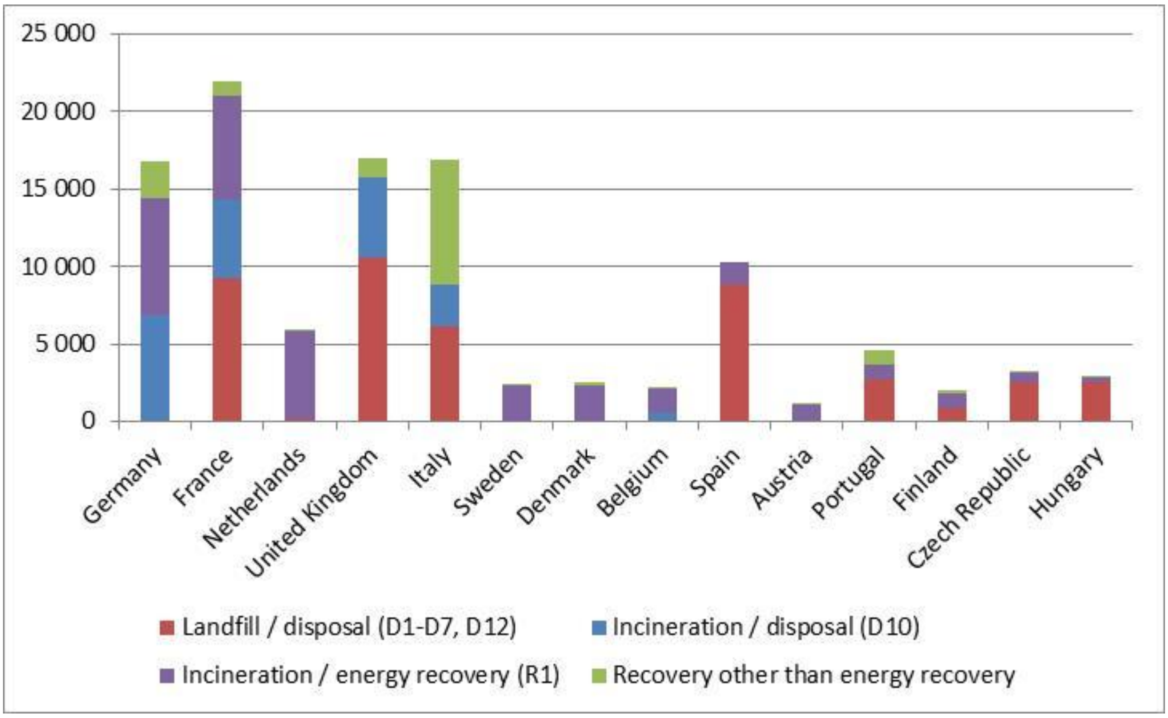


Figure 1.25: Treatment of household and similar wastes for the 14 EU-28 main contributors to energy recovery from household and similar wastes in 2012 (Source: Eurostat Waste Statistics – in thousand tonnes/yr)

Information provided in Figure 1.25 reflects the HSW management practices in some Member States:

- In Germany and Sweden, a landfill ban on organic substances was implemented several years ago and is proving to be efficient.
- In the case of Spain, landfilling is higher due to the low cost of this treatment method. This might change in the future as a few regions, such as Catalonia, have established taxes for landfilling in order to encourage source-separated collection and recycling. Also, according to Spanish experts interviewed for this study, HSW is an important source for waste-derived biogas production in Spain. However, this information has not been reported to Eurostat where it should appear within the treatment method "Recovery other than energy recovery".

Figure 1.26 shows the evolution of household and similar wastes treatment methods in the EU-28. Looking at Figure 1.26, it appears that the trends between 2010 and 2012 are in line with the European hierarchy for waste treatment: reduction of wastes sent for landfill and incineration disposal, and increase of the amount sent for material and energy recovery. Note: As explained above, the amount of HSW sent to material recovery is missing for the years 2006 and 2008.

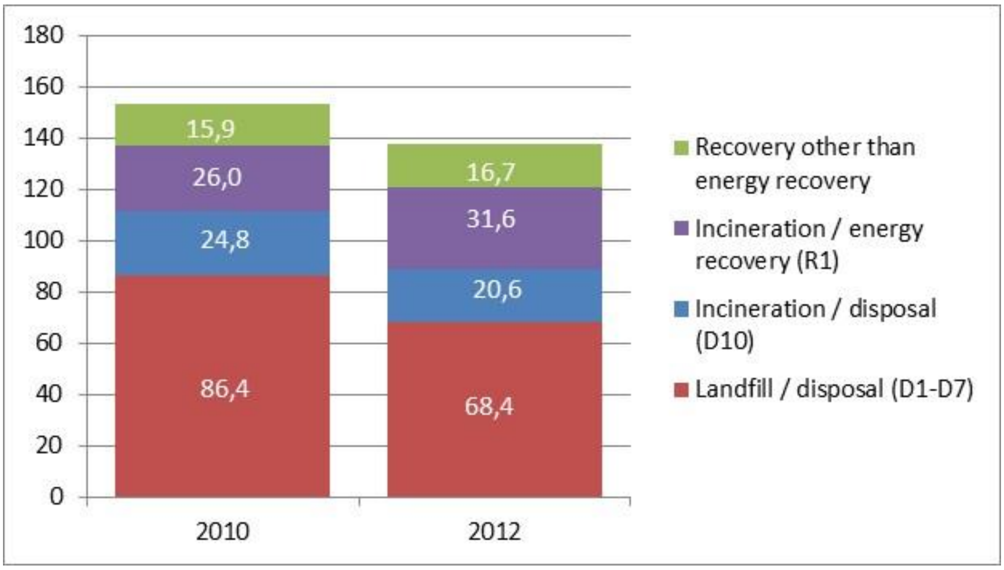


Figure 1.26: Evolution of household and similar wastes treatment methods in the EU-28 (Source: Eurostat Waste Statistics – in million tonnes/yr)[25]

It should be noted that, according to interviews with experts, data on recovery (other than energy recovery) should be used carefully. Indeed, in this category some countries report to Eurostat wastes entering Mechanical Biological Treatment (MBT) plants. However, only part of the wastes sent to MBT plants is really recovered, with some of the rest being sent to landfill after sorting. In addition, a number of experts reported that slag sent to be used as construction material is not accounted for in landfilled waste. However, the market for this construction material is not favourable and a significant amount of the slag is therefore stored, resulting in environmental pollution, similarly to landfill sites.

3.3.10 Mixed and undifferentiated materials

Generation of mixed and undifferentiated materials

Data on the generation of mixed and undifferentiated materials (M&UM) comes from Eurostat Waste Statistics. Eurostat's EWC-Stat category "10.2 mixed and undifferentiated materials" contains non-hazardous wastes.

The category and main NACE sectors that produce mixed and undifferentiated materials (M&UM) are described as follows by the Eurostat Manual on waste statistics[26]:

"*Mixed and undifferentiated materials (10.2): These are unspecified and mixed waste without any general waste source. This category covers not only mixed packaging but also mainly residual categories from different branches of industry (food production, textile industry, combustion plants, surface treatment of metals and plastics, etc.). These residual categories are often used for nation-specific waste codes. Mixed and undifferentiated materials are hazardous when containing heavy metals or organic pollutants*."

The Eurostat manual also indicates that, as of 2010, the category summarises all unspecified LoW codes..

[25] Section 3.5.2.3 provides further information on Eurostat data on R1 and D10.
[26] Additional information can be found in the "Guidance on classification of waste according to EWC-Stat categories" document.

Table 1.28: Evolution of the generation of mixed and undifferentiated materials by Member State (Source: Eurostat Waste Statistics)

	Mixed and undifferentiated materials (thousand tonnes/yr)			
	2006	2008	2010	2012
Austria	1,137	32	86	140
Belgium	3,340	1,132	4,641	3,061
Bulgaria	61	49	87	167
Croatia	45	20	258	59
Cyprus	99	62	89	78
Czech Republic	200	177	288	348
Denmark	1,080	939	961	1,039
Estonia	33	27	53	81
Finland	553	192	1,884	993
France	12,523	12,628	12,258	9,869
Germany	4,503	4,813	6,861	6,996
Greece	83	61	998	989
Hungary	234	197	392	380
Ireland	339	128	466	741
Italy	3,414	3,729	6,429	5,859
Latvia	12	2	13	307
Lithuania	8	22	82	51
Luxembourg	6	5	92	33
Malta	15	6	11	11
Netherlands	326	243	894	905
Poland	339	479	2,056	3,631
Portugal	778	532	369	387
Romania	3,316	2,105	2,610	288
Slovakia	83	82	130	130
Slovenia	18	29	86	134
Spain	1,134	1,587	2,068	2,021
Sweden	2,433	831	1,093	835
United Kingdom	7,404	4,392	7,117	7,408
Total EU-28	**43,518**	**34,500**	**52,372**	**46,941**

According to Table 1.28, the production of M&UM decreased by 21% and 10% from 2006 to 2008 and from 2010 to 2012 respectively, whereas the production increased by 52% between 2008 and 2010. Considering that the evolution between 2008 and 2010 was in part due to the category expansion (as explained above), then the generation of M&UM followed a downward trend between 2006 and 2012.

Based on data from Eurostat in Table 1.28, Figure 1.27 presents the evolution of the generation of waste M&UM for the 14 main EU-28 producers representing 95% of the total EU-28 generation in 2012.

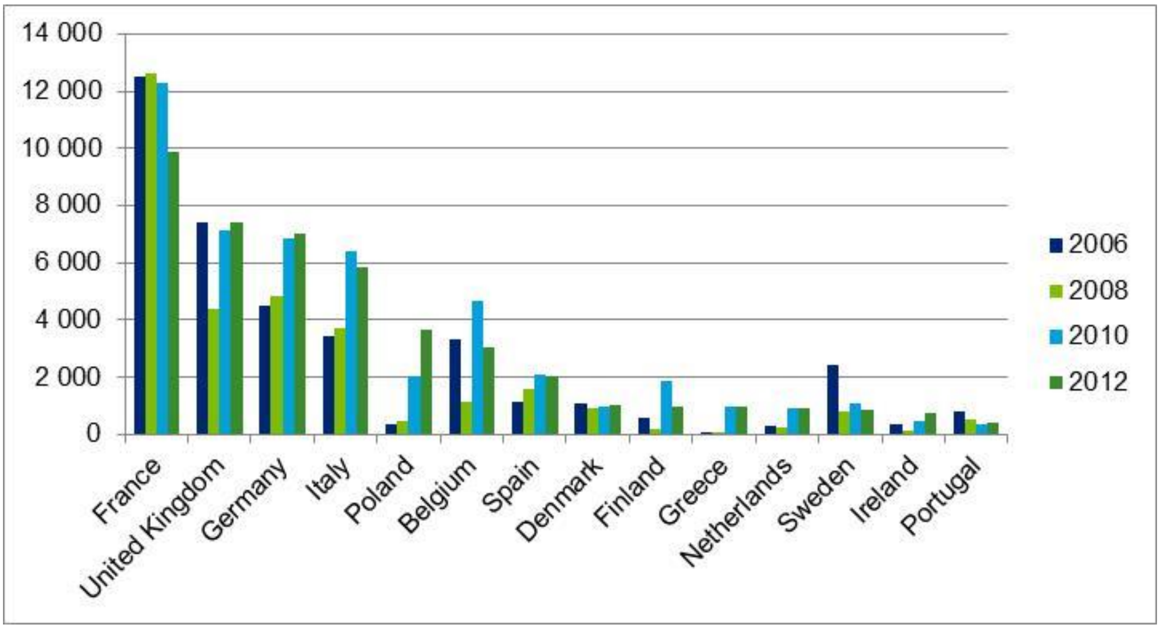


Figure 1.27: Evolution of the generation of mixed and undifferentiated materials for the 14 main EU-28 producers in 2012 (Source: Eurostat Waste Statistics – in thousand tonnes/yr)

Looking at Figure 1.27, most of the Member States included in this figure show a significant increase in the generation of mixed and undifferentiated materials between 2008 and 2010. This can probably be explained by the change to the scope of the definition.

As explained in the above definition, M&UM is mostly a leftover category with unspecified and country-specific waste streams. It is therefore very difficult to compare Eurostat data with any other database. No further information was provided by Member States that might explain the figures.

Import/export into/outside the EU-28

Comprehensive trade data was not identified.

Treatment of mixed and undifferentiated materials

Treatment data for mixed and undifferentiated materials comes from Eurostat Waste Statistics. Eurostat Waste Statistics provides data on material recovery only for the years 2010 and 2012, and data on other methods of treatment (energy recovery, incineration on land, and landfill) is available for the years 2006, 2008, 2010 and 2012. Table 1.29 presents the mass balance between the generation and treatment of M&UM. The detail of the mass balance per country is available in Annex 3.

Table 1.29: Mass balance between generation and treatment of mixed and undifferentiated materials in the EU-28 in 2010 and 2012 (Source: Eurostat Waste Statistics – in thousand tonnes/yr)

	2010	2012
Waste generation	52,372	46,941
Waste treatment	34,948	33,123
Difference[27]	-33%	-29%

There appears to be a discrepancy between the waste generation and the amount of waste treated in the EU-28. The import/export into/outside the EU-28 could be responsible for this as well as considerable uncertainties in reporting.

[27] Difference (%) = (Treatment-Generation)/Generation.

Table 1.30: Evolution of the mixed and undifferentiated materials sent for energy recovery and incineration by Member State (Source: Eurostat Waste Statistics)

	2010 (thousand tonnes/yr)		2012 (thousand tonnes/yr)	
	Energy recovery (R1)	Incineration/ Disposal (D10)	Energy recovery (R1)	Incineration/ Disposal (D10)
Austria	45	4	103	0
Belgium	558	242	2,882	617
Bulgaria	10	0	9	0
Croatia	8	2	0	0
Cyprus	0	0	0	0
Czech Republic	9	1	14	2
Denmark	300	0	356	0
Estonia	1	0	0	0
Finland	1,275	10	436	61
France	620	305	304	231
Germany	1,717	350	1,925	319
Greece	2	0	1	0
Hungary	17	1	208	2
Ireland	0	0	29	0
Italy	782	260	679	202
Latvia	52	0	2	0
Lithuania	0	0	3	0
Luxembourg	0	0	0	0
Malta	0	0	0	0
Netherlands	79	47	117	33
Poland	50	6	91	8
Portugal	28	1	13	1
Romania	27	5	69	1
Slovakia	3	1	2	2
Slovenia	1	0	7	0
Spain	0	3	194	0
Sweden	1,383	5	2,354	3
United Kingdom	1	153	65	131
Total EU-28	**6,967**	**1,394**	**9,863**	**1,613**

According to Table 1.30, between 2010 and 2012 the amount of M&UM sent for energy recovery increased by nearly 3 million tonnes at the EU-28 level, while over the same period the amount sent for incineration disposal increased by 0.2 million tonnes. According to Eurostat Waste Statistics, in 2012, wastes sent for energy recovery represented about 20% of the waste generation in the EU-28.

Figure 1.28 shows the repartition of M&UM treatment methods for the 14 EU-28 countries representing 99% of the M&UM sent to incineration and energy recovery in 2012.

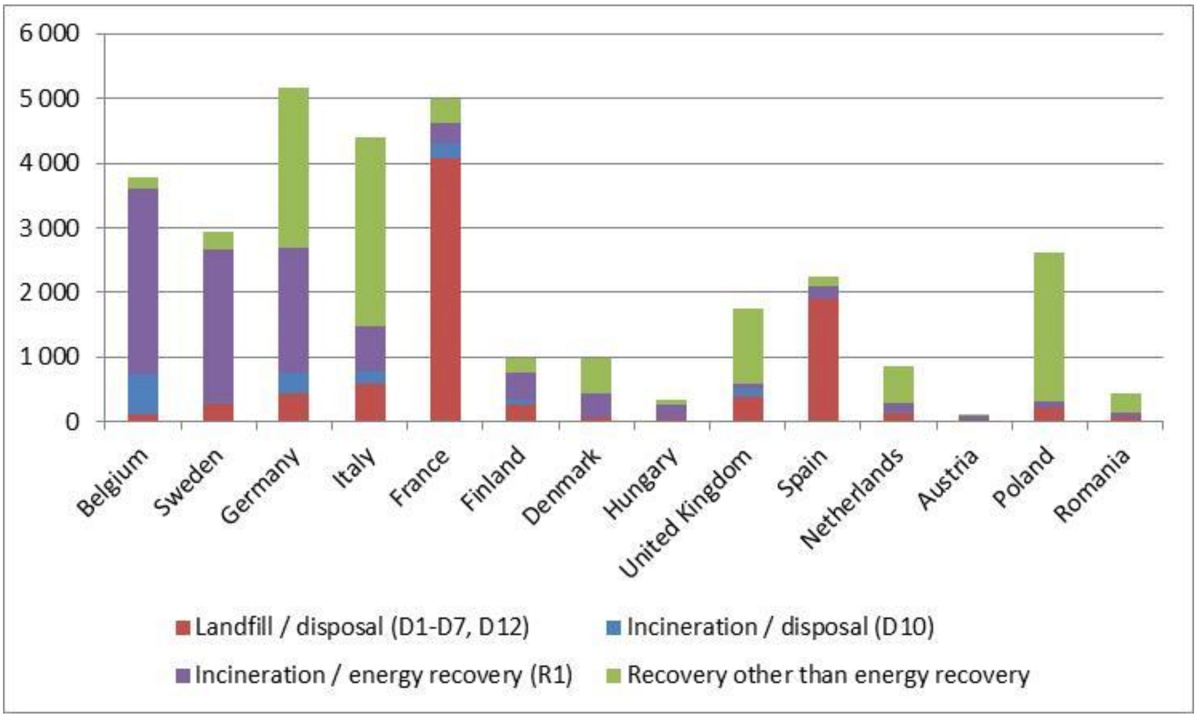


Figure 1.28: Treatment of the mixed and undifferentiated materials for the 14 EU-28 main contributors to energy recovery from mixed and undifferentiated materials in 2012 (Source: Eurostat Waste Statistics – in thousand tonnes/yr)

Figure 1.29 shows the evolution of M&UM treatment methods in the EU-28. As explained above, because of the evolution of the definition of M&UM between 2008 and 2010, it seems more relevant to study the trends for the years 2010 and 2012 only. Focusing on these years in Figure 1.29, it appears that the trends are in line with the European hierarchy for waste treatment: reduction of wastes sent for landfill and increase of the amount sent for energy recovery. Note: As explained above, the amount of M&UM sent to material recovery is missing for the years 2006 and 2008.

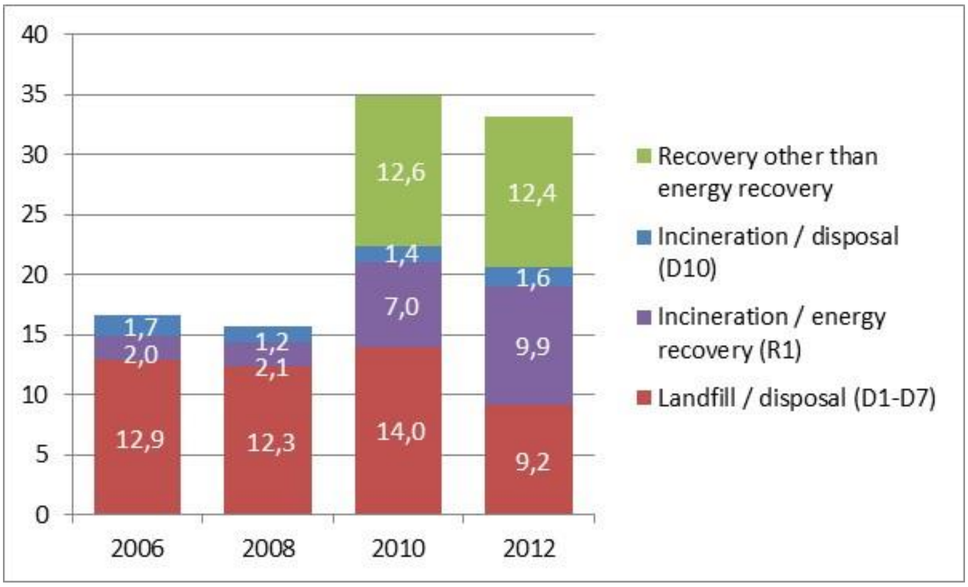


Figure 1.29: Evolution of mixed and undifferentiated materials treatment methods in the EU-28 (Source: Eurostat Waste Statistics – in million tonnes/yr)

Based on these data, it appears that M&UM has a significant potential for material and energy recovery. However, considering the great heterogeneity of the category and the lack of a clear definition of the type of wastes included, it is difficult to provide a robust analysis of generation and waste management trends. It is also difficult to provide an accurate estimate of its potential for material and energy recovery, in accordance with the treatment hierarchy.

3.3.11 Sorting residues

The distinction between "sorting residues" and SRF is discussed at the end of the chapter.

Generation of sorting residues

Data on the generation of sorting residues comes from Eurostat Waste Statistics. Eurostat's EWC-Stat category is referred to as "10.3 sorting residues". It is important to highlight that refuse-derived fuel produced from mechanical treatment plants is included in this waste category. In addition, as explained below in Eurostat's definition, the source of this waste stream includes mixed MSW and C&IW, as well as source-separated collection of MSW and C&IW.
Sorting residues contain hazardous and non-hazardous wastes.

The category and main NACE sectors that produce sorting residues are described as follows by the Eurostat Manual on waste statistics[28]:

"*Sorting residues (10.3): These wastes are sorting residues from mechanical sorting processes for waste;* ***combustible waste (refuse derived fuel***); *and non-composted fractions of biodegradable waste. They mainly originate from waste treatment and source separate collection. Sorting residues from demolition activities are excluded. They are hazardous when containing heavy metals or organic pollutants.*"

Table 1.31: Evolution of the generation of sorting residues by Member State (Source: Eurostat Waste Statistics)

	Sorting residues generation (thousand tonnes/yr)			
	2006	2008	2010	2012
Austria	568	534	1,395	1,611
Belgium	1,118	884	1,538	1,700
Bulgaria	61	105	56	323
Croatia	22	33	8	29
Cyprus	0	0	2	3
Czech Republic	315	228	295	352
Denmark	0	0	490	510
Estonia	15	39	35	144
Finland	409	529	683	293
France	3,617	4,151	6,193	5,857
Germany	11,182	12,902	13,972	16,396
Greece	252	21	155	253
Hungary	137	166	148	228
Ireland	41	8	501	491

[28] Additional information can be found in the "Guidance on classification of waste according to EWC-Stat categories" document.

	Sorting residues generation (thousand tonnes/yr)			
	2006	2008	2010	2012
Italy	7,878	10,831	9,971	13,536
Latvia	5	5	4	11
Lithuania	6	5	36	219
Luxembourg	21	12	41	34
Malta	17	7	8	50
Netherlands	3,204	2,787	2,336	1,412
Poland	1,354	2,862	4,664	5,651
Portugal	424	94	166	357
Romania	26	172	602	695
Slovakia	136	166	24	78
Slovenia	49	49	17	81
Spain	995	1,101	6,080	7,505
Sweden	1,276	2,298	1,278	1,656
United Kingdom	4,782	7,621	4,181	5,944
Total EU-28	37,910	47,610	54,877	65,417

According to Table 1.31, the production of sorting residues increased on average by 20% every two years from 2006 to 2008.

According to CEPI, the Confederation of European Paper Industries, the increasing trend in sorting residues is also noticed in the pulp and paper industry. Factories using waste paper as raw material are receiving lower waste paper qualities, which is resulting in more pulping rejects (sorting residues).

Based on data from Eurostat in Table 1.31, Figure 1.30 presents the evolution of the generation of sorting residues for the 14 main EU-28 producers representing 97% of the total EU-28 generation in 2012.

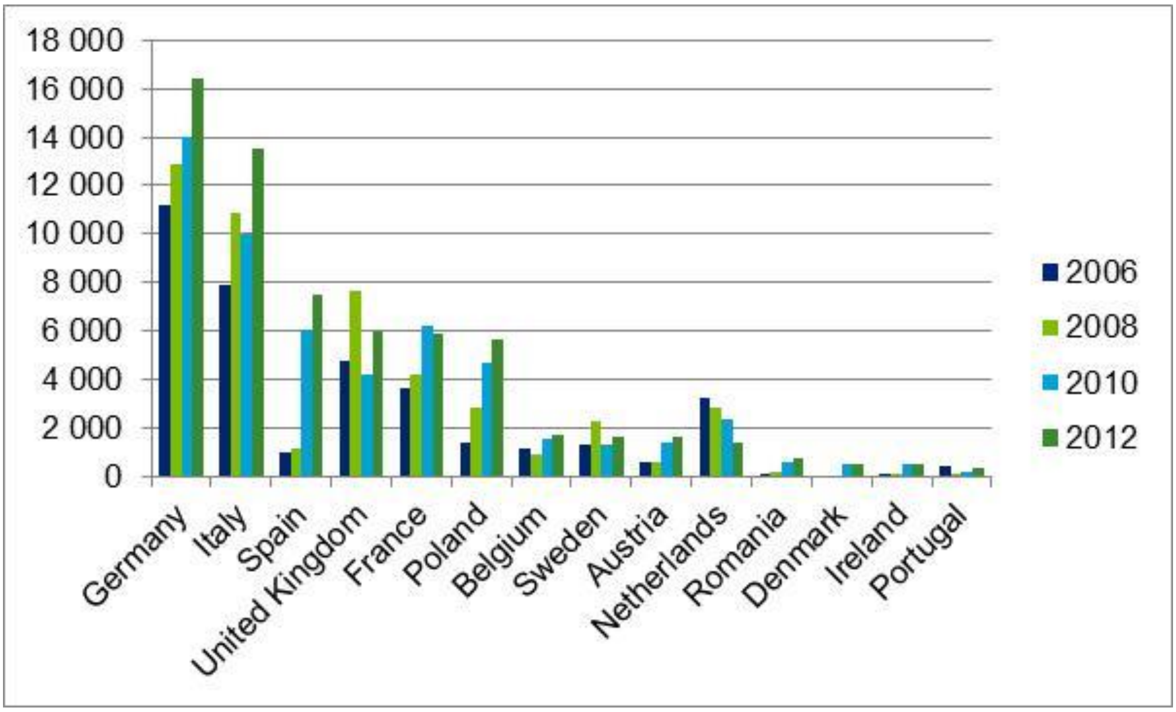


Figure 1.30: Evolution of the generation of sorting residues for the 14 main EU-28 producers in 2012 (Source: Eurostat Waste Statistics – in thousand tonnes/yr)

According to data provided in Table 1.31 and the information shown in Figure 1.30, Germany and Italy, which represented nearly half of the EU-28 production in 2012, showed a strong upward trend between 2006 and 2012.

In the case of the Spanish data, the tendency of the generation data could be due to a change in the methodology. In 2010, waste from MBT plants formerly included in category 09.1 (Animal and vegetal wastes) were classified under category 10.3 “sorting residues”. Therefore, data from 2010 and 2012 is more accurate. No further information was provided by Member States that might explain the figures.

Import/export into/outside the EU-28

Comprehensive trade data was not identified.

Treatment of sorting residues

In its 2011 report, UBA made the assumption that all sorting residues were used for energy recovery. However, Eurostat Waste Statistics provides data on material recovery only for the years 2010 and 2012, and data on other methods of treatment (energy recovery, incineration on land, and landfill) is available for the years 2006, 2008, 2010 and 2012.

Therefore, data from Eurostat Waste Statistics has been used. Table 1.32 presents the mass balance between the generation and treatment of sorting residues. The detail of the mass balance per country is available in Annex 3.

Table 1.32: Mass balance between generation and treatment of sorting residues in the EU-28 in 2010 and 2012 (Source: Eurostat Waste Statistics – in thousand tonnes/yr)

	2010	2012
Waste generation	54,877	65,417
Waste treatment	53,860	62,994
Difference[29]	-2%	-4%

The difference between the waste generation and the amount of waste treated in the EU-28 is below 4%. The import/export into/outside the EU-28 could be responsible for the difference observed.

Table 1.33: Evolution of sorting residues sent to incineration and energy recovery by Member State (Source: Eurostat Waste Statistics)

	2010 (thousand tonnes/yr)		2012 (thousand tonnes/yr)	
	Energy recovery (R1)	Incineration/ Disposal (D10)	Energy recovery (R1)	Incineration/ Disposal (D10)
Austria	411	346	1,151	0
Belgium	771	350	50	509
Bulgaria	30	0	52	0
Croatia	0	0	2	0
Cyprus	0	0	0	0
Czech Republic	45	2	114	2
Denmark	169	0	133	0
Estonia	19	0	52	0
Finland	135	24	41	15
France	847	126	394	148
Germany	7,495	2,167	9,606	1,952
Greece	1	0	0	0
Hungary	132	2	117	1
Ireland	49	0	178	0
Italy	284	2,239	573	2,479
Latvia	0	0	127	0
Lithuania	0	0	0	0
Luxembourg	6	7	12	11
Malta	0	0	0	0
Netherlands	533	498	1,337	13
Poland	734	78	958	85
Portugal	67	0	148	0
Romania	73	0	248	0
Slovakia	1	0	30	0
Slovenia	13	17	17	20
Spain	537	0	956	0
Sweden	486	0	442	0
United Kingdom	208	12	302	6
Total EU-28	13,045	5,868	17,040	5,242

[29] Difference (%) = (Treatment-Generation)/Generation.

According to Table 1.33, between 2010 and 2012 the amount of sorting residues sent for energy recovery increased by 31% (+7 million tonnes) at the EU-28 level, while over the same period the amount that was sent for incineration disposal decreased by 11% (-0.6million tonnes). According to Eurostat Waste Statistics, wastes sent for energy recovery represented about 26% of the sorting residues generation in the EU-28.

Figure 1.31 shows that landfilling of sorting residues was still very common in the EU-28 in 2012. For 5 of the 14 main producers of sorting residues (the UK, Spain, Italy, Poland and France), landfilling was the main treatment for sorting residues in 2012. Germany was the only country among the main producers to use energy recovery as the principal treatment method for sorting residues.

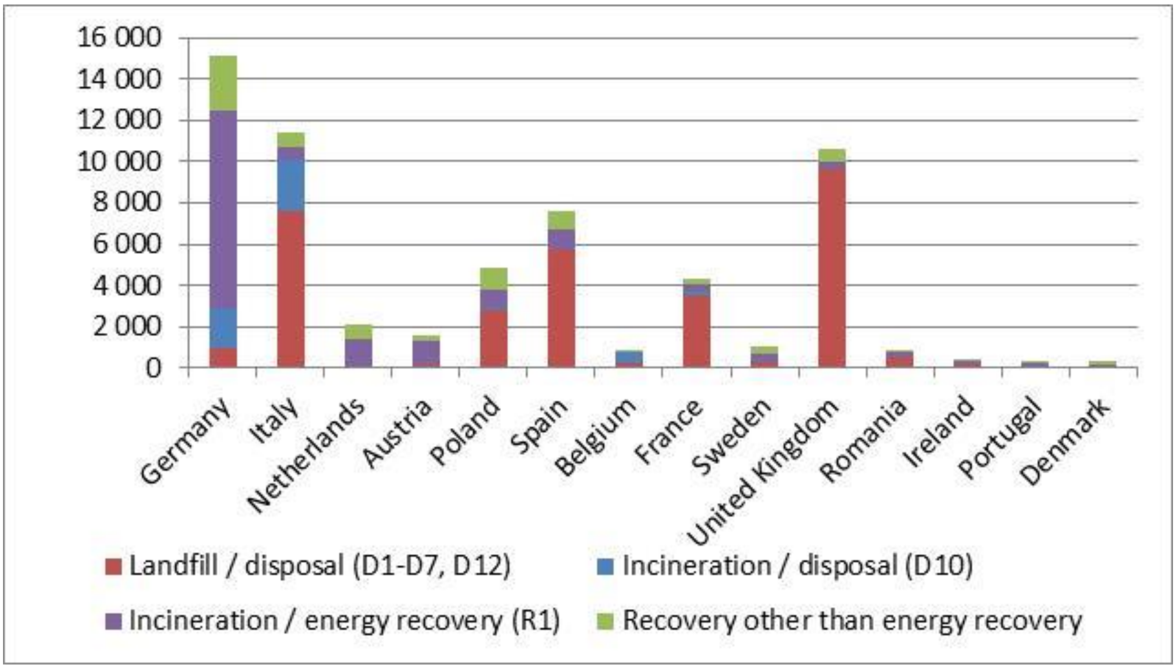


Figure 1.31: Treatment of sorting residues for the 14 EU-28 main contributors to energy recovery from sorting residues in 2012 (Source: Eurostat Waste Statistics – in thousand tonnes/yr)

According to European experts, the difference of treatment methods between Member States is based on local regulations. Germany, Austria and the Netherlands forbid landfilling many years ago while landfilling is still very common in countries like France and the UK.

Figure 1.32 shows the evolution of sorting residues treatment methods in the EU-28 (NB: material recovery was not estimated in 2006 and 2008).

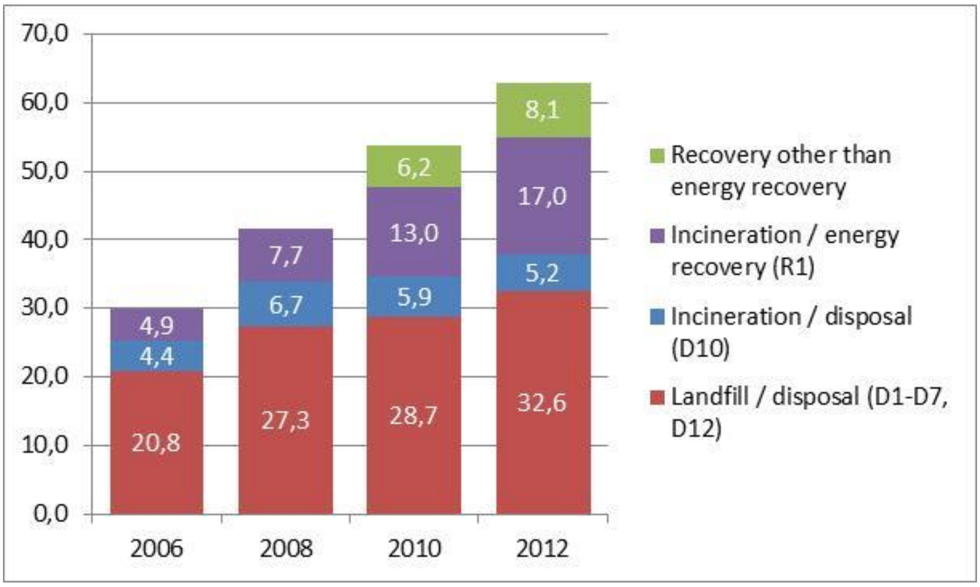


Figure 1.32: Evolution of sorting residues treatment methods in the EU-28 (Source: Eurostat Waste Statistics – in million tonnes/yr)

Looking at Figure 1.32, it appears that since 2006 the amount of sorting residues sent for incineration/disposal has been quite stable whereas waste sent for energy recovery has multiplied by 3.5 over the same period. Using these figures, it is however not possible to know which wastes have been redirected from D10 to R1 incineration plants, and which incineration plants changed from D10 to the R1 status. Also, the trend from 2006 until 2012 does not seem to be consistent with the European waste management hierarchy because the amount of wastes sent to landfill follows an upward trend over the same period.

In order to estimate the potential of this waste as an energy source, it is necessary to account for the impact of recent and future European waste policies and Member States' waste management models. The implementation of more efficient source-separated collection systems should increase the separated collection fractions, but, with higher quality separation at households, rejects of these fractions will be lower. Besides, the mixed residual waste fraction will be lower too as well as its sorting residues. All of it will result in a decrease in sorting waste. To conclude, sorting waste depends on the model of waste management established in the different countries and should vary in the future.

Sorting residues and Solid Recovered Fuels (SRF)

As mentioned above, according to Eurostat, sorting residues are defined as: "*sorting residues from mechanical sorting processes for waste;* ***combustible waste (refuse derived fuel)****; and non-composted fractions of biodegradable waste. They mainly originate from waste treatment and source separate collection".* Based on this definition, sorting residues represent the main source for the production of refuse-derived fuels (RDF), with the exception of construction and demolition wastes which can be used to produce RDF but are excluded from sorting residues. When RDF are produced according to EN standards, they may be called SRF.

A 2015 study[30] estimated that 13.5 million tonnes of SRF/RDF[31] are currently being used in the EU-28. About 12 million tonnes are burnt in cement plants and dedicated

[30] Study from 2015 "Markets for Solid Recovered Fuel - Data and assessments on markets for SRF" from CEMBUREAU and ERFO.

waste incineration plants. It is therefore considered that a significant part of the 17 million tonnes of sorting residues sent for energy recovery are, in fact, wastes prepared according to the European standard for SRF, and then burnt in cement plants and dedicated waste incineration plants.

3.3.12Animal and vegetal wastes

Generation of animal and vegetal wastes

Data on the generation of animal and vegetal wastes (A&VW) comes from Eurostat Waste Statistics. According the Eurostat Manual on waste statistics, this category is composed of three subcategories:

- Animal and mixed food wastes (09.1): *"These wastes are animal and mixed wastes from food preparation and products, including sludges from washing and cleaning; separately collected biodegradable kitchen and canteen waste, and edible oils and fats. They originate from food preparation and production (agriculture and manufacture of food and food products) and from source separate collection. Animal and mixed waste of food preparation and products are non-hazardous".*
- Vegetal wastes (09.2): "*These wastes are vegetal wastes from food preparation and products, including sludges from washing and cleaning, materials unsuitable for consumption and green wastes. They originate from food and beverage production, and from agriculture, horticulture and forestry. Vegetal wastes are non-hazardous*".
- Animal faeces, urine and manure (09.3): "*These wastes are slurry and manure including spoiled straw. They originate from agriculture. Animal faeces, urine and manure are non-hazardous*".

As explained in Section 3.1.5 "Risk of double counting", edible oil and fat represents a market of growing importance for waste-to-energy. However, this combustible waste is difficult to estimate based on Eurostat Waste Statistics, and it was decided to study it separately, as discussed in Section 3.4.3 on waste-derived biodiesel.

Even though the boundaries of the definition of the category animal and vegetal wastes (A&VW) have not changed since 2006, the subcategories 09.1 and 09.2 were restructured as of 2010. Therefore, it is possible to provide detailed data by subcategory for the years 2010 and 2012, but only aggregated data are available for the previous years.

Table 1.34: Repartition of the generation of animal and vegetal waste by subcategory in 2012

	Total	Animal and mixed food waste	Vegetal wastes	Animal faeces, urine and manure
EU-28 (thousand tonnes)	110,060	37,240	56,730	16,090
EU-28	100%	34%	52%	15%

[31] Solid Recovered Fuel (SRF) / Refused Derived Fuel (RDF)

Table 1.35: Evolution of the generation of animal and vegetal wastes by Member State (Source: Eurostat Waste Statistics)

	Animal and vegetal wastes generation (thousand tonnes/yr)			
	2006	2008	2010	2012
Austria	2,018	3,712	1,661	1,893
Belgium	4,390	4,266	4,588	4,891
Bulgaria	984	977	731	1,130
Croatia	284	110	120	133
Cyprus	181	200	201	221
Czech Republic	684	541	450	443
Denmark	187	166	973	890
Estonia	300	287	280	84
Finland	1,074	1,243	900	988
France	6,226	7,591	9,406	11,281
Germany	12,052	12,231	12,933	14,087
Greece	4,779	138	445	492
Hungary	3,360	1,379	808	791
Ireland	1,274	523	2,079	1,243
Italy	9,346	9,406	9,490	9,976
Latvia	204	145	166	137
Lithuania	901	1,062	536	578
Luxembourg	97	91	88	85
Malta	12	15	16	16
Netherlands	12,289	13,255	14,588	14,545
Poland	8,291	7,124	6,356	5,930
Portugal	1,188	526	392	203
Romania	22,655	19,838	18,895	18,212
Slovakia	1,229	1,225	904	863
Slovenia	297	256	264	310
Spain	20,665	15,647	9,763	8,297
Sweden	1,754	1,788	1,684	1,842
United Kingdom	12,025	12,842	9,187	10,497
Total EU-28	**128,744**	**116,581**	**107,904**	**110,057**

The decline in the generation of A&VW is due to two methodological changes:

- the exclusion of manure when used as a by-product;
- the reclassification of organic waste from MBT plants that was included in the sorting residues category.

Based on data from Eurostat in Table 1.35, Figure 1.33 presents the evolution of the generation of A&VW for the 14 main EU-28 producers representing 95% of the total EU-28 generation in 2012.

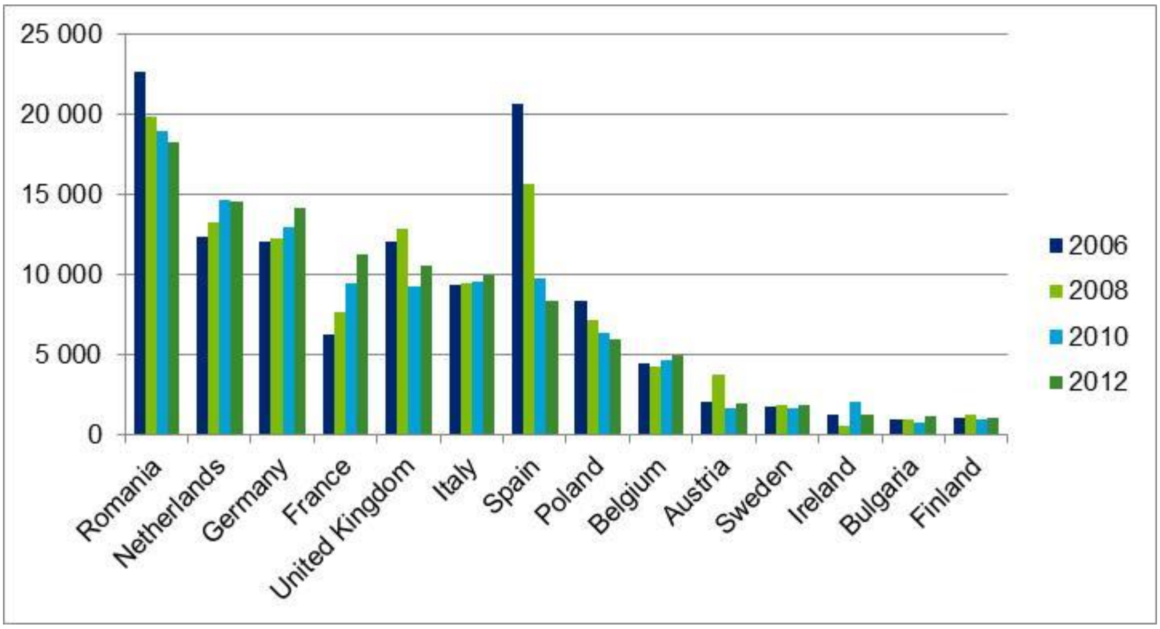


Figure 1.33: Evolution of the generation of animal and vegetal wastes for the 14 main EU-28 producers in 2012 (Source: Eurostat Waste Statistics – in thousand tonnes/yr)

Looking at Table 1.35 and Figure 1.33, it appears that, at the EU-28 level, generation of A&VW followed a downward trend from 2006 to 2010 (with an average decrease of 8% every two years) and was stable (slight increase of 2%) from 2010 to 2012. Some of the EU-28 Member States followed a downward trend from 2006 to 2012 (Romania, the UK, Spain and Poland), while others (the Netherlands, Germany and France) followed an upward trend over the same period.

Import/export into/outside the EU-28

No information on the import/export of A&VW outside the EU-28 has been identified.

Treatment of animal and vegetal wastes

A&VW treatment data comes from Eurostat Waste Statistics. Eurostat provides data on material recovery and landfill for the years 2006, 2008, 2010 and 2012, but data on other methods of treatment (energy recovery, and incineration on land) is only available for the years 2010 and 2012.

Table 1.36: Evolution of animal and vegetal wastes sent for energy recovery and incineration by Member State (Source: Eurostat Waste Statistics)

	2010 (thousand tonnes/yr)		2012 (thousand tonnes/yr)	
	Energy recovery (R1)	Incineration/ Disposal (D10)	Energy recovery (R1)	Incineration/ Disposal (D10)
Austria	81	2	14	0
Belgium	80	33	16	43
Bulgaria	5	0	11	0
Croatia	2	9	2	0
Cyprus	0	4	2	7
Czech Republic	46	4	53	2
Denmark	75	0	63	0
Estonia	41	0	0	0
Finland	145	32	61	152

	2010 (thousand tonnes/yr)		2012 (thousand tonnes/yr)	
	Energy recovery (R1)	Incineration/ Disposal (D10)	Energy recovery (R1)	Incineration/ Disposal (D10)
France	501	17	325	15
Germany	1,226	34	1,403	32
Greece	14	18	57	18
Hungary	200	1	167	1
Ireland	1	4	29	0
Italy	242	26	187	15
Latvia	0	0	3	0
Lithuania	2	0	9	0
Luxembourg	0	0	0	0
Malta	0	7	0	5
Netherlands	382	467	352	484
Poland	100	40	42	46
Portugal	103	7	15	11
Romania	17	0	100	40
Slovakia	6	17	5	28
Slovenia	7	0	6	0
Spain	21	29	100	0
Sweden	377	0	26	0
United Kingdom	78	907	589	312
Total EU-28	**3,752**	**1,656**	**3,637**	**1,213**

According to Table 1.36, between 2010 and 2012 the amount of A&VW sent for energy recovery was stable (-3% over the period), while the amount sent to incineration/ disposal decreased by 27%.

Figure 1.34 shows the repartition of A&VW treatment methods for the 14 EU-28 countries representing 96% of the A&VW sent to incineration and energy recovery in 2012.

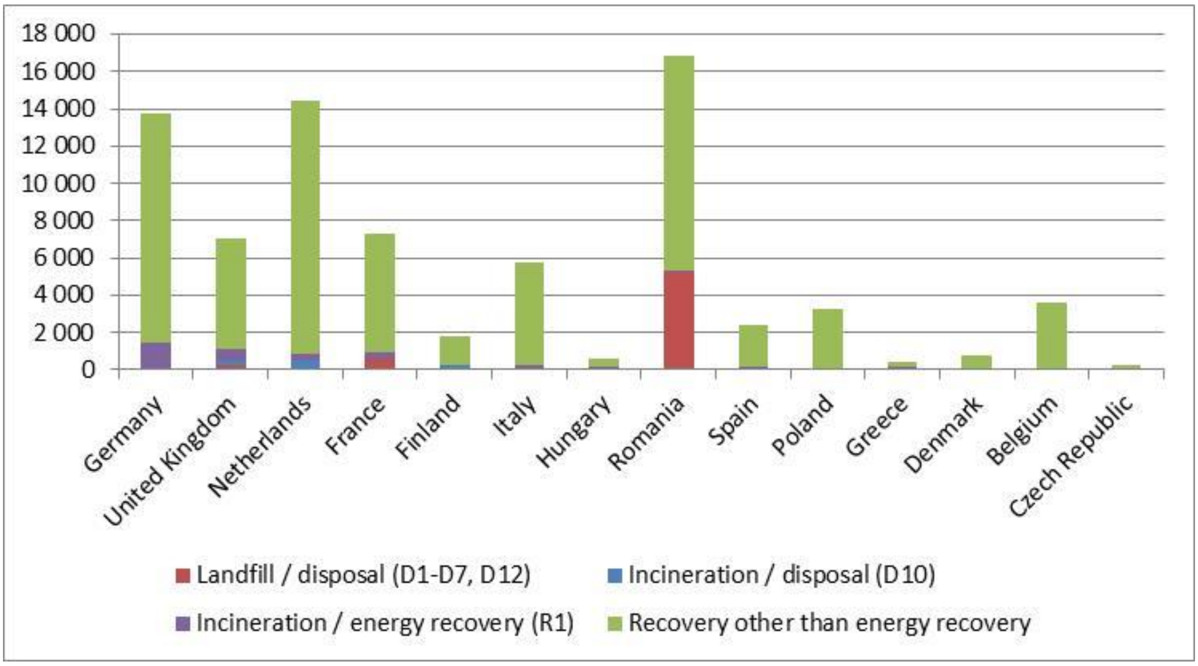


Figure 1.34: Treatment of animal and vegetal wastes for the 14 EU-28 main contributors to energy recovery from animal and vegetal wastes in 2012 (Source: Eurostat Waste Statistics – in thousand tonnes/yr)

Looking at Figure 1.34, it appears that material recovery is by far the main treatment method used for animal and vegetal wastes. Even if it is not possible to detail the amount of wastes sent to each recovery operation, it is probable that a significant share of these wastes are sent to R3 "*Recycling/reclamation of organic substances which are not used as solvents (including composting and other biological transformation processes)*".

Figure 1.35 gives an overview of the repartition of animal and vegetal waste treatment methods in the EU-28 and its evolution between 2010 and 2012. Considering that around 85% of wastes are sent for material recovery, the scale of the axis has been cut on purpose at 30 million tonnes to be able to analyse trends for other methods of waste treatment.

Looking at Figure 1.35, it appears that, at European level, the evolution of A&VW treatment pathways follows the waste management hierarchy: between 2010 and 2012, the wastes sent to landfill and to incineration/disposal decreased by 600,000 and 400,000 tonnes respectively, while, over the same period, the amount of wastes sent for material recovery and energy recovery decreased by 100,000 tonnes.

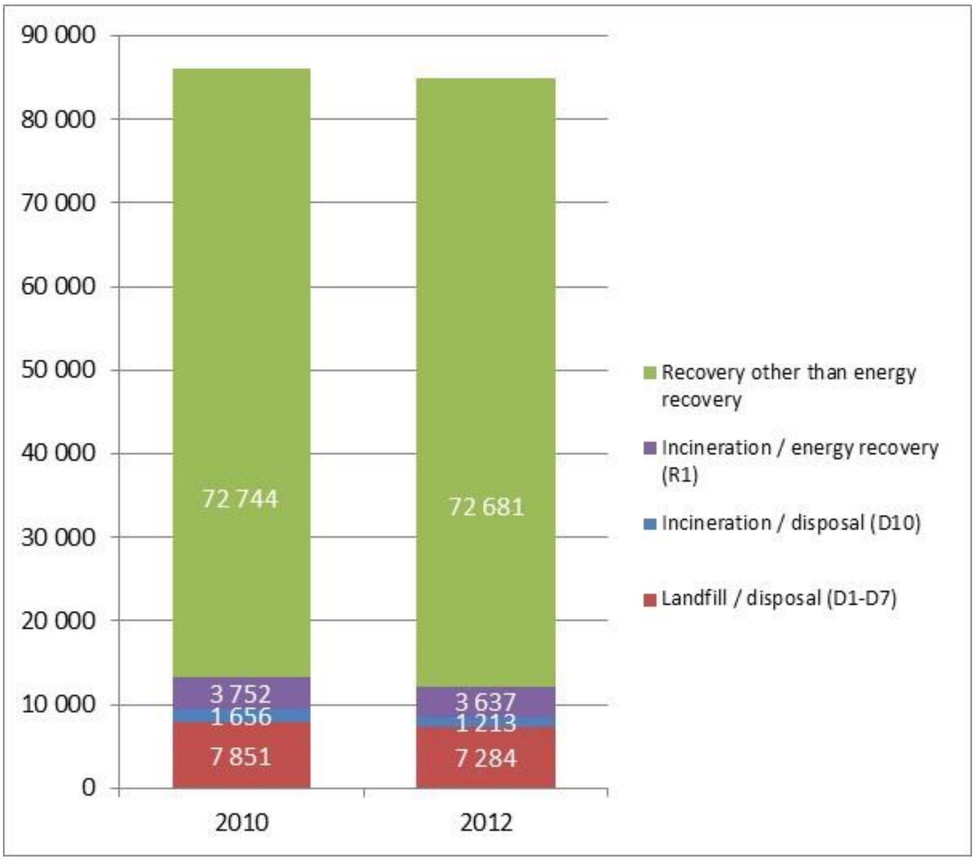


Figure 1.35: Evolution of animal and vegetal waste treatment methods in the EU-28 (Source: Eurostat Waste Statistics – in thousand tonnes/yr)

As explained above, several waste treatment methods are included in the category "recovery other than energy recovery" including composting and anaerobic digestion. A discussion on the use of composting or anaerobic digestion for biomass can be found in Section 3.6.

3.3.13 Dried municipal sewage sludge

Generation of municipal sludge

Specific data on the generation and treatment of municipal sewage sludge is not available from Waste Statistics.

Data on the generation of municipal sludge comes from Eurostat Water Statistics for urban waste water treatment plants, which is based on the OECD/Eurostat Joint Questionnaire - Inland Waters. In OECD/Eurostat, **sewage sludge is generally defined as the residual of waste water treatment**, and more specifically:

"*The accumulated settled solids separated from various types of water either moist or mixed with a liquid component as a result of natural or artificial processes*."

In principle, all NACE sectors and private households are covered by the data set produced.

Considering the definition of the waste stream, it is clear that industrial sludges are excluded from the scope.

According to the information provided by OECD/Eurostat[32], data are collected for each Member State of the EU. However, the EU-28 totals or averages have not yet been calculated by OECD/Eurostat as there are too many gaps in the data due to the voluntary nature of reporting. For some countries annual data are available.

Table 1.37: Evolution of municipal sewage sludge generation from urban waste water treatment plants by Member State. Data expressed in dry matter (Source: Eurostat Water Statistics)

	Municipal sewage sludge production (thousand tonnes DM/yr)			
	2006	2008	2010	2012
Austria	255	254	263	266
Belgium	128	140	176	157
Bulgaria	38	43	50	59
Croatia	n.a.	n.a.	30	42
Cyprus	n.a.	8	8	7
Czech Republic	203	220	196	263
Denmark	n.a.	108	141	141
Estonia	28	22	19	22
Finland	149	144	143	141
France	n.a.	1,087	966	987
Germany	2,100	2,053	1,911	1,849
Greece	126	136	n.a.	119
Hungary	238	172	170	162
Ireland	78	103	90	72
Italy	n.a.	n.a.	1103	n.a.
Latvia	24	19	21	20
Lithuania	n.a.	n.a.	n.a.	45
Luxembourg	15	13	10	8
Malta	0	0	1	10
Netherlands	373	353	351	346
Poland	501	567	527	533
Portugal	n.a.	n.a.	n.a.	339
Romania	226	79	82	85
Slovakia	55	58	55	59
Slovenia	19	20	30	26
Spain	1,065	1,156	1,205	2,757
Sweden	207	214	204	207
United Kingdom	1,809	1,814	1,419	1,137
Total EU-28	7,635	8,783	9,172	9,860
"n.a.:" not available in Eurostat.				

Taking into account missing data and the heterogeneity of the information provided, it seems that municipal sewage sludge production slightly increased in the EU-28 from 2006 to 2012.

[32] http://ec.europa.eu/eurostat/cache/metadata/en/env_nwat_esms.htm.

Import/export into/outside the EU-28

No information on the import/export of municipal sewage sludge outside the EU-28 has been identified.

Treatment of municipal sewage sludge

Data on municipal sewage sludge treatment for the period 2006-2012 comes from Eurostat Water Statistics. This database provides details for five subcategories:

- Incineration: all sludge that is disposed of by direct incineration or after mixing with other waste;
- Agricultural use: all sewage sludge that is used as fertiliser on arable land or pastures, no matter the method of application;
- Compost and other applications: all sewage sludge mixed with other organic material that is applied for composting in parks, horticulture, etc.;
- Landfill: all sludge which is disposed of in tips, landfill areas or special depot sites without any useful function;
- Other: other uses including dumping at sea, which has been forbidden since 1998[33].

It should be noted that the Eurostat data on waste treatment refers only to the final treatment. Therefore, there is no data on anaerobic digestion (AD) of sewage sludge as it is only pretreated before the residues (digestate) are incinerated, put on farmland or landfilled. AD of sewage sludge is not studied in this section, but Section 3.4.1 on waste-derived biogas production refers to it.

Considering that sewage sludge often has a high water content and therefore usually requires drying or the addition of supplementary fuels to ensure stable and efficient combustion[34], the total net energy recovery often does not reach the threshold to be considered as "R1 incineration". Therefore, sewage sludge incineration is considered as "D10 incineration" even if it is not specified in Eurostat Water Statistics database.

Data on the incineration of municipal sludge from Eurostat Water Statistics are presented in Table 1.38.

Table 1.38: Evolution of municipal sewage sludge incineration by Member State. Data expressed in dry matter (Source: Eurostat Water Statistics)

	Municipal sewage sludge incineration (thousand tonnes DM/yr)			
	2006	2008	2010	2012
Austria	98	91	115	139
Belgium	68	72	113	89
Bulgaria	0	0	0	0
Croatia	n.a.	n.a.	n.a.	n.a.
Cyprus	n.a.	2	0	0
Czech Republic	0	3	5	8
Denmark	n.a.	36	34	34
Estonia	0	0	n.a.	n.a.
Finland	0	2	0	32

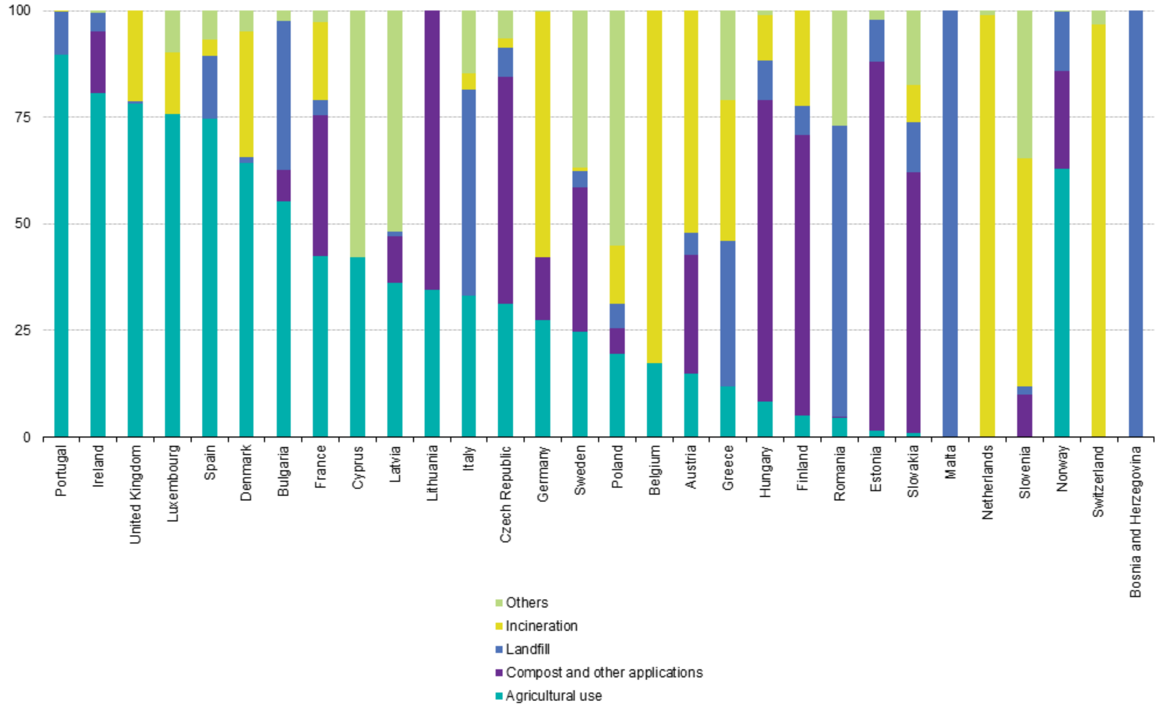
[33] The document "Data Collection Manual for the OECD/Eurostat Joint Questionnaire on Inland Waters" (Version 3.0 – September 2014) does not provide additional information on the treatment considered under the category "Other".

[34] Waste Incineration BREF, 2006

	Municipal sewage sludge incineration (thousand tonnes DM/yr)			
	2006	2008	2010	2012
France	n.a.	206	181	207
Germany	965	1,078	1,004	1,009
Greece	0	24	n.a.	39
Hungary	5	9	20	24
Ireland	0	0	0	0
Italy	n.a.	n.a.	37	n.a.
Latvia	0	0	0	0
Lithuania	n.a.	n.a.	n.a.	0
Luxembourg	1	1	1	1
Malta	0	0	0	0
Netherlands	325	336	330	321
Poland	4	6	20	57
Portugal	n.a.	n.a.	n.a.	0
Romania	n.a.	n.a.	0	0
Slovakia	0	0	0	3
Slovenia	5	7	13	13
Spain	41	n.a.	62	100
Sweden	0	0	2	1
United Kingdom	n.a.	n.a.	260	229
Total EU-28	1,513	1,873	2,195	2,306
n.a.: not available in Eurostat				

Eurostat's web platform on Water Statistics[35] provides graphics (see Figure 1.36) and explanations on the treatment of municipal sewage sludge in Europe in 2012.

[35] http://ec.europa.eu/eurostat/statistics-explained/index.php/Water_statistics#Wastewater_treatment.



(¹) Belgium, Denmark, Greece, Spain, Cyprus, Lithuania, Luxembourg, the Netherlands, Austria, Portugal, Finland, Sweden and the United Kingdom: 2012.
Italy: 2010. Croatia: not available.
Source: Eurostat (online data code: env_ww_spd)

Figure 1.36: Treatment of municipal sewage sludge in Europe in 2013 (Source: Eurostat Water Statistics)

Looking at Figure 1.36, it appears that municipal sewage sludge treatment pathways are different across Member States. This is in part due to variations in the composition of municipal sewage sludge: nutrients content, and concentrations of pollutants such as heavy metals. Agricultural use and composting is the main treatment for several countries including Portugal, Ireland, the United Kingdom, Luxembourg and Spain. According to Eurostat Water Statistics, alternative forms of sewage disposal may be used to reduce or eliminate the spread of pollutants on agricultural or gardening land; these include incineration and landfill. While the Netherlands, Belgium, Germany, Slovenia and Austria reported incineration as their principal form of treatment for disposal, discharge into controlled landfills was practised as the principal type of treatment in Malta (where it was the sole form of treatment), Romania and Italy.

It should be noted that reporting issues for sludge land-spreading might arise across Member States: land-spreading should be coded as R10 (Land treatment resulting in benefit to agriculture or ecological improvement) but often it might be reported as D2 (Land treatment, e.g. biodegradation of liquid or sludgy discards in soils).

Figure 1.37 shows the evolution of municipal sewage sludge treatment methods in the EU-28 over the period 2006 to 2012.

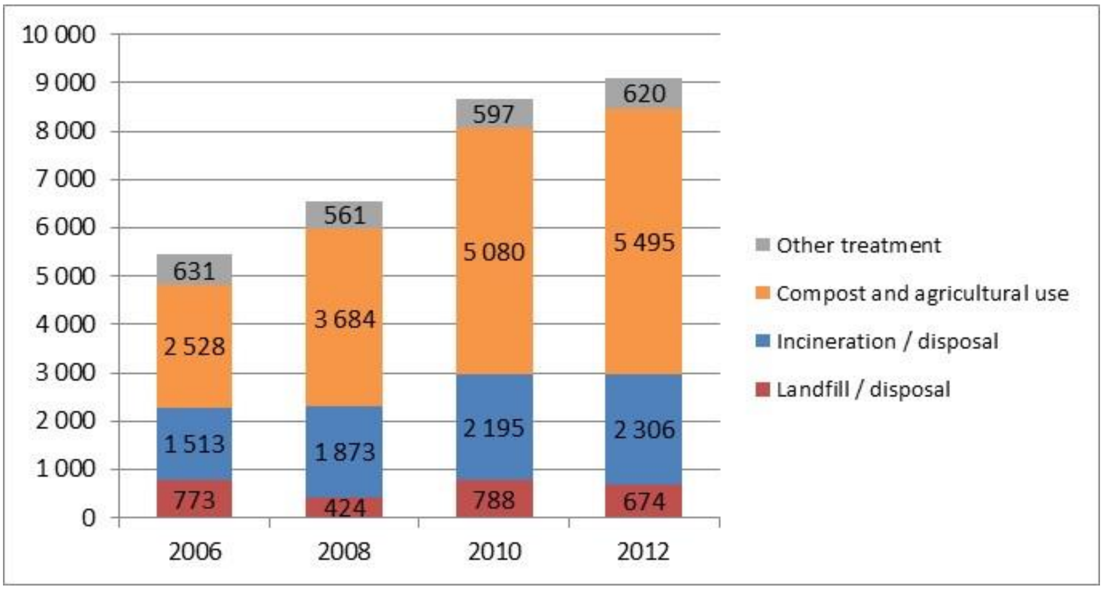


Figure 1.37: Evolution of municipal sewage sludge treatment methods in the EU-28 (Source: Eurostat Water Statistics – in thousand tonnes/yr)

In Figure 1.37, the upward trend from 2006 to 2010 for incineration can most probably be explained by an increase in the number of countries responding to the OECD questionnaire. Between 2006 and 2012, the share of sewage sludge sent to incineration was nearly constant at 25% of the total waste treated. As explained above, the net energy (taking into account the energy used for drying the sludge) recovered from sludge combustion is very low, which makes sewage sludge less interesting for incineration.

3.4 Results of waste-derived fuels data collection and analysis

3.4.1 Waste-derived biogas

Generation of biogas

In Eurostat Waste Statistics the treatment of biodegradable wastes for biogas production is considered as a recovery operation taken into account in the code R3 "R3 Recycling/reclamation of organic substances which are not used as solvents (including composting and other biological transformation processes)". Therefore, it is not possible to estimate the amount of biogas produced from wastes using the Eurostat Waste Statistics database.

In this context, data on the generation of biogas comes from Eurostat Energy Statistics and the European Biogas Association (EBA).

Eurostat's category "09 biogas" is defined as: "*gases composed principally of methane and carbon dioxide produced by anaerobic fermentation of biomass, or by thermal processes*".

As explained in Sections 2.2 and 3.1.1 related to the scope of the study, energy from combustible waste that has already been subjected to treatment and disposal is outside the scope of the present study. Thus, landfill gas is not discussed in the present study, even though it represents a significant amount of the total biogas produced in the EU-28.

Biogas can be produced from waste biomass and non-waste biomass such as energy crops. Eurostat Energy Statistics provides data on biogas production from two subcategories representing the main sources of biogas production:

- Sewage sludge gas: produced from the anaerobic digestion of sewage sludge; and
- Other biogases from anaerobic digestion of agricultural residues (animal slurries) and industrial wastes (waste in abattoirs, breweries and other agro-food industries).

It should be noted that Eurostat Energy Statistics do not provide data on biogas production from household and similar waste. However, according to Spanish experts interviewed for this study, this is an important source of waste-derived biogas production in Spain. As better and more widespread source-separated collection of animal and vegetal waste (A&VW) develops, it should lead to a better exclusion of the wet biodegradable fraction from HSW, resulting in a decrease in waste-derived biogas production from HSW and an increase in waste-derived biogas production from A&VW.

To estimate the share of waste-derived biogas, it is assumed that sewage gas is 100% waste-derived biogas, and that 17% of the other biogas from anaerobic digestion comes from wastes. For comparison, in its report from 2011, UBA used a ratio of 15% for "Other biogas".

The methodology used to estimate the 17% ratio is based on installed capacities (see Table 1.39) and estimated biogas yield (see Table 1.40) for:

- industrial waste biogas plants: 100% waste-derived biogas production; and
- agricultural plants: 13% biogas from agricultural waste and 87% from energy crops (not considered waste-derived biogas).

The 13% ratio was estimated using the average feedstock composition for seven Member States representing 87% of the installed agricultural plant capacities in Europe: France, Germany, Hungary, Italy, Latvia, Poland and the United Kingdom. This estimate is based on the best available data, but might underestimate the share of renewable biogas from agricultural plants[36].

Table 1.39: Repartition of anaerobic digestion plants in Europe in 2014 (source: EBA "Biomethane & Biogas report 2015")

	Sewage	Industrial waste	Agricultural
Installed capacity (MWel)	663	285	5,546
Number of plants	2,861	827	11,670
Average capacity (MWel/plant)	0.23	0.34	0.48

Table 1.40 presents the biogas yields used to estimate the 17% ratio of waste-derived biogas production from agricultural and industrial waste biogas plants in combination with data on average feedstock composition for agricultural waste, energy crop and industrial residues. The figures are only averages[37] and do not represent the large variety of feedstocks and biogas yields used for biogas production:

- agricultural wastes: from 20 to 30 m^3/t FM (fresh matter) for cattle manure, to 130 to 270 m^3/t FM for poultry manure;

[36] For instance, according to Danish experts, the ratio for agricultural plants in this country would be around 90%.
[37] Source: interviews with EBA experts.

- energy crops: from 120 to 140 m^3/t FM for sugar beets, to 170 to 230 m^3/t FM for maize silage;
- industrial residues: from 60 to 75 m^3/t FM for sugar beets pulp, to 290 to 340 m^3/t FM for molasses.

Table 1.40: Average biogas yields used for calculations (source: EBA from various sources)

	Agricultural wastes	Energy crop	Industrial residues
Biogas yield (m^3/t FM)	30	200	180

Results of calculations for each Member State are presented in Table 1.41 at two-year intervals.

Table 1.41: Evolution of the generation of waste-derived biogas by Member State (Source: Deloitte calculation based on Eurostat Energy Statistics and EBA data)

	Waste-derived biogas production (million Nm^3/yr)				
	2006	2008	2010	2012	2014
Austria	63	76	71	81	95
Belgium	10	13	43	58	79
Bulgaria	0	0	4	0	5
Croatia	0	7	6	7	10
Cyprus	0	1	2	4	4
Czech Republic	53	63	89	148	214
Denmark	52	51	53	58	66
Estonia	2	1	2	1	2
Finland	19	20	23	26	28
France	91	93	101	122	129
Germany	776	1,253	1,598	2,239	2,617
Greece	16	9	14	27	27
Hungary	14	16	22	43	36
Ireland	13	15	17	14	14
Italy	18	23	55	280	499
Latvia	3	4	6	15	21
Lithuania	3	3	6	6	13
Luxembourg	3	4	5	6	7
Malta	0	0	0	1	0
Netherlands	91	115	137	144	156
Poland	71	98	106	139	167
Portugal	2	3	3	3	7
Romania	0	0	1	8	5
Slovakia	11	16	16	35	34
Slovenia	2	6	10	13	10
Spain	98	40	75	134	199
Sweden	34	96	103	131	141
United Kingdom	281	340	431	482	594
Total EU-28	**1,726**	**2,364**	**3,000**	**4,223**	**5,181**

Table 1.41 shows that EU-28 waste-derived biogas production has been increasing by 20% to 40% every two years between 2006 and 2014. Table 1.41, Table 1.42 presents the repartition of waste-derived biogas production from sewage sludge and other biogas from anaerobic digestion in the EU-28. Since 2006, the share of sewage sludge gas has decreased continuously, representing less than half of the total waste-derived biogas production after 2012. Based on this downward trend, sewage sludge might represent less than 40% in the future compared to other waste-derived biogas produced from agricultural and industrial residues.

Table 1.42 Evolution of the production of waste-derived biogas for sewage sludge gas and other biogas (Source: calculation based on Eurostat Energy Statistics)

		2006	2008	2010	2012	2014
Sewage sludge gas	million m^3/yr	1,399	1,499	1,664	1,954	2,220
	%	81	63	55	46	43
Other biogas	million m^3/yr	328	865	1,336	2,269	2,960
	%	19	37	45	54	57

Based on data from Eurostat in Table 1.41, Figure 1.38 shows the evolution of the generation of waste-derived biogas for the 14 main EU-28 producers representing 96% of the total EU-28 generation in 2014.

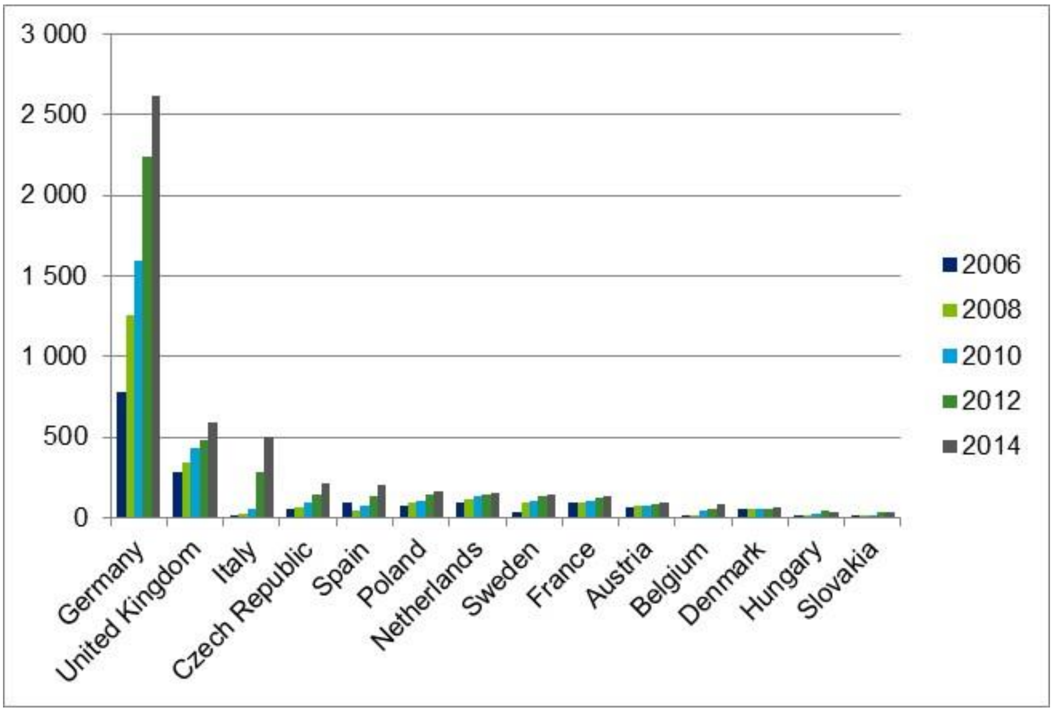


Figure 1.38: Evolution of the generation of waste-derived biogas for the 14 main EU-28 producers in 2014 (Source: Eurostat Waste Statistics – in million Nm^3/yr)

According to Figure 1.38, in 2014, Germany represented more than 50% of the EU-28 production, and production continues to increase in this country.

Comments on data calculation

In Spain, national data from the Ministry of Environment are in line with results, and, in Finland, national data for sewage sludge are 20% below the data from Eurostat. In addition, in its 2015 biogas report, EBA estimated that, in 2014, 140 567 GWh of biogas (including landfill gas and non-waste-derived biogas) was produced in the EU-28, which is 20% below the Eurostat estimate for the period.

Based on this, it is considered that calculated data represents a high-range estimate of the current situation.

In 2014, agricultural plants using agricultural wastes and energy crops were dominating the market, driven by Germany and to a lesser extent Italy[38]. However, in 2015, the share of agricultural plants decreased in Europe, due to new installations in the water sector as well as the food and drink sector and waste management industries. This evolution might continue and change the landscape of biogas plants in coming years.

Some feedstock can be either sent to anaerobic digestion plants or composting plants. A discussion on the use of composting or anaerobic digestion for biomass can be found in Section 3.6.

Finally, it is important to remember that, as explained in Section 3.1.1, the definition of “waste” vs “by-product” for industrial and agricultural residues is provided by the Waste Framework Directive, but remains subject to interpretation. Therefore, all countries do not apply the same rules. This should be kept in mind when looking at the methodology and results on waste-derived biogas.

Import/export into/outside the EU-28

No information on the import/export of biogas outside the EU-28 has been identified. Historically, biogas has been produced and used locally, but more countries are allowing biomethane injection in the gas network making it possible to sell biomethane to other countries.

Treatment of biogas

Except for leakage of biogas that could not be estimated, biogas is used entirely for energy recovery.

Energy recovery from biogas

Biogas is used to produce electricity, heat and biomethane. Biomethane can then be used for transportation, grid injection, and industrial processes.

Data from the European Biogas Association has been used to estimate the amount of waste-derived heat, electricity and biomethane produced in the EU-28. Results are considered as low-range estimates, because EBA collected data from the main biogas producers, but not all Member States provided information. Considering data gaps, it is only possible to provide estimates for 2014 at the EU-28 level.

The methodology used to calculate the amount of heat, electricity and biomethane from waste-derived biogas is described below (see Table 1.43):

- At the end of 2014, there were 367 biomethane plants in the EU-28, representing an overall upgrading capacity of 199 204 Nm^3/h[38]. The estimation of waste-derived biomethane production is based on biomethane production data for 2014[38], and an estimate of the share of waste-derived biomethane at national level[39]. For Germany and Sweden (representing 84% of the total biomethane produced in the EU-28), it represents respectively 13% and 100% of the total production. Using this approach,

[38] Information from the EBA 2015 annual biogas report and from personal communication with EBA.

[39] For Germany and Sweden, the estimation of the share of waste-derived biomethane is based on the feedstock repartition, and, for other Member States, a conservative estimate of 50% has been used.

it was calculated that, in 2014, 12 PJ of waste-derived biomethane was produced in the EU-28. Germany and Sweden represent respectively 37% and 39% of the waste-derived production in the EU-28.

- At the end of 2014, there were 17 240 biogas plants in the EU-28, representing an overall installed capacity of 8 293MW_{el}. The estimation of waste-derived heat production (after exclusion of internal use) is based on the production of heat for agricultural, sewage and other (biowaste and industrial biogas) plants at national level. It was considered that 100% of the heat recovered from sewage, biowaste and industrial biogas is waste-derived. For agriculture, a ratio of 13% has been applied[40]. Using this approach, it was estimated that, in 2014, 33 PJ of waste-derived heat (after exclusion of internal use) was recovered in the EU-28. Germany and Italy represent 39% and 53% respectively of the waste-derived production in the EU-28.
- Data on the recovery of electricity for agricultural, sewage and other (biowaste and industrial biogas) plants was not available. Therefore, the share of waste-derived electricity was estimated using the total amount of electricity produced in Europe, multiplied by the share of waste-derived heat (26%, see Table 1.43). Using this approach, it was estimated that, in 2014, 70 PJ of waste-derived electricity was produced in the EU-28.

Table 1.43: Production of heat, electricity and biomethane from anaerobic digestion plants in Europe in 2014 (source: Deloitte estimate based on EBA "Biomethane & Biogas report 2015")

	Heat	Electricity	Biomethane
Total production (PJ)	108	229	44
Waste-derived production (PJ)	33	70	12
Waste-derived production (%)	31	31	26

The amount of biogas converted into biomethane should increase in the coming years, due to the fact that, since 2011, the number of new biomethane plants has followed an upward trend, with 2014 representing the highest increase with 83 new biogas upgrading units commissioned in Europe[38].

3.4.2 Waste-derived bioethanol

The Eurostat Energy Statistics database provides annual data on the production of biogasoline (including bioethanol) for all EU-28 countries for the period 2006 to 2014.
Biogasoline is described as follows according to Eurostat's "Renewables annual questionnaire 2014"[41]:

"Biogasoline: This category includes bioethanol (ethanol produced from biomass and/or the biodegradable fraction of waste), biomethanol (methanol produced from biomass and/or the biodegradable fraction of waste), bioETBE (ethyl-tertio-butyl-ether produced on the basis of bioethanol; the percentage by volume of bioETBE that is calculated as biofuel is 47%) and bioMTBE (methyl-tertio-butyl-ether produced on the basis of biomethanol: the percentage by volume of bioMTBE that is calculated as biofuel is 36%).

[40] Refer to the aforementioned methodology for calculation of waste-derived biogas production.
[41] The "Annual renewable questionnaire 2014" provides Member States information on how to complete the questionnaire as part of their annual obligation of reporting to Eurostat energy statistics. http://ec.europa.eu/eurostat/documents/38154/6935814/AQ2014-RENEWABLES-instructions.pdf/e16338f5-bbed-4c13-bdbf-903307420d45

− Of which Bioethanol: this category includes ethanol produced from biomass."

From this definition, it appears that the Eurostat Energy Statistics database does not provide specific information for bioethanol production, nor does it make the distinction between bioethanol produced from waste or from biomass. Therefore, this database could not be used in this study.

In Europe (Finland, Spain, etc.), there are several industrial and demonstration plants producing bioethanol from process residues (bakery waste, residues from enzyme production, from breweries, etc.) and by enzymatic hydrolysis of the organic fraction from household and similar waste. In 2009, the share of wastes in feedstock materials for the production of bioethanol was considered negligible (Gaupmann, 2009)[42]. In Finland, five plants producing 10 million litres of bioethanol from process residues (wastes and by-products) are in operation. It is therefore considered that waste-derived bioethanol production has increased since 2009. However, it was not possible to estimate the growth of the market in the EU-28 since 2009 for the following reasons:

- the lack of waste-related data at European level;
- the reluctance of plant operators to provide detailed information on feedstocks for confidentiality reasons;
- differences across Member States on the classification of by-products vs wastes (see discussion in Section 3.1.1).

In this context, waste-derived bioethanol techniques are studied in this report as part of the emerging WtE techniques.

3.4.3 Waste-derived biodiesel

Generation of biodiesel

The Eurostat Energy Statistics database provides annual data on the production of biodiesel for all EU-28 countries for the period 2006 to 2014. Biodiesel is described as follows according to Eurostat's "Renewables annual questionnaire 2014"[43]:

"Biodiesels: This category includes biodiesel (a methyl-ester produced from vegetal or animal oil, of diesel quality), biodimethylether (dimethylether produced from biomass), Fischer Tropsch (Fischer Tropsch produced from biomass), cold pressed biooil (oil produced from oil seed through mechanical processing only)."

However, this database only refers to "biomass" and does not make the distinction between biodiesel produced from waste or from by-products (see discussion in Section 3.1.1 for the difference between waste and by-products).

It is difficult to get a precise estimation of the share of biodiesel produced from wastes because Member States do not agree on how to determine whether a biomass feedstock used for biodiesel production is a waste or a by-product. In addition, it is impossible to base this estimate on the number and capacity of existing plants

[42] Source Gaupmann (2009): Setting the scene – Bioethanol production in the EU. RSB Consultation (Version Zero). Europe stakeholder outreach meeting. Brussels, 19 March 2009.

[43] The "Annual renewable questionnaire 2014" provides Member States information on how to complete the questionnaire as part of their annual obligation of reporting to Eurostat energy statistics. http://ec.europa.eu/eurostat/documents/38154/6935814/AQ2014-RENEWABLES-instructions.pdf/e16338f5-bbed-4c13-bdbf-903307420d45.

because most of them produce biodiesel from wastes and non-waste animal fat and vegetable oils, and for confidentiality reasons they are not willing to provide detailed information (type and quantity) on their feedstock.

In this context, it was estimated that waste-derived biodiesel represents around 5% of the total generated biodiesel (UBA, 2011). This is considered a low-range estimate.

The results of the calculations are presented below in Table 1.44 at two-year intervals.

Table 1.44: Evolution of the generation of waste-derived biodiesel by Member State (Source: Eurostat Energy Statistics)

	Waste-derived biodiesel production (tonnes/yr)				
	2006	2008	2010	2012	2014
Austria	6,583	12,543	13,835	10,399	13,408
Belgium	0	14,392	16,323	15,390	19,424
Bulgaria	0	500	629	409	3,119
Croatia	0	177	698	1,987	1,782
Cyprus	0	342	282	333	0
Czech Republic	5,568	3,876	10,008	8,731	11,086
Denmark	3,596	5,072	3,928	0	0
Estonia	0	0	0	0	0
Finland	0	4,801	16,995	14,524	20,257
France	30,066	89,672	101,470	111,231	118,655
Germany	118,181	127,923	156,492	142,534	174,029
Greece	2,400	3,598	6,434	7,108	8,101
Hungary	0	7,018	7,242	7,373	6,719
Ireland	126	2,168	3,626	1,370	1,382
Italy	11,272	33,765	40,384	14,505	29,293
Latvia	342	1,429	2,208	4,597	3,809
Lithuania	523	3,265	4,507	5,394	6,051
Luxembourg	0	0	0	0	0
Malta	0	0	31	56	58
Netherlands	934	4,195	19,309	59,493	86,940
Poland	4,677	13,583	19,911	31,754	37,349
Portugal	4,578	8,264	15,998	15,376	16,387
Romania	0	4,666	618	5,075	5,542
Slovakia	2,423	5,765	6,387	5,680	5,305
Slovenia	101	402	944	54	0
Spain	3,232	11,338	43,165	25,428	61,248
Sweden	2,483	7,431	10,148	19,170	6,111
United Kingdom	13,039	14,470	7,895	12,656	7,251
Total EU-28	210,124	380,656	509,467	520,628	643,305

Table 1.44 shows that EU-28 waste-derived biodiesel production has been increasing since 2006.

In comparison with estimations based on edible oil and fat generation, we can make the following observations:

- Edible oil and fat comprises various waste fractions of vegetal and animal origin, such as used cooking oil from restaurants and households or fat arising in the food industry. No database on the generation of waste edible oil and fat at the EU-28 level has been identified. Information available from the literature review and experts show significant differences at national level for edible oil and fat generation and collection efficiency: 0.44 kg/capita in Germany (Statistisches Bundesamt 2009) and 1 kg/capita in Slovenia (EPA Slovenia 2010) to 3.3 kg/capita in the Austrian province of Burgenland (AMT Der Burgenländischen Landesregierung 2006).
- In 2011, UBA estimated that, on average in the EU-28, 1 kg of edible oil and fat is collected per capita. This represents 500,000 tonnes of wastes collected and an equivalent amount of biodiesel produced. This value is in line with the data from Table 1.44 considering that edible oil and fat is the main feedstock for waste-derived biodiesel production in the EU-28.

Based on data from Eurostat in Table 1.44, Figure 1.39 shows the evolution of the generation of waste-derived biodiesel for the 14 main EU-28 producers representing 95% of the total EU-28 biodiesel production in 2014.

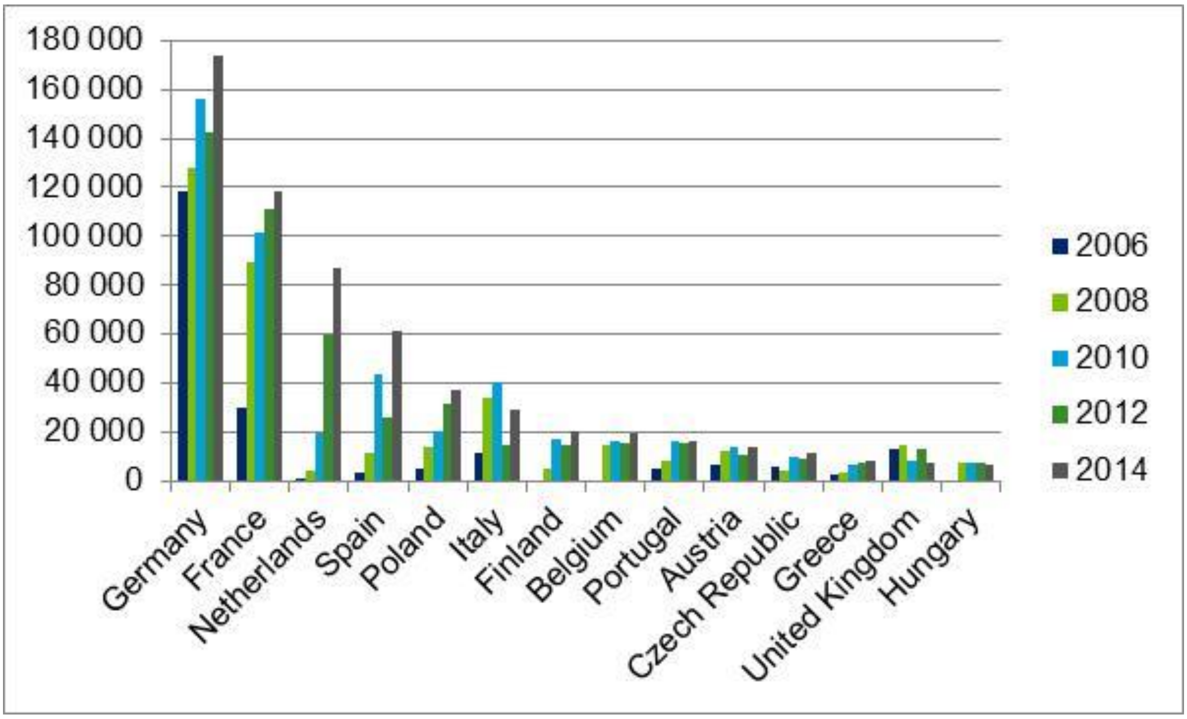


Figure 1.39: Evolution of the generation of waste-derived biodiesel for the 14 main EU-28 producers in 2014 (Source: Eurostat Waste Statistics – in tonnes/yr)

Looking at Figure 1.39 it appears that, between 2006 and 2014, all main biodiesel-producing EU countries increased their production significantly.

Finland reported that national data are in line with the Eurostat data for biodiesel production. However, for confidentiality reasons they cannot estimate the share of waste-derived biodiesel produced.

A downward trend can be observed for the UK - Figure 1.39 is not in line with experts' observation of the national market. Indeed, according to UK experts, most UK biodiesel producers moved to nearly 100% waste-based production over the period.

Comments on calculations

There are two main limits in the current methodology applied:

- The 5% ratio for waste-derived biodiesel production and the 1 kg/capita ratio for edible oil and fat collection in the EU-28 are based on the UBA study from 2011. The Renewable Energy Directive (RED 2009/28/CE) establishes the "double-counting" system[44], an incentive for the production of waste-derived biodiesel. This has led to "*important and continuous progress during the past 5 years* (2010-2015)*, including the opening of commercial production facilities*"[44]. In addition, according to Fediol, because of the double counting for biodiesel, the trade in edible oil and fat as raw material for biodiesel has increased dramatically in the past years. Therefore, the two ratios provide the best available estimates, but represent a low-range estimate of the current situation.
- The 5% average is applied to all Member States, while it is to be expected that the share of waste-derived biodiesel varies significantly across Member States. Indeed, feedstock used for biodiesel production is country-specific, and ratios for edible oil and fat collection per capita are different across Member States. In addition, a few Member States[44] (such as Belgium, France, Malta, Spain) have implemented the double-counting system in their legislation, which provides further incentives for waste-derived biodiesel production. Therefore, country-specific data in Figure 1.39 should be used carefully.

Import/export into/outside the EU-28

There is no specific data for the import/export of waste-derived biodiesel. The Eurostat COMEXT Database only provides trade data for biodiesel.

Quantities are available on a monthly and yearly basis from 1988 to 2014. For the purpose of the study, yearly imported and exported quantities from 2006 to 2014 were considered. Relevant data were identified based on their CN8 code. According to the methodology used in the UBA 2011 study, the following CN8 codes were used for biodiesel:

WDF	CN8 Code	Description
Biodiesel	15162091	Vegetable fats and oils and their fractions, partly or wholly hydrogenated, inter-esterified, re-esterified or elaidinised, whether or not refined, in immediate packings of <= 1 kg (excl. hydrogenated castor oil "opal wax" and further prepared)
	15162095	Rapeseed, colza, linseed, sunflower-seed, illipe, karite, makore, touloucouna or babassu oils and their fractions, partly or wholly hydrogenated, inter-esterified, re-esterified or elaidinised, whether or not refined, for technical or industrial uses, in immediate packings with a net content of > 1 kg or otherwise prepared (excl. for the manufacture of foodstuffs for human consumption)
	15162098	Vegetable fats and oils and their fractions, partly or wholly hydrogenated, inter-esterified, re-esterified or elaidinised, whether or not refined, in immediate packings of > 1 kg or in another form (excl. fats and oils and their fractions, further prepared, hydrogenated castor oil and subheadings 1516.20.95 and 1516.20.96)

Table 1.45 shows that the EU-28 has a positive biodiesel trade balance.

[44] European Commission, SWD(2015) 117 final, *Technical assessment of the EU biofuel sustainability and feasibility of 10% renewable energy target in transport.*

Table 1.45: Evolution of biodiesel trade outside the EU-28 (Source: Eurostat COMEXT Database)

	Import/export into/outside the EU-28 (tonnes/yr)		
	Import	Export	Trade balance
2006	16,438	40,326	23,888
2008	27,657	36,145	8,488
2010	26,232	37,035	10,803
2012	24,086	39,564	15,478
2014	20,510	40,095	19,584

Treatment of biodiesel

Biodiesel is used entirely for energy recovery.

3.4.4 Gaseous output from gasification

According to UBA (2011), coal, petroleum and gas are the dominating feedstock to gasification plants. Data extracted from the NETL/DOE 2010 World Gasification Database (NETL/DOE 2010), UBA (2011) estimated that around 1.5% (215 MW_{th}) of the total European syngas is produced annually from wastes. This amount is negligible compared to the calculated 1.9 million TJ of energy contained in waste sent to incineration annually (see Table 1.1).

European experts have divergent opinions on gasification projects' outlooks: while some experts consider that the current small-scale pilot operations in the UK could lead to commercial-scale projects, other experts think that waste-based gasification projects are not economically viable.

Therefore, it was decided not to study this technique further in this report.

3.4.5 Gaseous, liquid and solid output from pyrolysis

According to UBA (2011) and interviews with European experts from ETRMA and GEIR, the number of pyrolysis plants in Europe has been decreasing in recent years and there are now very few active plants remaining. However, for some countries, the situation departs from the current trend at European level. For instance, in Spain, several pyrolysis-gasification plants of tyres and plastic waste have been authorised in the last two years. Also, in the UK, several companies seem to be willing to develop pyrolysis infrastructure, particularly in respect of the flash pyrolysis of high-calorific-value mixed wastes. This remains a niche area, but there is considerable interest from innovators in the UK.

It is difficult to know exactly how many plants remain active in the EU-28 or to estimate how much energy they produce and from which feedstock. However, based on the information gathered, the numbers seem to be low. European experts have differing opinions on the possible development of the technology for waste-to-energy.

Therefore, it was decided not to study this technique further in this report.

3.5 Discussion on data collection and trend analysis

3.5.1 Eurostat methodology for data collection

This section provides details on Eurostat's methodology for data collection on waste generation and waste treatment.

The Eurostat Manual on waste statistics provides, in its Section 2.1, a definition of waste within the scope of the Eurostat Waste Statistics database in accordance with the Waste Statistics Regulation (WStatR), including consequences of double counting.
The WStatR covers substances and materials which are defined as wastes in EU legislation, and which are covered by the Waste Framework Directive.

Waste included:
The Waste Statistics Regulation makes a clear distinction between 'waste generation' and 'waste treatment'. Waste generation includes all wastes generated by economic activities and by households. Because economic activity includes activities of treatment facilities, waste generated by these facilities (secondary waste) should also be reported under waste generation.

Waste treatment includes all waste entering treatment facilities for final treatment (this includes both public and private waste treatment facilities).

Note: The different concepts of the WStatR for the handling of secondary waste have consequences with regards to the double counting of waste:

- Data on waste generation shall cover all waste (primary and secondary waste) generated by the statistical units, which means that double counting of waste is part of the concept.
- Data on waste treatment refers to the final treatment; treated waste should thus be counted only once. The only exemption[45] is the double counting of combustion residues from waste incineration and energy recovery.

Waste excluded:
Some waste streams are however not covered by the WStatR. These are:

- wastes excluded from the scope of the Waste Framework Directive;
- wastes that are internally recycled (see paragraph below for further details).

However, some waste streams are excluded from the scope of the Waste Framework Directive because they are covered by other Community legislation, yet they fall within the scope of the Waste Statistics Regulation. This applies in particular to animal carcasses and animal by-products covered by Regulation (EC) No 1069/2009.

Exclusion of some recovery and disposal operations, and pretreatments:
Disposal and recovery operations defined as preparatory operations are excluded from reporting on waste treatment. Among others, it excludes biological treatment (D8): operations which use aerobic or anaerobic biological processes in order to prepare the waste for subsequent disposal, e.g. by reducing the amount of biodegradable components, or by degradation of organic pollutants. This includes, in particular:

- biological-mechanical treatment of municipal waste;
- biological treatment of contaminated soil, sludges or mineral wastes, if followed by disposal.

The following operations are also excluded from reporting on waste treatment:

- Blending, mixing and repackaging of waste (D13 and D14);
- Exchange of wastes (R12);
- Temporary storage (D15 and R13).

Exclusion of co-incineration plants using specific biomass wastes:

[45] As explained in Section 3.3.9, there is also evidence of double counting for HSW sent to MBT plants. However, this is not discussed in the Eurostat Manual on waste statistics.

The Waste Statistics Regulation excludes co-incineration plants[46] for which the waste-based secondary fuels fall into the following biomass waste categories:

- vegetal waste from agriculture and forestry;
- vegetal waste from the food processing industry;
- fibrous vegetal waste from virgin pulp production and from the production of paper from pulp;
- uncontaminated wood waste (excluding wood from construction and demolition or other wood waste that may contain halogenated organic compounds or heavy metals);
- cork waste.

Therefore, no statistics are compiled in Eurostat Waste Statistics on the amount of waste treated in such facilities.

It is important to emphasise that the exemptions refer only to co-incineration plants that use no other wastes besides the biomass wastes listed above. Statistics have to be compiled for:

- all co-incineration plants that use as a fuel other wastes besides those listed above;
- all incineration plants dedicated to the thermal treatment of waste, with or without energy recovery.

Exclusion of internal recycling:
No statistics have to be compiled for waste that is recycled on the site where the waste is generated, i.e. internal recycling. Companies which recycle waste internally may also receive waste from other companies for recycling. In these cases, statistics should include recycling of external waste and exclude recycling of internal waste.
Internal recycling excludes:

- any disposal operation, such as the disposal of waste at a company's own landfill;
- energy recovery operations.

3.5.2 Quality of the Eurostat data and resulting limitations in data interpretation

3.5.2.1 Evolution of the Eurostat Waste Statistics methodology and trend analysis

Significant evolutions in the Eurostat Waste Statistics methodology occurred after 2010. These evolutions have an impact on some waste category definitions, such as mixed and undifferentiated materials. For those wastes, the scope of the data is different before and after 2010. Also, for seven waste streams (i.e. wood, plastics, papers, textiles, solvents, chemicals, and animal and vegetal wastes), waste treatment data for landfill, incineration (D10) and energy recovery (R1) is only available for the years 2010 and 2012. In addition, Eurostat Waste Statistics did not provide data for the year 2014 at the time this report was drafted.

Fortunately, Eurostat Waste Statistics provides in its User Manual guidance on methodological changes, and resulting evolutions in Eurostat data. Thanks to this manual, it is possible to use and analyse Eurostat Waste Statistics with all necessary caution.

[46] Co-incineration plants according to the meaning of Directive 2000/76/EC on the incineration of waste.

Furthermore, Member States improve their own reporting methodologies. For instance, Spain considers that data from 2010 and 2012 are more accurate, due to improved methodology and better quality control of the data.

As a conclusion, some experts consider that Eurostat data does not reflect the current situation for all waste streams studied. However, most experts also agree that, for most waste streams, there is no better database available to provide an overview of waste generation and treatment at European and national level. Some inconsistencies in Eurostat data were noted during the project. Such inconsistencies are well known (see discussion on double counting in Section 3.1.5) but are already the subject of significant rectification efforts at European and Member State level.

3.5.2.2 Discussion on trends from 2006 to 2012 and after 2012

The economic crisis in Europe that began in 2008 may explain some downward trends for several waste streams including plastics and papers and cardboards.

In addition, the period from 2006 to 2012 corresponds to the latest information available from Eurostat Waste Statistics at the time of the project, but significant evolutions have occurred since then. Based on feedback from Member States and industry experts, some of them have been taken into account from a qualitative point of view during the analysis of the graphics. For instance, in Finland since 2012, the waste-to-energy capacity has more than doubled, and as a consequence MSW sent to incinerators have followed the same pattern.

3.5.2.3 Discussion on incineration disposal (D10) and incineration with energy recovery (R1)

The distinction between incineration disposal (D10) and incineration with energy recovery (R1) is based on the R1 factor calculation explained within a guideline published in June 2011 by the European Commission[47]. Data on R1/D10 referring to years before that are thus not comparable.

According to Member States and industry expert feedback, the approach for implementing the formula is different between the Member States. As a result, several Member States, including Germany (only one waste-to-energy plant has not achieved the R1 status) and the Netherlands (all waste incinerator plants being R1), indicated that Eurostat data are not representative of the current situation.

In addition, most installations with the D10 status produce a certain amount of energy. Also, some plants shift from D10 to R1 from one year to another depending on the type of waste used or on technical issues faced when reducing the overall energy efficiency of the plant.

As a conclusion, most experts consider that, when using data from 2006 to 2012, it is not relevant to make a distinction between R1 and D10; adding up both gives a more accurate estimate of overall energy recovery operations. As a consequence, in Task 3, calculations are based on total waste incinerated (D10 and R1).

For more information on the R1 formula and its implementation in the EU-28, reference is made to the JRC report from 2014 "*Report on the impact of R1 climate correction factor on the waste-to-energy (WtE) plants based on data provided by Member States*". This report provides a good overview of the consequences of the R1 formula, and discusses the opportunity for changing the R1 formula to integrate a

[47] http://ec.europa.eu/environment/waste/framework/pdf/guidance.pdf.

climate factor aiming at taking into account the impact of climate conditions on the R1 formula.

3.5.2.4 Discussion on reporting for industrial/agricultural "waste" vs "by-product"

It is important to recall that, as explained in Section 3.1.1, the definition of "waste" versus "by-product" for industrial and agricultural residues is provided by the Waste Framework Directive, but remains subject to interpretation. Therefore, not all countries apply the same rules. In addition, for confidentiality reasons, many plants producing energy from waste are reluctant to provide detailed information (type and quantity) on their feedstock, which makes it impossible to determine whether it concerns a waste or a by-product. This is mostly the case for "Animal and vegetal wastes" treatment, and for waste-derived fuels production (biogas, biodiesel, bioethanol).

This should be kept in mind when looking at the methodology and results for these combustible wastes.

3.5.2.5 Information on hazardous waste

According to Hazardous Waste Europe (HWE), the European association for hazardous waste (HW), 50 million tonnes of HW are generated in the EU-28, a third of which is produced by France and Germany. Of these 50 million tonnes, the association estimates that 20 to 25 million tonnes contain an organic part and should not therefore be sent to landfill. Approximately 5 million tonnes are sent to incineration and co-incineration:

- 3 to 4 million tonnes are burnt in dedicated hazardous waste incinerators;
- 1 to 2 million tonnes are burnt in co-incineration in cement kilns; and
- 1 to 2 million tonnes are burnt in co-incineration in non-hazardous waste incinerators.

In comparison, Eurostat estimates that 75 million tonnes of HW were produced in the EU-28 in 2012, nearly 28 million tonnes of which were non-inert. Unfortunately, it was impossible to identify the reason for the 50% difference between the estimations made by HWE and Eurostat or the main waste streams impacted by this difference.

3.6 Identification of combustible waste containing high overall amounts of energy

This selection is based on the current amount (in PJ) of waste sent for incineration (with or without energy recovery) and the amount (in PJ) sent to landfill because the part of it **that is unsuitable for recycling** could be sent for energy recovery in the coming years. In accordance with the waste management hierarchy, the amount (in PJ) of wastes sent for energy recovery should not increase at the expense of material recovery, unless this is justified by life-cycle thinking about the overall impacts of the generation and management of such waste (see Article 4, paragraph 2, of the WFD).

Table 1.46 presents the amount of wastes that was sent to incineration and landfill in 2012 in the EU-28 (for the 15 most significant combustible wastes studied).

Table 1.46: Amount of wastes sent to incineration and landfill in 2012 in the EU-28 (Source: Deloitte – in blue, waste categories containing high overall amounts of energy)

	Incineration (D10+R1) - PJ		Landfill / disposal (D1-D7-D12) – PJ	
Wood wastes	375	21%	7	0%
Plastic wastes	61	3%	51	4%
Paper and cardboard wastes	6	0%	3	0%
Textile wastes	2	0%	3	0%
Wastes Tyres	35	2%	2	0%
Spent solvents	29	2%	0	0%
Waste oils	32	2%	0	0%
Chemical wastes	93	5%	31	2%
Household and similar wastes	470	26%	616	44%
Mixed and undifferentiated materials	149	8%	120	9%
Sorting residues	334	18%	489	35%
Animal and vegetal wastes[1]	70	4%	80	6%
Dried municipal sewage sludge[1]	22	1%	7	0%
Waste-derived biogas[2]	108	6%	0	0%
Waste-derived biodiesel[2]	19	1%	0	0%
Total	**1,805**	**100%**	**1,409**	**100%**

1- For "Animal and vegetal wastes" and "Municipal sewage sludge", energy recovered from anaerobic digestion is taken into account within "waste-derived biogas".
2- Biogas and biodiesel are used only for energy purposes, so data for "Incineration (D10+R1) – PJ" is the same as the amount of waste-derived biofuel produced.

According to Table 1.46, the 6 following combustible wastes appear to contain the lion's share of energy. Of the 15 combustible wastes studied, they jointly contain 83% of the energy embedded in the wastes sent to incineration, and 94% of the energy embedded in the wastes sent to landfill:

- Animal and vegetal wastes;
- Household and similar wastes;
- Mixed and undifferentiated materials;
- Sorting residues;
- Wood wastes;
- Waste-derived biogas.

Of those six waste types, a mere two, household and similar waste and sorting residues, jointly account for nearly four fifths of the energy contained in all landfilled waste. Moreover, these same two waste types combined with wood waste comprise almost two thirds of the energy contained in all waste sent for incineration.

In accordance with the waste hierarchy, waste currently sent to landfill should be sent for energy recovery only when other recovery options are not possible. In other words, just because a combustible waste contains high amounts of embedded energy available for recovery, it does not meant that the WtE pathway should be the first choice.

In addition, Figure 1.40 shows the evolution of the amount of wastes sent to incineration (with and without energy recovery) in the EU-28. Considering that, for a large number of the wastes studied, data on incineration is only available as of 2010, Figure 1.40 is limited to that year and 2012.

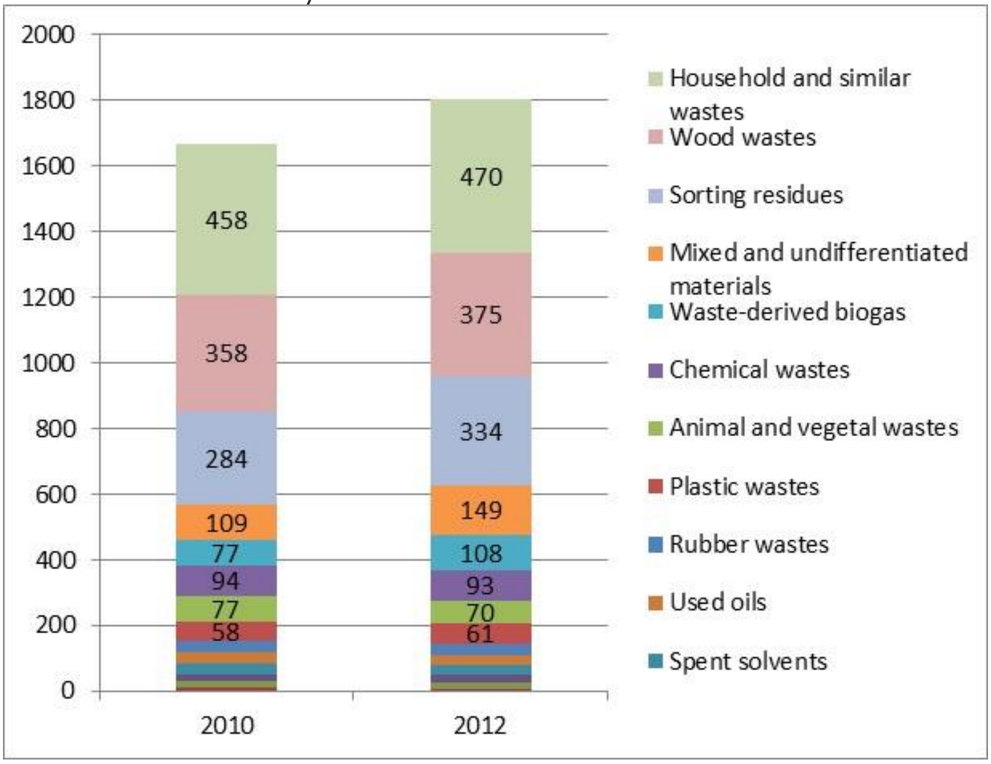


Figure 1.40: Evolution of the amount (in PJ) of wastes sent to incineration (with and without energy recovery) in the EU-28 (Source: Deloitte)

<u>Discussion on the waste hierarchy for composting and anaerobic digestion</u>
The evolution of waste-derived biogas production depends, among other things, on the choice between sending relevant biodegradable feedstock to composting or anaerobic digestion. The waste hierarchy does not say which of the two treatment methods should be prioritised.

In its report from 2011 "Supporting Environmentally Sound Decisions for Bio-Waste Management - A practical guide to Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA)", the JRC provides some information to help prioritise between the two treatment methods. The report provides a decision tree to help the user make the right decision, which depends on the characteristics of the feedstock (water content, methanogenic potential, etc.), on the technology available and its efficiency. However, as the main guidance, the report states that "*As Anaerobic Digestion (AD) (including composting of digestate) allows combining both benefits, it is likely to be the preferable environmental option in many instances*."

3.7 Main pathways for waste-to-energy

3.7.1 Identification of the main pathways for waste-to-energy

The identification of the main pathways for the recovery of energy from waste constitutes the prelude to Task 2 "Analysis of the technical improvement potential for waste-to-energy". Therefore, the list of pathways should include installations that recover most of the energy from waste in Europe, and for each pathway it should be possible to compare techniques and identify technical improvement potential for waste-to-energy.

Based on the current situation, five main pathways were identified:

- **Group 1 - Combustion plants**: Combustion plants which utilise waste as a secondary energy source in combination with other types of fuels (these installations include all kinds of conventional power plants used for the generation of mechanical and/or electrical power generation and heat, as well as recovery boilers). CL plants are excluded.
- **Group 2 – Waste incineration plants**[48]: Waste incineration plants dedicated to the thermal treatment of waste, with recovery of the combustion heat generated, through the direct incineration by oxidation of waste.
- **Group 3 - CL plants**: Cement and lime production plants.[49]
- **Group 4 - AD plants**: Anaerobic digestion plants.
- **Group 5 - Other WtE plants**: Other waste-to-energy plants (including pyrolysis, gasification, plasma treatment and hazardous waste incinerators).

In the report the five main pathways will be referred to as:

- Group 1 - Combustion plants;
- Group 2 – Waste incineration (WI) plants;
- Group 3 - CL plants;
- Group 4 - AD plants;
- Group 5 - Other WtE plants.

Hazardous waste incinerators are studied separately from waste incineration plants because it was considered that their techniques should not be compared when trying to identify technical improvement potential for waste-to-energy.

3.7.2 Waste-derived energy recovery for each main pathway

Overview of waste-to-energy plants in the EU-28

The European Commission published in March 2016 the "WID implementation final report" (EC, 2016). This report provides information (see table below) on the number of incineration and co-incineration plants in Europe and by Member State (excluding Croatia), according to the definition of Art. (3) of the WID (2000/76/EC). Data comes from the reports submitted by Member States for the third and last reporting period under the WID which covered the period 2012-2013.

[48] Certain stakeholders may use the wider term waste-to-energy plant when actually referring to waste incineration plants only. It should be noted, however, that in the context of this study the term WtE has been maintained to refer to all processes that recover energy from waste and not only to dedicated waste incineration plants.

[49] The current report focuses on cement plants. We are awaiting data from Eula (the European Lime Association) on lime production plants. This will be updated in the final report.

	WI plants[1]	Co-incineration[1]				AD plants
		Cement kilns	Combustion plant	Other industrial facilities[2]	Total	
Total number of plants	939	176	305	207	688	15,725
Plants recovering heat	562	Not available			469	15,725

(1) Definition according to Art. (3) of the WID (2000/76/EC) including also thermal treatment processes such as pyrolysis, gasification or plasma processes.
(2) 95 facilities not covered by Annex II.1 or II.2 to the WID (2000/76/EC) and 112 uncategorised.

Energy from waste recovered as heat/electricity in the EU-28

Miscellaneous sources provide information on the amount of heat and electricity recovered from combustible waste in Europe:

- Energy recovered from waste as electricity: CEWEP, the Confederation of European Waste-to-Energy Plants, estimates that, in 2013 in the EU-28, 110 PJ of electricity was recovered from the incineration of 76.5 million tonnes of MSW and similar waste in 411 WI plants. The same year, Eurelectric, the association of the electricity industry in Europe, estimated that 86 PJ[50] of electricity was recovered from renewable waste in the EU-28. It represented 4% of total renewable electricity production.
- Energy recovered from waste as heat: In 2012-2013, 79% of total incineration and co-incineration plants reported recovering heat in Europe (EC, 2016). 54% of the plants that did not recover energy as heat were located in two Member States: France (34%) and Germany (20%). Over the same period, CEWEP estimated that 275 PJ of waste-derived heat were recovered from 411 WI plants. For cement kilns, waste-derived thermal energy conversion was estimated at 176 PJ in 2013 (see Table below).

Table 1.47 presents the estimation of waste-to-energy recovery in the EU-28 by pathway.

Table 1.47: Estimation of the waste-derived energy recovery in the EU-28 for the five pathways studied

	Combustion plants	WI plants[1]		CL plants[2]	AD plants[3]			Other WtE plants[4]
		Heat recovery (PJ)	Electricity recovery (PJ)	Thermal energy conversion (PJ)	Heat recovery (PJ)[5]	Electricity recovery (PJ)	Biomethane production (PJ)	
2006	n.a.	180	81	127	n.a. (not available)			n.a.
2007		165	89	141				
2008		183	92	149				
2009		177	97	154				
2010		199	105	165				
2011		228	106	184				
2012		265	106	177				
2013		275	110	176				
2014		n.a.	n.a.	n.a.	33	70	12	

[50] 24 TWh. Source: Eurelectric 2015, "A sector in transformation: Electricity industry trends and figures".

1- Source: CEWEP.
2- No information for Lime production plants. Information for cement kilns from CEMBUREAU.
3- Source: Deloitte calculation based on Eurostat Energy Statistics and EBA data.
4- Information only for hazardous waste plants from Hazardous Waste Europe.
5- Heat recovery after exclusion of internal use.

Table 1.47 shows that, in the period 2006-2013, the amount of energy recovered from waste increased by 39% for cement kilns, by 36% for electricity from WI plants, and by 53% for heat from WI plants. The latter can be explained by the significant increase in the number of WI plants relying on CHP.

According to Eurostat data, the final energy consumption in the EU-28 in 2013 and 2014 amounted to 46,331 PJ and 44,451 PJ, respectively. Therefore the 2013-2014 energy output from WI plants, CL plants and AD plants covered about 1.49% of the final energy used on average in the EU-28 in the same time period.

Estimation of waste consumption for energy recovery

The amount of wastes consumed by cement kilns and waste-to-energy plants has been analysed in order to assess whether the figures are representative compared to the total waste-derived energy recovered in the EU-28.

Table 1.48: Amount of waste consumed by waste-to-energy plants and cement kilns in the EU-28 in 2013

	Amount of wastes treated in 2013 – thousand tonnes	Source
WI plants	76,500	CEWEP
Cement kilns	8,000	CEMBUREAU
Total	84,500	

Looking at both Table 1.1 and Table 1.48, it appears that waste incineration plants and cement kilns account for only 63% of the 138 million tonnes of wastes sent for incineration in the EU-28[51]. There are several explanations for this difference of 51 million tonnes of wastes:

- A number of plants recovering energy from wastes are not accounted for in Table 1.47, especially combustion plants and to a lesser extent other WtE plants such as hazardous waste incineration plants. Although it was not possible to estimate the amount of wastes used by combustion plants, it might represent a significant amount of the 26 million tonnes of wood wastes reported by Eurostat. A more in-depth analysis based on data from all industries using process residues in co-incineration should provide a better understanding of this aspect. Also, according to Hazardous Waste Europe, only 5 million tonnes of hazardous wastes were sent for incineration, instead of the 10.5 million tonnes according to the Eurostat Waste Statistics database, in 2012.
- As explained in previous paragraphs, the definition of “waste” and “by-products” is open to interpretation. It is, however, impossible to estimate how much of the difference could be explained by this.
- Based on the Eurostat Waste Statistics database, 36.5 million tonnes of wastes were sent for incineration/disposal (D10) in 2012. It was not possible to estimate the share which goes to incineration plants without any kind of energy recovery and the share that goes to incineration plants with an energy efficiency below the R1 threshold and which are therefore not considered as recovering energy.

[51] Waste-derived biogas is not taken into account in the 138 million tonnes.

- Finally, a number of experts that were interviewed considered that the Eurostat Waste Statistics data represent a high-range estimate.

4 Task 2 - Analysis of the technical improvement potential for waste-to-energy

The objective of Task 2 is to provide an analysis of the technical improvement potential for waste-to-energy with respect to energy recovery.

4.1 Identification of techniques

Task 2 commences with the identification of WtE techniques. The three-step data collection strategy used for this task is illustrated in the figure below.

In Task 1, the main waste treatment pathways were defined and arranged into five groups as follows:

Group	WtE pathway
Group 1	Combustion plants: Combustion plants which utilise waste as a secondary energy source in combination with other types of fuels (these installations include all kinds of conventional power plants used for the generation of mechanical and/or electrical power generation and heat, as well as recovery boilers)
Group 2	WI plants: Waste incineration plants dedicated to the thermal treatment of waste, with recovery of the combustion heat, through the direct incineration by oxidation of waste
Group 3	CL plants: Cement and lime production plants
Group 4	AD plants: Anaerobic digestion plants
Group 5	Other WtE plants: Other waste-to-energy plants (including pyrolysis, gasification, plasma treatment and hazardous waste incineration)

Within each group, the techniques are split into two subgroups: the first subgroup lists techniques which are considered to be proven techniques that could be implemented immediately in any Member State to improve the deployment of WtE with respect to energy recovery. They will have a Technology Readiness Level (TRL) of at least 9 (for further discussion of TRL, please refer to Section 4.2.2 below).

The second subgroup lists emerging WtE techniques which are considered 'Technologies to watch'. These technologies all have a TRL level of 8 or less. This TRL level indicates that they are currently not commercially mature but may offer potential in the future. An evaluation of all techniques was performed according to the methodology described below in Section 4.2.

4.1.1 Summary of WtE pathways

A high-level summary of the advantages and disadvantages of each of the five WtE pathways is provided below.

	Advantages	Disadvantages
Combustion plants co-incinerating waste	• Existing combustion plants may be able to be modified, avoiding extensive new build • The efficiency of electrical energy recovery can be high due to high boiler operating temperatures and pressures	• Requires the whole combustion plant to be permitted by the relevant national environmental agency and to be compliant with the IED • The percentage of waste by weight that can be co-incinerated with most non-waste feedstock is small in many cases (often around 5%)
Waste incineration plants	• Proven and bankable technology which tolerates a wide range of wastes • Ideal for district heat and cooling connections to increase overall plant energy efficiency	• Electrical energy recovery efficiency in a steam boiler is limited due to the corrosive nature of waste feedstock • The siting of waste incinerators can be controversial due to public perception
Cement and lime (CL) plants	• Some of the waste material content is recycled into the cement clinker • The thermal conversion process will always recover a high proportion of the waste input energy content regardless of plant location	• CL plants require a highly processed waste-derived fuel (SRF) with exacting quality standards which requires energy to produce • The demand for cement is variable meaning that CL plants demand less waste feedstock during periods of low economic activity • CL plants can have higher emissions compared to WI plants
Anaerobic digestion (AD) plants	• AD plants are relatively uncontroversial due to low or negligible emissions • AD plants produce a digestate by-product which can be spread on land under most circumstances	• Energy recovery through a gas engine gives low overall electrical efficiency • Collecting large quantities of suitable uncontaminated organic feedstock can be challenging
Other waste-to-energy plants	• Some forms of other WtE plants can recover energy in the form of fuels or	• Some of the technologies are not proven and have struggled to make the

	products (such as polymers) rather than just heat and power • Although not an advantage of the technology itself, due to the innovative nature of some other WtE processes, financial support through grants or incentives may be available in some Member States	transition from demonstration scale to commercial reality • Some waste streams suitable for other WtE processes are limited in size and availability

The energy efficiency of each pathway is also summarised below for both current average (Av) and optimised (Opt) net annual average energy efficiency. Average net annual average energy efficiency represents the current situation, optimised net annual average energy efficiency represents the efficiency WtE could reasonably achieve if improvement techniques are implemented. The methodology which has been used to calculate these efficiencies is explained in full within Section 4.2.

	Energy recovered as electricity, efficiency [1]		Energy recovered as heat, efficiency [2]		CHP recovery efficiency [3]				Energy recovery to fuel, efficiency	
	Av %	Opt %	Av %	Opt %	Av %		Opt %		Av %	Opt %
					Electric	Heat	Electric	Heat		
Combustion plants [4]	36	40	-	-	-	-	-	-	-	-
WI plants	22 [5]	33 [6]	72 [7]	80 [8]	17 [9]	51 [9]	27 [10]	66 [10]	-	-
					Total 68		Total 93			
CL plants [11]	-	-	75	80	-	-	-	-	-	-
AD plants	18 [12]	23 [13]	-	-	18 [14]	18 [14]	-	-	-	41 [15]
					Total 36					
Others	20 [16]	35 [17]	75 [16]	80 [8]	-	-	-	-	-	40 [18]

Net annual average efficiency:

[1] 100% electrical load.
[2] 100% heat load.
[3] CHP - 80% of heat sold annually, 100% electrical load.

References:

[4] LCP BREF, coal / lignite pulverised combustion.
[5] ISWA CE report 2015, gross existing plant efficiency corrected to net efficiency.
[6] AEB Amsterdam / Martin GmBH statistics, refer also *High Steam Parameters for Boilers and Superheaters* proven technique.
[7] CEWEP.
[8] Ricardo estimate based on known boiler efficiencies.
[9] Annual average efficiency based ISWA CE report 2015 existing CHP plant gross efficiencies, corrected to net efficiency with annual average heat load.

[10] Annual average efficiency based on optimised AEB / Martin GmBH net electrical efficiency and ISWA CE report 2015 high efficiency CHP plant gross efficiencies, corrected to net efficiency with annual average heat load.
[11] CEMBUREAU.
[12] ISWA CE report 2015, AD plant net efficiency.
[13] UK Department of Energy and Climate Change, Advanced AD net efficiency.
[14] ISWA CE report 2015, net efficiency with annual average heat load.
[15] ISWA CE report 2015, net efficiency of biomethane production at 100% annual load.
[16] Typical net power / heat only efficiency of a gasification system as an emerging technique.
[17] High efficiency claimed by optimised emerging techniques such as *Two Stage Combustion with Plasma* with energy recovery through an internal combustion engine.
[18] Typical net efficiency of an emerging technique producing a fuel product.
-: no data available or not applicable

4.2 Technique evaluation methodology

The approach used for evaluating the improvement techniques is described in the following sections.

4.2.1 Evaluation definitions

Table 2.49 below describes the two key criteria assessed for each technique and a descriptor of how a 'Red, Amber, Green' rating was applied to each of the two criteria.

Table 2.49: Evaluation and rating definitions (see Section 4.2.1.1 for a detailed explanation of +, ++ and +++ notes)

Criteria		Rating		
		(Red)	(Amber)	(Green)
1. Net **annual average** energy efficiency		Reduced efficiency:	No change in efficiency:[+]	Increased efficiency:
		Net electrical efficiency[52] less than 22%	Net electrical efficiency between 22% and 29%	Net electrical efficiency above 29%
		Net heat-only energy efficiency[++] below 70%	Net heat-only energy efficiency[++] approx. 75%	Net heat-only energy efficiency[++] above 80%
		Net CHP energy efficiency[+++] below 68%	Net CHP energy efficiency[+++] approx. 71%	Net CHP energy efficiency[+++] above 76%
		Net gas network / liquefaction energy efficiency below 35%	Net gas network / liquefaction energy efficiency between 35% and 40%	Net gas network / liquefaction energy efficiency above 40%[53]
2. Applicability		(Red)	(Amber)	(Green)
	Location	High dependence on location	Some restrictions on location which may restrict deployment	Independent of location
	Waste stream	Only applicable to waste streams with low total energy content	Applicable to waste streams with medium total energy content	Applicable to waste streams with high total energy content
	Retrofit potential	New installations only	Can be retrofitted in some instances	Can be retrofitted in the majority of installations

[52] ISWA CE Report 5 Table 5 – Based on gross efficiencies corrected to net efficiencies. It is assumed that in electricity only mode, electrical parasitic load is 10% of power recovered. Available at: http://www.iswa.org/fileadmin/galleries/Task_Forces/Task_Force_Report_5.pdf.
[53] ISWA CE Report 5, Table 2 – Methane output represents increased efficiency.

4.2.1.1 Net annual average energy efficiency

It is important to note a WtE plant producing power only, or one producing heat only, or a CHP plant cannot be compared in terms of energy efficiency.

$^{+}$ The middle column ('No change in efficiency') represents the baseline or, in other words, the average value in the range that we encounter in practice today. 'Reduced efficiency' applies to techniques which are below the expected level of energy efficiency (there are limited numbers of these techniques) and, at the other end of the spectrum, 'Increased efficiency' represents techniques which deliver above average performance.

$^{++}$ In the calculation of annual average heat-only energy efficiency, it is assumed that this category applies to cement/lime kilns, waste heat boilers combusting hazardous/non-hazardous waste and industrial boilers where the heat-producing plant only runs when it is required and therefore **all the heat recovered is sold.** It should also be noted that cement/lime kilns included in this category directly consume the heat recovered in their material production process (rather than recovering heat via a steam boiler). Pretreatment is required to produce the SRF and the process produces a material product as a result of combustion[54]. An estimation of the energy consumption required to pretreat waste is provided below in Section 4.2.1.3.

$^{+++}$ In the calculation of net annual average CHP energy efficiency, it is assumed that **80% of the heat recovered per annum can be sold** for heating or cooling purposes[55]. This is calculated as shown in Annex 4[56]. It should be noted that electrical output is reduced when a thermal plant is run in CHP mode (80% of the time) and that the electrical output will improve again during periods when heat is not supplied (the remaining 20% of the time). This is reflected in the calculation.

4.2.1.2 Applicability

A key aim of this study is to understand how the technical potential of waste-to-energy can be further exploited. In order to do this, an evaluation of the applicability of different techniques has been carried out. The applicability of each technique has been considered as the combination of three subcriteria:

- location dependence;
- waste streams; and
- opportunity for retrofitting to existing installations.

Location

In general, the main restriction on the location of techniques is the viability of district heating/cooling. Other factors relating to location are considered the same across Member States. Therefore, the location criterion has been evaluated in a qualitative way. Some examples of location dependence are shown below:

[54] CEMBUREAU interviews, January - April 2016.
[55] ESWET estimate, May 2016.
[56] ISWA CE Report 5 Table 5 - Based on ISWA gross efficiencies corrected to net efficiencies. It is assumed that, in electricity-only mode, the electrical parasitic load is 10% of the power recovered. In CHP mode, the electrical parasitic load is 20% of the power recovered. The parasitic heat load is around 1% in both cases.

High dependence on location	Some restrictions on location which may restrict deployment	Independent of location
Techniques delivering heating will be highly dependent on location. For example, northern Europe has a longer heating season, whereas there may be little or no demand for district heating in southern Europe	There may be some restrictions on techniques delivering cooling, for example a shorter cooling season in northern Europe, or they may be dependent on proximity to another user of a cooling network, i.e. data centre	Techniques delivering power only will be applicable to a wide range of location types

Waste stream applicability

This has been assessed using a quantitative method, based on the amount of energy (in PJ) currently being recovered from each waste stream; this assessment takes account of both the quantity and calorific value of the waste stream. For example, for the wastes that already contribute higher amounts of energy, there is more potential to increase the efficiency of the energy recovery from these waste streams. For waste streams with smaller volumes, or those that contain less energy, there is less potential. Each technique was assessed as to which of the 18 wastes the technique was applicable to, and therefore also the percentage of potential energy in PJ that was applicable.

The scoring assigned is set out below:

Applicable to <33% of total potential energy	Applicable to 34-66% of total potential energy	Applicable to 67% of total potential energy

Opportunity for retrofitting to existing installations

To enable the WtE landscape to be changed in the short to medium term, it is important to identify techniques which can be more easily retrofitted to existing WtE installations. Scoring was assigned as follows:

New installations only	Can be retrofitted in some instances	Can be retrofitted in the majority of installations

Combining the applicability subcriteria

As there are three subcriteria which are used to evaluate the overall applicability of each technique, to get an overall score, the RAG scores (R=1, A=2, G=3) for location, waste streams and retrofitting are multiplied together. The rounded cube root of each score is then calculated to determine the overall score of Red, Amber, or Green. This process is in line with the guidance set out by the JRC for aggregating non-numerical indicators[57].

This will result in the lowest score being 1 (i.e. Red in each applicability subcriterion) and the maximum being 27 (i.e. Green in each applicability subcriterion).

Multiplied scores of 1,2 or 3 = rounded root value of 1	Multiplied scores of 4,6,8,9 or 12 = rounded root value of 2	Multiplied scores of 18 or 27 = a rounded root value of 3

[57] Available at: https://ec.europa.eu/jrc/en/coin/10-step-guide/step-7.

Two red subscores automatically lead to a red overall score, whereas at least two subscores of green and one amber are needed for an overall green score.

The overall applicability score will still be a qualitative indicator, rather than a quantitative indicator, but gives a good idea of how much of the actual market can be affected by the energy efficiency gain delivered by a given technique. The most relevant techniques today will be those that can be implemented in existing installations, without geographical limitations and for an important fraction of waste materials. The subscoring for applicability (Location / Waste streams / Retrofittability) is provided in detail within Annex 5 for each technique.

4.2.1.3 Energy input required for the production of Solid Recovered Fuel (SRF)

In order to be able to compare different WtE techniques objectively, it is necessary to take into account the energy input required to pretreat the waste, where pretreatment is necessary. There are different levels of pretreatment, ranging from simple metals removal and shredding (which has a very small effect on process electrical efficiency) to the production of SRF which requires significantly more effort and should be taken into account. Processes which require SRF include cement and lime kilns, many forms of co-incineration in large combustion plants and some advanced conversion technologies.

SRF is a high-quality recovered fuel with a CV of around 20.2MJ/kg[58] (which equals 5,611kWh of energy per tonne) when derived from MSW; this is due to the significant contribution of paper, cardboard and plastics. Nasrullah also calculated that, to produce 1 tonne of SRF from MSW, the ‘in plant’ energy input was 97kWh (where ‘in plant’ energy is the energy required for the sorting process). Therefore the percentage of the total energy input taken up by the pretreatment (in plant) process is calculated as 1.7%.

The ‘out plant’ energy is more significant than the ‘in plant’ energy input and refers to waste collection and transportation etc. but, as this applies equally to any waste treatment process, this element is not considered.

Another aspect which impacts total energy recovery is the energy content of material lost during the SRF sorting process, i.e. material which is not suitable for inclusion within the tight specification of an SRF product (which, for example, requires halogens such as chlorine to be strictly limited to ensure the IED compliance of the CL plant). Nasrullah estimates that this equates to 15% of the energy content of the waste, with 8% lost to rejects and 6% to the fine fraction. A high mass fraction of rubber material, plastic (PVC plastic) and inert elements (stone/rock and glass particles) was found in the reject material stream. Although the halogenated elements of this reject fraction are high in energy, the inert elements have no energy value and are generally best excluded from most WtE processes.

As such, the lost fraction (15% of the waste energy content) may be of more significance than the energy directly consumed in the SRF production process (1.7% of the waste energy content).

[58] Nasrullah, Material and energy balance of SRF production, 2015.

4.2.1.4 Other considerations

In addition to the two rated criteria, for each technique further comment is provided on:

- Exclusion criteria – the technique could be excluded for further consideration if it causes possible conflicts with the waste hierarchy, has a negative effect on emissions or for other specific reasons.
- Technology Readiness Level – each technique is rated for Technology Readiness Level as described in Section 4.2.2 below.

4.2.2 Approach and Technology Readiness Level

Where possible, each technique and system has been assigned a Technology Readiness Level (TRL) as shown below in Table 2.50. The TRL indicates how close the technique is to commercial deployment, and this has been recorded in the scoring notes for each technique. A technique with a high TRL should have low residual risks and good availability of operational data. Many highly innovative techniques have a low TRL and there is likely to be very little operational data available.

Table 2.50: Technology Readiness Level

Technology Readiness Level	Description
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or proof of concept
4	Basic validation of technology in laboratory environment
5	Basic validation technology in a laboratory environment, where basic technological components are integrated together with realistic supporting elements
6	Technology model or prototype demonstration verified in a relevant environment
7	Technology prototype demonstrated in an operational environment
8	Actual technology completed and qualified through testing and demonstration
9	Actual technology qualified through successful commercial operation
9 +	More than one commercial-scale plant and over five years' operational experience

4.3 Task 2 - Technique dashboard

This section of the report is not intended to be read from beginning to end, although it can be, but to present techniques in each of the five groups, outlined below.

1		Combustion plants co-incinerating waste
2		Waste incineration (WI) plants
3		Cement and lime (CL) plants
4		Anaerobic digestion (AD) plants
5		Other waste-to-energy plants

4.4 Combustion plants (other than CL plants) co-incinerating wastes

This section considers combustion plants (other than CL plants) co-incinerating wastes. In this group, waste is a secondary fuel and the primary fuel is a non-waste such as coal or biomass.

4.4.1 Overview of waste as a secondary fuel in large combustion plants

Besides incineration in specially designed and operated waste incineration plants, certain wastes such as contaminated biomass, sewage sludge and SRF may also be co-incinerated in regular combustion installations such as power plants. The waste fraction in co-incineration is termed the secondary fuel with the majority fossil (or biomass) fuel known as the primary fuel.

Combustion plant operators may find co-incineration of certain wastes attractive as it offers economic benefits where a gate fee may be charged and waste with a high biogenic content can help offset GHG emissions from fossil fuel combustion. A barrier to co-incineration of waste is the requirement for the plant to conform to all legislation concerning the incineration of waste, including IED compliance and environmental permitting; both of these carry risk and a high administrative burden which may not outweigh the achieved economic and carbon reduction benefits. Other technical issues for a large combustion plant (LCP) considering co-incineration of waste include (based on fuel quality and characteristics):

- boiler design;
- fuel handling and feeding;
- slagging, or bed sintering (fluidised bed boiler);
- fouling of heat transfer surfaces;
- hot corrosion;
- effects on emission levels compared to the emissions that occur when only a conventional primary fuel is used;
- ash properties, bottom ash removal;
- storage of waste fuel;
- utilisation and/or disposal options for solid waste/residues from co-incineration.

The main types of secondary fuel that have been used for co-incineration in large combustion plants are shown below; the most important ones on this list are sewage sludge, paper sludge and biomass/wood[59].

Type of secondary fuel	Examples of secondary fuel
Animal by-products	Animal meal, tallow, meat and bone meal Cattle manure and chicken litter
Chemicals	Organic acids and liquid solvents Phosphor oven gas
Pretreated	Waste paper

[59] LCP BREF.

municipal waste to produce a secondary fuel	Waste packing materials Waste plastics Mixed wastes
Oily materials	Tar Waste oil
Sludge	Sewage Paper sludge (such as de-inking, bio and primary sludge)
Tyres	Shredded tyres
Vegetables	Energy crops such as willow Agricultural residues such as straw, cereal plants, pasture from landscape cultivation
Wood	Wood residues, demolition wood, waste wood, forest residues, wood chips Biomass pellets/briquettes

The range of energy efficiency in existing combustion plants is shown below in Table 2.51[60] using data from the LCP BREF. It is assumed that co-incineration will be applied to existing plants, and it is noted that new combustion plants will be more energy-efficient.

Table 2.51: Net annual average energy efficiency of combustion plants

Plant fuel	Net annual average energy efficiency (%) Electricity only
Coal / lignite pulverised combustion +	36 – 40
Biomass fluidised bed combustion ++	28 - 30
Gas turbine	32 – 35
CCGT power only	50 - 54
CCGT with CHP	< 35

+ Pulverised combustion is the most likely form of lignite/coal-fired LCP for the addition of waste.
++ Fluidised bed combustion is the most likely form of biomass-fired LCP for the addition of waste.

The highest plant efficiencies are found in those plants which operate a combined cycle gas turbine (CCGT) and where a combustion plant also has the ability to operate in CHP mode. Biomass-fired plants have a markedly lower energy efficiency.

4.4.2 Combustion plants co-incinerating wastes - Proven improvement techniques

A list of proven improvement techniques for the co-incineration of wastes in combustion plants is provided below in Table 2.52.

[60] LCP Reference Document on Best Available Techniques - July 2006 pp. vii to viii.

Table 2.52: List of proven improvement techniques for co-incinerating wastes in combustion plants

#	Technique title
a	Mixing of waste with a primary fuel prior to incineration
b	High-efficiency circulating fluidised bed gasification and co-firing of syngas in the combustion plant
c	Special grate for co-incineration of waste
d	Feeding of secondary fuels into a fluidised bed combustion plant

Note on Methanisation: To avoid repetition, it should be noted that the production of biomethane through anaerobic digestion and injection to the gas grid for use in a natural-gas-fired combustion plant is described under Group 4.

A full description of each technique and the evaluation is provided below.

4.4.3 Large combustion plant techniques evaluation

Technique title:	**Mixing of waste with a primary fuel prior to combustion**	
Description	The easiest way to introduce a secondary (waste) fuel into a combustion process is by mixing it with the primary fuel[61]. In a coal- or lignite-fired boiler, fuel can be mixed in the following locations: 1. on the coal conveyor belt; 2. in the coal bunker; 3. in the coal feeder; 4. at the coal mill; 5. on the pulverised coal lines. In the first three situations, the secondary fuel is spread over the primary fuel (coal). In this way an adequate mixing of the fuel streams occurs. This results in a grinding of the secondary fuels together with the primary fuel in the coal mill to create a pulverised dust. It is only possible to apply this technique when the grinding behaviour of both fuels is more or less the same or when the amount of secondary fuels is very small compared with the main fuel flow. Secondary fuels that are pulverised separately from the main fuel can be injected into the coal mill or into the pulverised coal pipelines between the coal mill and the boiler (situations 4 and 5). Other secondary fuels, such as biomass, can also be injected into the coal mill together with the coal, although they cannot be pulverised. To allow for a complete combustion of the comparably large biomass particles, a grate at the bottom of the boiler can be used (see below). Wastes which are most suitable for mixing prior to combustion include sewage sludge, paper sludge and animal meal and manure. These wastes can be most readily used in coal-fired combustion plants where there is excess drying capacity in the installed coal mill drying plant (note that the drying requirements of sewage sludge are large compared to coal, when compared on a fresh weight basis). Otherwise new or off-site drying facilities will be required.	
Criteria	Rating	Notes
Net annual average energy efficiency		A substantial amount of heat energy is required to dry sewage sludge / manure down to a suitable moisture content (<10%) prior to co-incineration. For small quantities of sewage sludge, it can be assumed that the heat energy for drying is spare heat which would otherwise be wasted. Once dry, the overall net electrical efficiency obtained in a coal-fired combustion plant with small amounts of waste (<5%) will be between 36% and 40%. Where pretreatment of mixed waste is required to produce SRF, this will require an additional energy input of approximately

[61] LCP Reference Document on Best Available Techniques - July 2006.

Technique title:		**Mixing of waste with a primary fuel prior to combustion**
		1.7% of the waste input energy.
Applicability		The technique is limited to coal- or lignite-fired LCPs, which are being phased out. The amount of sewage sludge secondary fuel that can be added is currently limited to a maximum of 5% by weight. Many combustion plant operators will not want the extra burden of IED compliance.
Exclusion criteria	No	Some concern has been noted in the LCP BREF on mercury emissions but this can be controlled through suitable abatement measures. Spreading of sewage sludge / manure in the coal yard or bunker is excluded due to the fire risk from methanation and odour issues.
TRL	9+	There are numerous examples of co-incineration of waste in combustion plants over the past 20 years, particularly in Germany.

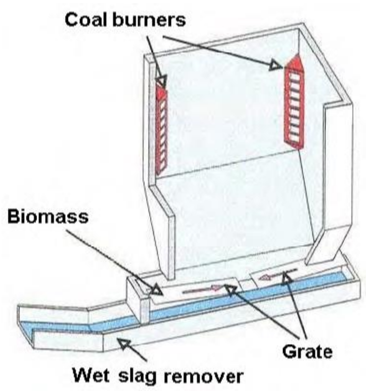
Technique title:	**High-efficiency circulating fluidised bed gasification and co-firing of syngas in the combustion plant**
Description	An alternative approach to building stand-alone plants to generate electricity is to install gasification plants at existing fossil fuel power plants[62]. The syngas generated can then be burnt in the existing boiler, displacing fossil fuels. There are several examples of this operating worldwide, for example the Kymijärvi I plant built in Lahti, Finland, in 1998 where refuse-derived fuel and biomass are gasified and the resulting syngas burnt in the existing coal-fired plant to produce power and heat for the city of Lahti. This plant has operated since 1998, with a 60 MWth fluidised bed generating syngas, which, with limited clean-up, successfully displaced fossil coal in the existing boiler. At the Vaskiluoto coal-fired power station in Vaasa, Finland. Biomass is gasified with the resulting syngas blown into the existing coal-fired boiler to directly displace up to 40% of coal. As the syngas secondary fuel has very different physical properties to pulverised coal, the syngas is burnt using specially developed gas burners. There are other examples in the Netherlands and North America. The direct displacement of coal by syngas generated from waste in existing power stations can be an attractive environmental and economic option. Whilst there are a great number of fossil fuel power stations, age, environmental and regulatory issues or economics mean that the number of potential plants which could be converted to use syngas is much more limited. Pretreatment is required to prepare the fuel for gasification. The resulting gas is cleaned of corrosive components and therefore it

[62] Fichtner Consulting Engineers – Valmet Gasification Of Waste Technology Review – November 2015.

Technique title:	**High-efficiency circulating fluidised bed gasification and co-firing of syngas in the combustion plant**	
	is possible to achieve efficient energy recovery as electricity by using high steam temperature and pressure. Typically for a coal-fired combustion plant, this will be between 36 and 40%.	
Criteria	Rating	Notes
Net annual average energy efficiency		The net annual electrical efficiency obtained in a co-fired coal combustion plant will be between 36% and 40%. As the gasifier is no more than a thermo-mechanical mill for fuel preparation, it is assumed that the energy required to gasify the waste is broadly similar to the energy input to prepare coal for combustion. Where pretreatment of mixed waste is required to produce SRF, this will require an additional energy input of approximately 1.7% of the waste input energy.
Applicability		In many countries, coal-fired power stations are not yet fitted with low-emission technology. As firing of waste in a coal-fired power station means the plant is regulated as a co-incinerator under the original Waste Incineration Directive, and now the Industrial Emissions Directive, this has limited the displacement of fossil fuels by these means.
Exclusion criteria	No	None noted.
TRL	9+	There are two technique examples in Finland, one in the Netherlands and several in North America.

Technique title:	**Special grate for co-incineration of waste**
Description	For waste which cannot be pulverised or injected as a liquid/gas, a different approach is required to co-incinerate these larger particles of waste in a coal-fired combustion plant. Typical wastes which fall into this category are waste wood or SRF derived from household and similar wastes. Special moving grates at the bottom of the boiler hopper used for the introduction of secondary fuel lengthen the residence time of those materials in the furnace. Household and similar wastes will need preparation to form an SRF product. As shown below, the waste wood / SRF is fed into the boiler via the small front sides of the grate, which transport the fuel during combustion to the centre of the coal-fired boiler[63]. Ash from the waste and bottom ash from the coal combustion, with less than 5 % unburnt carbon, falls into the slag remover below the grates. Resulting flue-gases from the grate rise directly into the furnace without any heat

[63] LCP BREF 2006/2007.

Technique title:	**Special grate for co-incineration of waste**	
	losses. Energy will be recovered through the existing energy recovery plant; typically net annual electrical efficiency is between 36% and 40% for a coal-fired combustion plant.  Image courtesy of LCP BREF	
Criteria	Rating	Notes
Net annual average energy efficiency		In a coal-fired combustion plant, a net annual electrical efficiency between 36% and 40% can be expected where low rates of substitution are adhered to. Where pretreatment of mixed waste is required to produce SRF, this will require an additional energy input of approximately 1.7% of the waste input energy.
Applicability		Substitution rates of waste as a secondary fuel will generally be limited to <5% to avoid significant impacts on LCP performance. Many LCP operators will not want the extra burden of IED compliance. The installation of such a grate requires a lot of free space below the boiler, which is rarely available.
Exclusion criteria	Possible	SRF as a secondary fuel in coal-fired combustion plants has experienced boiler issues such as difficulty in achieving the flue-gas residence time required under the WID (at least 2 seconds), corrosion and fouling[64].
TRL	9+	There are numerous examples of co-incineration of waste in combustion plants over the past 20 years, particularly in Germany.

[64] MVW Lechtenberg & Partner, EfW London Conference, 2015.

Technique title:	**Feeding of secondary fuels into a fluidised bed combustion plant**	
Description	This technique generally refers to the partial substitution of SRF with biomass in biomass-fired fluidised bed combustion plants. Other combinations of primary and secondary fuel combustion in a fluidised bed combustion plant (such as coal and sewage sludge) are also possible. There are a number of operational biomass co-incineration plants which are in some cases able to successfully increase the ratio of SRF co-incineration to over 50%[65] (whereas waste substitution ratios in coal-fired plants are much more restricted). For co-incineration in a fluidised bed boiler, appropriate feeding of the main and secondary fuels is one of the most essential factors for good operation. One of the benefits of SRF co-incineration is that some biomass fuel sources are of a relatively low quality with a high moisture content of up to 60%. This can result in a low net calorific value (NCV) fuel, typically between 5 and 15 MJ/kg. SRF is a fast-burning material and has a high NCV of typically between 15 and 25 MJ/kg and an oxygen content close to zero. CO_2 emission factors are ~25% lower than that of coal. Thus, SRF can operate as a support fuel to biomass, assisting in ignition and supporting a more stable combustion and better burning of low-grade biomass[66]. Initial pilot tests in Finland[67] in 2008 revealed that the co-firing of biomass and SRF is not without problems. Biomass contains high quantities of alkali metals (such as sodium and potassium) which react during combustion with chlorine (which is present in SRF plastics) to form alkali chlorides with low melting points. The existence of alkali components in fuel ash has an important role in deposit formation which can create technical problems such as boiler incrustation and fouling/slagging in the furnace/boiler.	
Criteria	Rating	Notes
Net annual average energy efficiency		In a modern biomass fluidised bed combustion plant, the net annual average electrical efficiency will be around 28% to 30%. In older plant designs, the net electrical efficiency will be nearer to 20%. Where pretreatment of mixed waste is required to produce SRF, this will require an additional energy input of approximately 1.7% of the waste input energy.
Applicability		Substitution rates of SRF as a secondary fuel are relatively high in this technique in comparison to others, making it much more applicable. However, many operators will still not want the extra burden of IED compliance and will be wary of corrosion issues.

[65] FEAD comments to the WtE background document, April 2016.
[66] ERFO, February 2016.
[67] Plastics Europe 2008 available at: http://www.localnet.abertay.ac.uk/media/Co-combustion%20of%20Solid%20Recovered%20Fuel%20and%20Solid%20Biofuels.pdf.

Technique title:		**Feeding of secondary fuels into a fluidised bed combustion plant**
Exclusion criteria	No	None.
TRL	9+	There are over 10 biomass and SRF co-incineration plants located in Finland alone.

4.5 Waste incineration plants

This section considers waste incineration plants dedicated to the thermal treatment of waste, with recovery of the combustion heat, through the direct incineration by oxidation of waste

4.5.1 Overview of waste incineration

Prior to considering techniques to improve energy efficiency in waste incineration, an overview of the currently deployed waste incineration technology is provided below.

Moving grate

Residual waste is taken from a storage bunker by a crane and dropped into a chute. Waste at the bottom of the chute is mechanically pushed onto the combustion grate; the pusher rate is carefully controlled to ensure an even feed of waste. The waste on the grate is combusted at a temperature of 1,000°C or more, with combustion air injected from below the grate.

The waste is moved forward on the grate and the resultant incinerator bottom ash (IBA) drops into a water bath at the end of the grate. Complete gas phase combustion is reached by injection of secondary air above the grate. The system ensures that a temperature of at least 850°C is reached for a minimum of 2 seconds (IED requirement) in the secondary combustion zone. Auxiliary fuel is only used for start-up and shutdown to achieve proper temperature conditions for the waste feed.

The roller grate is a variation of the pushing-type grate; instead of moving the waste forward, the roller grate passes waste over a series of inclined rotating rollers. This form of combustion grate is much less common than the moving grate.

A rotary kiln may also be used to combust MSW. In the rotary kiln, the waste is mechanically pushed into the top of a tapering cylinder or kiln. In order to pass the waste through the kiln and control the rate of combustion, the kiln oscillates from side to side, passing the waste between paddles set into the internal walls of the kiln. In other respects, the rotating kiln is a conventional combustion process. There are more applications of the rotary kiln in the treatment of hazardous waste (due to the ability of the kiln to operate at elevated temperatures) than for MSW, but both are established.

Fluidised bed combustion

Fluidised bed reactors are suitable for more homogeneous feedstocks such as chipped wood waste or residual waste resulting from a process of metal removal and shredding for size reduction. The prepared feedstock is transferred to the reactor chamber. The reactor chamber contains very hot sand, which is fluidised by an air stream from the wind box below. The IED requirement of a minimum of 2 seconds at 850°C is achieved in the secondary combustion zone. Energy is transferred to a boiler system similar to a pushing-type grate-fired facility. However, both the availability and energy efficiency of fluidised bed plants utilising treated MSW/C&IW have proven to be as good as or better than in pushing-type grate plants.

Energy recovery boiler

Typically, hot gases from the combustion chamber pass to a boiler, which converts the energy from the gases into superheated steam which powers steam turbine generators that make electrical energy. Such a process generates heat as a by-product which can also be recovered in a combined heat and power system. The most efficient designs incorporate an integrated furnace boiler, rather than the transport of hot gases via ducting to a separate boiler.

Typical steam data are 400°C and 45 bar. The boiler system typically has an energy efficiency of around 85% for steam production.

Boiler feed water should be preheated in an economiser, which recovers the maximum heat from the flue-gases leaving the boiler.

All boilers in WI plants have radiation passes (empty waterwalls for heat transfer) and convective passes (bundles in the gas stream). The final superheater is, in most cases, located in the convective section.

Steam turbine and generator set

High-pressure steam generated by the boiler is fed to the steam turbine. Steam enters the turbine and expands through the turbine blade system, converting energy (enthalpy) in the steam to mechanical motion. A typical net electrical efficiency of 25% (of the waste input energy) is achieved at the standard steam conditions of 400°C and 45 bar.

To maximise the electrical energy recovery, a condensing turbine is specified, where the expansion of the steam across the turbine is maximised and, at the exhaust of the turbine, steam will generally be below atmospheric pressure.

Where a significant heat load (process or heat network) is required, a back pressure turbine can be specified where the pressure drop will be less, thus retaining more energy in the condensed steam for heating purposes. CHP-enabled condensing turbines have a controlled bleed point to extract steam mid-way along the turbine casing at a pressure suitable to provide high-grade heat for district heating/cooling purposes.

The turbine is mechanically linked to a generator through a gearbox. The generator rotation is synchronised to the grid at 50 Hz, with electrical output stepped up to a voltage of 11KV through a transformer. Typically air-cooled condensers are installed on site to condense the exhaust from the steam turbine, depending on the local features (ambient climate, river for cooling water supply, etc.)

District heating and cooling

A district heating network will supply hot water to consumers through a pipeline loop. Steam from a WI plant is bled from the turbine system (see turbine description) and supplies heat energy to the district heating system through a heat exchanger located in or close to the WI plant (the energy centre). There are a range of hot water flow and return temperatures in operation across Europe, but current best practice guidance for maximum system efficiency is 70°C/40°C. The pipeline is lagged to limit heat loss and, in urban areas, is generally laid in trenches in the road network.

Within the energy centre, a backup system (normally natural-gas-fired) is needed in the event that the WI plant heat generator is shut down. This can be mitigated if there are several WI plants or other heat sources supplying the network. Backup stations may also operate as peak-load stations in the event that the heat demand outstrips supply.

District cooling refers to the use of heat from a WtE plant to provide chilled water for air conditioning and other cooling applications. One option is to use steam from the WtE plant to drive the compressor for a vapour compression refrigeration system. However, a more commonplace option is to use lower-grade heat (e.g. low-pressure steam or hot water) within an absorption refrigeration system. Absorption-based chiller systems are more widely used on account of their ability to use lower-grade heat, thereby reducing the penalty on the electrical output of the WtE plant.

High-grade heat for industrial users

Some WI plants are located in close proximity to commercial steam users, providing an opportunity to supply steam which can be used in industrial processes. Ideally the consumer would be located less than 1km from the WI plant, but longer pipelines are feasible. Steam is normally bled from the turbine at higher pressures than for a DHN, but the distribution system is designed according to the requirements of the consumer. Steam pipelines require higher maintenance than medium-temperature hot water (MTHW) pipelines, so some supply systems are being de-steamed in favour of MTHW. Backup facilities are required to provide for WI plant supply outages. These can be installed either at the WI site or at the works.

4.5.2 Energy efficiency

The most efficient waste incineration plants are characterised by the following features:

- A waste feedstock which is constant in terms of both composition and calorific value and low in moisture content. This can be achieved through effective pretreatment, but it should be noted that this will increase the plant's parasitic (or in plant) load.
- Effective cleaning techniques to keep boilers free from fouling thereby allowing heat transfer surfaces to operate most effectively.
- Optimised control of combustion conditions and stability of steam production.
- Optimisation of the furnace including:
    - reduction of excess air;
    - low flue-gas temperature at boiler outlet.
- Optimisation of the steam cycle, including:
    - high steam parameters (p, T);
    - steam reheating;
    - preheating of condensate and feed water;
    - preheating combustion air with steam bleed from the turbine;
    - air preheating with a flue-gas heat exchanger.
- Reduction of auxiliary power consumption.
- Plant location - connection to a heat consumer, where heat is supplied at lower temperatures (close to 40°C).
- Plant location - connection to a consumer which has a constant annual demand such as heat to an industrial plant or cooling to a data centre.
- Demand, such as heat to an industrial plant or cooling to a data centre.

The range of energy efficiency in waste incinerators is shown below in Table 2.53.

Table 2.53: Net annual average energy efficiency of waste incinerators assuming that 80% of the heat is sold in CHP mode [68]

Net annual average energy efficiency (%)	
Electricity only	**CHP mode (80% heat load factor)**
22 – 29	68 – 76

4.5.3 Waste incineration - Proven energy efficiency improvement techniques

A list of proven waste incineration energy efficiency improvement techniques is provided below in Table 2.54.

Table 2.54: List of proven waste incineration energy efficiency improvement techniques

	Technique title
	Energy efficiency techniques related to waste firing
a	Waste pretreatment for incineration
b	Advanced moving grates
c	Advanced combustion control
d	Environmentally optimised incineration processes
e	High steam parameters for boilers and superheaters
f	Efficient boiler cleaning
	Energy efficiency techniques related to flue-gases
g	Flue-gas condensation (FGC) and component cooling
h	Reduced parasitic energy consumption through flue-gas recirculation
i	Heat pumps
	Energy efficiency techniques related to energy distribution [69]
j	4th generation heat networks
k	District cooling networks

A full description of each waste incineration technique and the evaluation is provided below.

[68] Please refer to Section 4.2.1 above for calculations and reference documents.
[69] It should be noted that these heat distribution techniques could apply to any energy recovery process which produces large quantities of surplus heat. As they apply most frequently to waste incineration plants, they are included within this grouping.

4.5.4 Waste incineration techniques evaluation

Technique title:	Waste pretreatment for incineration
Description	There are two main categories of waste pretreatment techniques of relevance to energy recovery. These are homogenisation and extraction/separation[70]. <u>Homogenisation</u> of waste feedstock mixes the wastes received at the plant using physical techniques (e.g. bunker mixing and sometimes shredding) in order to supply a feed with consistent combustion qualities. The main benefits achieved are the improved process stability that results, which allows smooth downstream process operation. Steadier steam parameters result from the boiler, which can allow for increased electricity generation. The overall energy efficiency benefits are thought to be limited but cost savings and other operational benefits may arise. <u>Extraction/separation</u> involves the removal of certain fractions from the waste before it is sent to the combustion chamber. Techniques range from extensive physical processes for the production of Solid Recovered Fuels (SRF) and the blending of liquid wastes to meet specific quality criteria, to the simple spotting and removal by crane operators of large items that are not suitable for combustion, such as concrete blocks or large metal objects. The main benefits achieved are: • increased homogeneity, particularly where more elaborate pretreatment is used (see comments above for homogeneity benefits); • the removal of bulky items – thus decreasing the risk of obstruction and therefore non-scheduled shutdowns; • that the waste composition can be modified into a form which enables the use of other techniques that may improve energy efficiency or enable alternative material products to be produced (such as cement or biofuels); • the ability to remove certain wastes which give rise to corrosion, allowing higher steam parameters to be used which gives higher energy efficiency. Extraction, separation and homogenisation of the waste can improve the energy efficiency of the incineration plant itself. This is because these processes can significantly change the nature of the waste that is finally delivered to the incineration process, which can then allow the incineration process to be designed around a narrower input specification, and lead to optimised (but less flexible) performance. However, it is important to note that the techniques that are used in the preparation of this different fuel will themselves require energy and result in additional emissions. Other forms of pretreatment specifically for organic feedstocks include extrusion and hydrothermal carbonisation. These techniques reduce the moisture content of organic feedstocks through either mechanical

[70] WI BREF 2006/2007.

Technique title:	**Waste pretreatment for incineration**	
	or thermochemical means to produce a solid fuel with a low moisture content and a high calorific value. The energy input to these processes must be balanced by the gain in energy output when they are combusted.	
Criteria	Rating	Notes
Net annual average energy efficiency		The energy consumption of a sorting process will depend on how elaborate it is. Numerous operational benefits are provided by pretreatment but net energy efficiency gains are likely to be relatively modest or potentially negative. Where pretreatment of mixed waste is required to produce SRF, this will require an additional energy input of approximately 1.7% of the waste input energy. The main benefit is its applicability (as described below) and the ability of pretreatment to support energy recovery processes other than a conventional moving grate.
Applicability		Pretreatment supports the waste hierarchy as it enables residual recyclable elements in the waste to be removed (recyclable elements which are not captured through source separation) so that only non-recyclable waste is left for incineration. Pretreatment can be used for many emerging technologies.
Exclusion criteria	No	None noted.
TRL	9+	Pretreatment of waste is a well-established and proven technique. It should be acknowledged that some pretreatments such as extrusion or hydrothermal carbonisation are not so well proven.

Technique title:	**Advanced moving grates**
Description	The moving grate has continually improved over many decades to optimise its performance[71]. Two notable developments in recent years to improve combustion efficiency and environmental performance are as follows: • Water cooling of the grate bars to reduce excess air. With water cooling, cooling is independent of combustion so the amount of combustion air can be more carefully controlled. This enables combustion air to be adjusted for optimal combustion conditions, flue-gas volumes to be reduced (which reduces the plant's parasitic load), higher CV waste material can be treated and heat from the cooling water can be recovered in full through the boiler steam cycle. Water cooling is best suited to WI plants operating on higher waste NCVs of >11MJ/Kg.

[71] Ricardo Energy & Environment.

	• Individually controlled grate zones. This technique is based on the proven reverse-acting principle where the grate is divided into three drive zones which can each be controlled individually as opposed to one speed across the whole grate surface. This enables the speed at which the fuel is fed and the combustion conditions to be optimally adjusted to fluctuating waste quality. This makes it possible to agitate the fuel/the combustion residues in several zones without adversely affecting the residence time. The replacement of the grate in a WI plant is a major outlay and is unlikely to be economic for an existing plant.	
Criteria	Rating	Notes
Net annual average energy efficiency		Small gains in energy efficiency can be achieved.
Applicability		The technique is applicable to most waste types but retrofitting may be expensive.
Exclusion criteria	No	None noted.
TRL	9+	These improvements feature in many of the latest WI plants.

Technique title:	**Advanced combustion control**
Description	Waste incineration is a complex process which needs to be closely controlled to minimise emissions and to maximise process energy efficiency and cost efficiency. Advanced fuzzy logic combustion control systems have been implemented in a number of WI plants in Europe to provide optimised process performance. Fuzzy logic can provide a number of benefits by tightly controlling process variation rather than just checking the process operating values. To provide a similar level of control through plant operating personnel would require a large number of experienced workers. A number of WI plants have reported achieving good results through the implementation of advanced control including[72]: • increased waste throughput and steam generation; • increased energy efficiency (by between 1% and 2.5% where a plant is not already optimised); • reduced consumption of reagent; and • implementation costs should enable a payback period of under one year as the existing optimised plant control system can be utilised.

[72] Viridor Waste Management, Lakeside WtE plant, UK, 22 November 2015.

Technique title:	**Advanced combustion control**	
Criteria	Rating	Notes
Net annual average energy efficiency		Advanced combustion control is not able to provide a step change in combustion energy efficiency but will help to maximise the performance of older plants within the current range of 22-29% net annual average electrical efficiency.
Applicability		This technique can be retrofitted with a relatively short payback time, although some additional process equipment such as valves and instrumentation may be necessary which add to capex. It will be most suited to older plants which are not already using an optimised control system.
Exclusion criteria	No	None noted.
TRL	9+	There are around 25 reference installation examples in the EU-28 from a number of suppliers.

Technique title:	**Environmentally optimised incineration processes**
Description	A process has been developed to provide an environmentally optimised incineration process[73]. The complex combustion control system, which makes use of infra-red thermography, and the adjusted secondary air injection system ensure that the combustion process is optimised. Tests were performed at the Coburg waste-to-energy plant in Germany. Following this, the first commercial plant was built in Arnoldstein, Austria. Since the second half of 2004, this plant has been operating on a continuous basis. In Sendai, Japan, a further plant started operating in 2005. The developer claims that the optimised process provides: • more intense, more uniform combustion; • significantly reduced CO content in the flue-gas; • temperature in the fuel bed in the main combustion zone approx. 100°C higher with partial sintering of the bottom ash and consequently improved burnout and less leaching of heavy metals; • flue-gas flow reduced by approx. 35 %; • higher boiler efficiency; • reduced pollutant burden at stack; • reduced fly ash flow. Although the technology has been commercially available for a number of years, take-up has been low. There are other forms of environmentally optimised incineration processes on the market.

[73] WI BREF 2006/2007.

Criteria	Rating	Notes
Net annual average energy efficiency		Small gains in energy efficiency can be achieved which will be within the current expectations of a modern incineration plant
Applicability		The technique is applicable to most waste types but retrofitting may not be cost-effective.
Exclusion criteria	No	None noted.
TRL	9+	There are a small number of plants which have been operating the environmentally optimised process for a number of years.

Technique title:	**High steam parameters for boilers and superheaters**
Description	Numerous techniques have been developed to help boost the energy efficiency of conventional incineration to above 30%. Compared to fossil-fuel-fired LCP boilers, waste-fuelled boilers have low electrical generation efficiency. This is primarily because of the severe corrosive environment created by waste incineration which limits steam temperatures and pressures to around 425°C and 50 bar. • External superheaters - An innovative solution is to provide an external superheater which is powered by the gasification of a cleaner and more homogeneous fuel such as waste wood. This additional, cleaner heat source can raise the steam generated by the waste-fired 'base plant' to temperatures over 500°C without risking early failure of superheater tubes. This technique is offered commercially, and the most suitable application would be co-located with MSW and biomass waste treatment plants. • Radiant pass superheaters - A number of technology providers have fitted superheaters in the radiant or first pass area of the boiler. This is where flue-gases are hottest; the radiant section of the boiler is normally lined with refractory with the boiler tubes located behind the refractory wall. As the boiler tubes do not come into direct contact with the flue-gases, the energy transfer is considered to be radiant. Unprotected steel components would not be able to withstand the intense heat of this section of the boiler and would rapidly corrode. Some plants with this boiler arrangement experience a superheater lifetime of under one year. To overcome this, a radiant superheater can be coated with silicon carbide (SiC) tiles. The radiant superheater operates in combination with the conventional downstream convection superheater bundles. A radiant superheater can raise steam temperatures by between 40°C and 80°C, which corresponds to an increase in electrical energy efficiency of around 3%. • Utility-scale power plants using biomass and fossil fuels as a feedstock commonly reheat turbine steam after its first pass

Technique title:	High steam parameters for boilers and superheaters	
	through the turbine to increase electrical efficiency. For this application, the steam temperature is limited to 400°C, but the steam pressure increases considerably. After the first pass through the high-pressure section of the turbine, the resulting steam is superheated again and subsequently used in the turbine's medium and low-pressure sections. Usually, after expanding in the high-pressure turbine, the steam has a lower pressure (typically 20% that of its pressure on entry) and is reheated with flue-gas in the boiler to the same temperature. One of the benefits is increased electrical efficiency by approximately 3 percentage points to reach 30% net electrical efficiency. In order to maximise the effect of this set-up, the steam pressure has to be increased to at least 120 bar. However, with the corrosive elements present in waste-fuel-derived flue-gases, at this temperature level there is a high risk of corrosion, even if Inconel cladding is used for boiler tube protection[74]. The Amsterdam AEB plant in the Netherlands employs a steam reheat system through an intermediate superheater and operates at steam conditions of 480°C and 130 bar[75]. The superheaters are designed to be removed easily and, due to rapid corrosion, need replacement around every two years. At a very large plant such as AEB Amsterdam, the revenues from increased electrical production outweigh the cost of superheater replacement. At most WI plants, this is not the case and the superheater lifetime needs to be at least five years.	
Criteria	Rating	Notes
Net annual average energy efficiency		High steam parameters offer year-round net electrical efficiencies of up to 33%. Net electrical efficiencies of 35% are being targeted by developers but have not yet been achieved.
Applicability		Such high efficiency brings both high capex and opex and is mainly interesting for very large plants where large amounts of power are exported and where power export prices are high.
Exclusion criteria	No	None noted.
TRL	9	Due primarily to cost-benefit issues, there are only a few commercial examples of the highest steam parameters which currently provide a net electrical efficiency over 33%.

[74] http://www.volund.dk/~/media/Downloads/Conference_papers_-_WTE/NAWTEC_16_-_High_electrical_efficiency_by_dividing_the_combustion_products.pdf.
[75] Martin GmbH, London EfW conference, 2016.

Technique title:	**Efficient boiler cleaning**	
Description	Clean boiler tubes and other heat-exchange surfaces result in better heat exchange. Where extensive fouling has been allowed to build up in a boiler, steam temperatures can fall by as much as 50°C. As a technique, effective boiler cleaning encompasses both technical and operational elements. Boiler cleaning may be carried out on-line (during boiler operation) and off-line (during boiler shutdowns and maintenance periods). The dimensions of the boiler and heat exchanger design (e.g. tube spacing) influence the cleaning regime. Techniques for on-line cleaning include: • mechanical rapping; • soot-blowing by steam injection; • high- or low-pressure water spraying (mainly on the wall in the empty passes of the boiler); • ultra-/infra-sonic cleaning; • shot cleaning or mechanical pellet scouring; • explosive cleaning; and • high-pressure air injection (from 10 to 12 bar) with movable lances. Off-line techniques include: • periodic manual cleaning (in general once a year in a waste incinerator); and • chemical cleaning. In addition to these techniques, it can also be beneficial to prevent higher temperature gases (above 650°C when fly ash is more sticky and hence more likely to adhere to surfaces it comes into contact with) from coming into contact with convective heat-exchange bundles by suitable boiler design such as: • including three vertical radiant boiler passes with waterwalls only; and • specifying larger furnace dimensions and hence lower gas velocities before the bundles. Effective cleaning can improve plant energy efficiency by 1.5% to 3% where its performance is currently poor[76].	
Criteria	Rating	Notes
Net annual average energy efficiency		More effective cleaning can help improve the energy efficiency of a poorly performing boiler.
Applicability		This technique is applicable to all boilers and cleaning systems and can normally be retrofitted.
Exclusion criteria	No	None noted.
TRL	9+	These cleaning techniques are widely practised.

[76] WI BREF 2006/2007.

Technique title:	**Flue-gas condensation (FGC) and component cooling**	
Description	An extremely cost-effective method of recovering energy for a district or local heating grid is by condensing the water in flue-gases. The amount of energy recovered depends on the district heating water temperature. Flue-gas condensation (FGC) is a technique to recover further energy from the flue-gases. The flue-gases still contain water vapour following clean-up which can be condensed to a liquid form to enable additional low-grade heat to be recovered. As a rough guide, a flue-gas condensation installation can increase heat energy recovery by up to 15%[77]. There is a small decrease in electrical energy efficiency associated with this. Smaller amounts of useful heat can also be recovered from water-cooled plant components which generate large amounts of waste heat such as water-cooled grates and HV transformers.	
Criteria	Rating	Notes
Net annual average energy efficiency		There will be a small impact on electrical power production from FGC (around 0.5% to 1% reduction) but, where heat is exported, the overall energy efficiency will increase considerably. The CHP net annual average efficiency is estimated to rise from 76% to 88% with the addition of FGC for the most advanced plants.
Applicability		The full benefits of FGC will only be realised where the plant exports heat. Otherwise the energy recovered by FGC can only be used for boiler feed water preheating which is limited.
Exclusion criteria	No	Plume visibility may increase due to low stack gas exit temperatures - this may have a visual impact but does not impact health.
TRL	9+	The latest installations of waste incineration plants employ FGC, particularly in Scandinavia.

[77] ISWA CE Report 5, 2015.

<table>
<tr><th colspan="2">Technique title:</th><th>Reduced parasitic energy consumption through flue-gas recirculation</th></tr>
<tr><td>Description</td><td colspan="2">Flue-gas recirculation (FGR) can reduce combustion plant energy consumption as the induced draft fan size / power consumption can be reduced which is a major power consumer in a combustion plant. The boiler efficiency also increases as flue-gas mixing is more effective.

FGR reduces nitrogen oxides (NO_x) emissions in boilers by recirculating a portion (~25%) of the boiler flue-gas back into the main combustion chamber. This process reduces the peak combustion temperature and lowers the percentage of oxygen in the combustion air/flue-gas mixture, thus retarding the formation of NOx caused by high flame temperatures (thermal NOx). FGR is normally combined with an SNCR system to achieve the required ELVs. The energy and environmental benefits are that it:

• can reduce overall plant energy consumption;
• increases boiler efficiency;
• is a relatively cheap and compact solution; and
• can reduce NO_x production by 10-30%.

Disadvantages are:

• the oxidising atmosphere, so corrosion can be an issue;
• leaks from recirculation ducting can be dangerous due to the low O_2 content; and
• FGR systems on their own cannot meet the emissions requirements of the IED, so an additional flue-gas treatment plant is required in tandem with FGR.</td></tr>
<tr><td>Criteria</td><td>Rating</td><td>Notes</td></tr>
<tr><td>Net annual average energy efficiency</td><td></td><td>Boiler efficiency is increased by up to 3% and induced draft fan power consumption reduced by 20%[78]. The overall plant energy efficiency gain from these improvements is estimated at around 0.75-2%[79].</td></tr>
<tr><td>Applicability</td><td></td><td>FGR is not able to reduce NO_x to the required ELV so a secondary abatement system will also be needed – this increases overall capex and reduces the attractiveness of fitting FGR.</td></tr>
<tr><td>Exclusion criteria</td><td>No</td><td>None assuming FGR is fitted with a secondary abatement process.</td></tr>
<tr><td>TRL</td><td>9+</td><td>There are a large number of FGR installations across the EU-28.</td></tr>
</table>

[78] SUEZ Environmental, February 2015.
[79] WI BREF 2006/2007.

Technique title:	**Heat pumps**	
Description	It is possible to improve energy recovery by using a heat pump installation, located within the flue-gas treatment plant. A compressor-driven heat pump is the most widely used heat pump. It is used in cooling equipment such as air conditioning and to extract heat from ground sources. An electrical motor normally drives the heat pump, but, for big installations, steam-turbine-driven compressors can be used. In a closed circuit, a refrigerant substance is circulated through a condenser, expander, evaporator and compressor. The compressor compresses the substance, which condenses at a higher temperature and delivers the heat to the district heating water. There the substance is forced to expand to a low pressure, causing it to evaporate and absorb heat from the water from the flue-gas condenser at a lower temperature. Thus the energy at low temperatures in the water from the flue-gas condenser is transformed to the district heating system at a higher temperature. In typical incineration conditions, the ratio between output heat and compressor power (heat to power ratio) can be as high as 5[80]. Heat pumps are frequently used in tandem with flue-gas condensation equipment. A flue-gas condensation installation can increase heat energy recovery by up to 15% of the furnace energy output but, in tandem with a heat pump installation, this figure increases to just over 20%[81]. A feasibility study[82] conducted within an operational WI plant into increasing efficiency by the use of heat pumps (combined with flue-gas condensing) concluded that energy recovery for district heating increased by 9.4MWth through the use of a 2.3 MW_{el} heat pump combined with flue-gas condensing; an estimated investment cost of EUR 6 million (including EUR 3 million for the heat pump) was required. Flue-gas temperatures at the exit were reduced from 60°C to 37°C; reductions to as low as 30°C may be possible.	
Criteria	Rating	Notes
Net annual average energy efficiency		The CHP net annual average efficiency is estimated to rise from 76% to over 88% with the addition of heat pumps in tandem with FGC for the most advanced plants.
Applicability		The full benefits will only be realised where the plant exports heat in the form of district heating or steam.
Exclusion criteria	No	None noted.
TRL	9+	Many of the latest generation of WI plants incorporate FGC and heat pumps working in tandem.

[80] WI BREF, 2006/07.
[81] ISWA CE Report 5, 2015.
[82] Statkraft, Norway.

<table>
<tr><th>Technique title:</th><th colspan="2">4th generation heat networks</th></tr>
<tr><td>Description</td><td colspan="2">This refers to the technological and institutional concepts to broaden the suitability of district heating and cooling networks beyond their current areas of greatest suitability (densely populated areas located within cold climates). These concepts seek to reduce the minimum heat demand density required to make a network commercially viable. This allows networks to continue to be appropriate in areas where heat demand densities are lower, either through lower dwelling density or as a result of energy efficiency improvements.

The four main features of 4th generation heat networks are as follows[83]:

• Ability to supply low-temperature district heating for space heating and hot water. This concerns the use of heat delivery temperatures below 50°C, compared to 100° for current generations.
• Ability to distribute heat in networks with low grid losses.
• Ability to utilise renewable heat and recycled heat from low-temperature sources. This includes waste heat from power generation (including WtE) as well as heat from other renewable sources (e.g. geothermal and solar thermal).
• Ability to form an integral part of smart energy systems (e.g. through intelligent control of demand and supply through demand-side response and thermal storage).

The deployment of 4th generation heat networks would make district heating viable in a greater number of situations, increasing the potential for heat networks to be developed in areas in the vicinity of WI plants. This would enable these plants to operate in a co-generation mode and, as a consequence, increase their energy efficiency. In addition, the use of lower operating temperatures would enable WI plants to supply the necessary heat with less impact on their power output, leading to higher power to heat ratios.

Examples of 4th generation heat networks are available. However, these are currently limited to small-scale networks such as the 5MWth system installed at Stadsoevers in the Netherlands. It is reported that the delivery of heat does not reduce electricity production when run in CHP mode[84]. Hot water is delivered at 40°C and may be raised to 65°C locally using heat pumps so power consumption from the grid will be required.</td></tr>
<tr><td>Criteria</td><td>Rating</td><td>Notes</td></tr>
<tr><td>Net annual average energy efficiency</td><td></td><td>Low supply temperatures means turbine electricity generation losses in the WI plant are minimal. Where this is the case, the net annual average energy efficiency is estimated to rise from 76% to 82% for the most advanced plants.</td></tr>
</table>

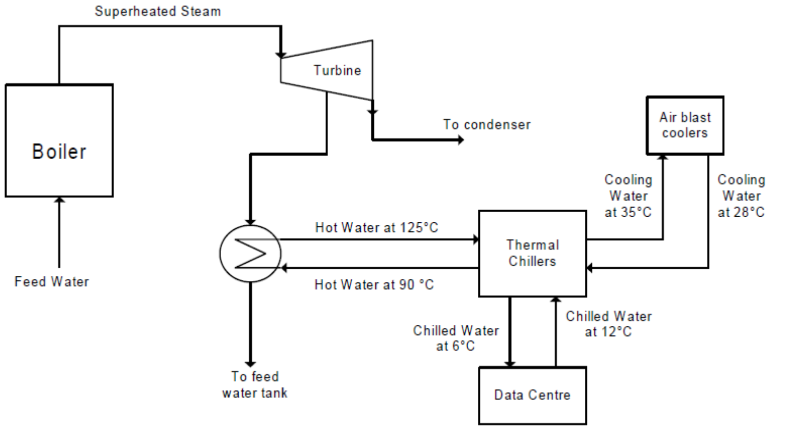
[83] Lund et al, 2014.
[84] SUEZ Environment, Showcase for WtE efficiency, February 2015.

Technique title:	**4th generation heat networks**	
		Heat pumps may be required to raise water supply temperatures locally for some applications; these will require additional energy input.
Applicability		4th generation networks still require a local energy user but the technology will help to expand the applicability of district heating and cooling.
Exclusion criteria	No	None noted.
TRL	9	The only operating applications to date are relatively small-scale.

Technique title:	**District cooling**
Description	This refers to the use of heat from a WI plant to provide chilled water for air conditioning and other cooling applications. One option is to use steam from the WI plant to drive the compressor for a vapour compression refrigeration system. However, a more commonplace option is to use lower-grade heat (e.g. low-pressure steam or hot water) within an absorption refrigeration system. Absorption-based chiller systems are more widely used on account of their ability to use lower-grade heat, thereby reducing the penalty on the electrical output of the WI plant. The overall energy efficiency of cooling systems is less than that of a system delivering heat energy, particularly refrigeration absorption. The performance of the chiller system is expressed in terms of its coefficient of performance (CoP, the ratio of cooling output to heat input). Steam-based absorption systems can achieve CoPs in the order of 1.2 while hot water systems achieve CoPs of 0.6. In comparison to district heating which typically has a heat energy efficiency of 65%, district cooling energy efficiency is typically around 42%[85] (both these efficiency figures relate to the heat / cooling energy only and exclude any power recovered by the WI plant). Backup facilities are normally required to provide for WI plant supply outages. This will typically be provided by electrically powered vapour compression chiller systems. As a district cooling system would replace many individual smaller cooling units, there are environmental gains from reduced slippage of refrigerant gases. A large system will typically only emit 1% of refrigerant gases, whereas a small installation may emit around 10-20%[86]. Applications are currently limited to a small number of schemes (e.g. Districlima in Barcelona, Spain). However, one area of potential growth is the provision of cooling services to data centres, which have

[85] Ricardo Energy & Environment.
[86] Swedish Ministry of the Environment and Energy, July 2016.

Technique title:	**District cooling**
	constant and very high cooling requirements. A schematic is shown below:



Criteria	Rating	Notes
Net annual average energy efficiency	100% load	Where district cooling is linked to a consumer such as a data centre, year-round cooling is required. In these cases, net annual average energy efficiency (in a combined cooling and power configuration) is estimated at 68%, even for the most efficient systems.
	80% load	Otherwise where cooling is assumed to be required only 80% of the year due to seasonal demand, a net annual average energy efficiency of 60% can be expected (in a combined cooling and power configuration), even for the most efficient systems.
Applicability		Cooling effort requires the input of primary (electrical) energy and is therefore more highly valued than heat energy and should attract more revenue. Better annual energy efficiency is dependent on being connected to large cooling energy consumers such as hospitals or data centres. Hot climates within the EU-28 will also offer seasonal demand.
Exclusion criteria	No	None noted
TRL	9+	All technology is proven but uptake and examples remain limited for commercial reasons.

4.5.5 Waste incineration plant techniques - Technology to watch

In addition to the proven waste incineration plant techniques discussed above, there are emerging techniques which are not currently ready for widespread deployment but have the potential to increase the energy recovered from waste in the future. These are listed in Table 2.55.

Table 2.55: List of emerging waste incineration plant energy efficiency improvement techniques

#	Technique title
a	High steam parameters (emerging techniques)
b	Use of the mass and energy balance method to measure waste biogenic content
c	Heat and power decoupling through heat pumps
d	Use of ilmenite as a bed material in a circulating fluidised bed (CFB) reactor
e	Organic Rankine Cycle turbine for low-grade heat utilisation

A full description of each emerging waste incineration plant energy efficiency improvement technique and the evaluation is provided below.

4.5.6 Waste incineration techniques evaluation

Technique title:	High steam parameters (emerging techniques)
Description	Numerous techniques are also emerging to help boost the energy efficiency of conventional incineration to above 30%. Compared to fossil-fuel-fired LCP boilers, waste-fuelled boilers have low electrical generation efficiency. This is primarily because of the severe corrosive environment created by waste incineration which limits steam temperatures and pressures to around 425°C and 50 bar. • In incineration of MSW, the major parts of the corrosive species are released in the first part of the combustion grate and thereby in the front of the furnace. The rear parts of the grate are characterised by a burnout of a relatively clean char, thereby releasing relatively clean combustion products which are much less corrosive. This phenomenon can be exploited to split the flue-gases from the grate into two or more fractions, one of which exhibits high heat flux and a low chlorine concentration. That fraction could then be used in a high-temperature superheater to increase the steam temperature and thereby the electrical efficiency of waste-fired power plants. In order to ensure the separation of the two flue-gas fractions in the furnace, a water-cooled membrane wall is installed above the middle of the combustion grate. When the two streams of flue-gases enter the post-combustion chamber, they are then mixed by the secondary air system for final burnout. The basic idea of the concept is to use all the advantages of a modern waste-fired power plant combined with an integrated final superheater. The final superheating increases the steam to, for example, 500°C and 80 bar and results in an increase in electrical efficiency of 3 percentage points over the baseline steam conditions of 400°C and 45 bar. The overall objective is to achieve a net electrical efficiency of between 27% and 33%, depending on the design of the cooling system for the condenser. The concept has been trialled in a modified operational waste plant in Denmark and the results have shown that the concept is feasible[87]. • Sulphur recirculation is an emerging technology that is able to reduce high-temperature corrosion in superheaters. Alternatively, it can increase electricity generation at waste incineration installations, if the superheater steam pressure and temperature are raised. In the process, sulphur from a wet flue-gas cleaning system is returned to the furnace. The recirculated sulphur raises the SO_2 concentration in the furnace and reduces the chlorine to sulphur ratio in deposits and ashes, and the environment becomes less corrosive. Furthermore, the formation of dioxins

[87] Venice 2014, Fifth International Symposium on Energy from Biomass and Waste, http://www.volund.dk/~/media/Downloads/Brochures_-_WTE/BWV_NextBAT_technology.pdf.

Technique title:	**High steam parameters (emerging techniques)**	
	is reduced, and the proportion of sulphates in the effluent water discharged from the wet flue-gas cleaning is reduced. The process works in two stages. First, sulphur dioxide is removed from the flue-gases in the wet flue-gas cleaning stage. The removed sulphur compounds are then sprayed into the boiler through nozzles with a surrounding carrier gas. In this way the level of sulphur in the water is raised. Thus each sulphur atom passes through the furnace several times. The process has been demonstrated in Gothenburg, Sweden. Dioxin samples, impactor measurements, deposit probe measurements, ash samples and 1,000-hour corrosion measurements were taken in full-scale trials with and without sulphur recirculation. With sulphur recirculation, corrosion rates in the superheaters for all materials evaluated (16Mo3, Sanicro 28 and Inconel 625) were reduced by more than 50% compared to the reference case[88].	
Criteria	Rating	Notes
Net annual average energy efficiency		High steam parameters offer year-round net electrical efficiencies of up to 33%.
Applicability		Traditionally, high steam parameters have been restricted to the largest plants due to the high costs of corrosion. It is too early to determine whether these techniques will lower the costs of operating WI plants at higher temperatures and pressures.
Exclusion criteria	No	None noted.
TRL	7	Small-scale tests in commercial WI facilities have been conducted with encouraging results.

[88] Sulphur Recirculation for Low-corrosion waste-to-energy, available at: www.iswa.org/uploads/tx_iswaknowledgebase/Andersson.pdf

Technique title:	**Use of the mass and energy balance method to measure waste biogenic content**	
Description	Municipal solid waste is an extremely heterogeneous feedstock and, unless properly managed and mixed before firing, can cause significant variation in combustion control and pollution abatement. Use of the mass and energy balance method to measure waste biogenic content is a measurement technique developed by the Technical University of Vienna[89]. It was originally designed to provide a method to determine the biogenic content in order to facilitate carbon accounting and access to renewable benefit schemes. It is an approved method for reporting and obtaining applicable renewable energy support credits. The balance method is based on the mathematical solution of theoretical balance equations for materials, substances and energy together with plant data such as flue-gas volume, steam production and bottom ash mass. It utilises operational plant data and can provide a continuous output of results. The method determines biogenic content (ratio of green energy), fossil CO_2 emissions and calorific value. These results, properly analysed and interpreted, can assist operators with improving both the reception and mixing of waste prior to firing and the operation of combustion and pollution control systems, effectively providing an improved conversion efficiency and reduced operational costs. For example, reducing the variations in fuel quality leads to improved efficiency of combustion and therefore greater energy recovery per tonne of waste.	
Criteria	Rating	Notes
Net annual average energy efficiency	(amber)	Some improvement in energy efficiency will be obtained through more stable process conditions.
Applicability	(green)	The technique can be applied to most waste incineration plants relatively easily.
Exclusion criteria	No	None noted.
TRL	8	A number of trials have been conducted in operational WI plants across the EU-28.

[89] BIOMA - software for balance method, available at: http://iwr.tuwien.ac.at/ressourcen/downloads/bioma.html.

Technique title:	**Heat and power decoupling through heat pumps**	
Description	Heat pumps can be used to decouple heat and power recovery in a waste-fired plant district heating application[90]. An innovative design has been proposed whereby, to maximise turbine power generation efficiency, no steam bleeds are provided to tap off steam for district heating energy and a condensing turbine set-up for maximum power recovery is specified. The resulting turbine condensate is relatively cool so an array of heat pumps are used to increase the temperature of the turbine condensate from (approx. 40°C) to a temperature more suitable for district heating purposes (70°C). To enable this, electrical energy can be drawn from the grid when there is an excess of electrical energy available (e.g. peaks from wind power and otherwise the grid is not accepting power) to be transformed into heat energy within the district heating system. When there is no demand for heat, the heat pumps would not operate and only power export from the plant would occur. In this way heat and power can be produced independently according to demand and thus providing a way of storing excess grid power generation capacity. Although the system is highly flexible, it is anticipated that the overall energy efficiency will be low compared to a state-of-the-art heat-enabled waste incineration plant with a condensing turbine. A small-scale operational example of a similar proposal is located in Drammen, Norway. The heat pump energy source is deep water (rather than WI plant turbine condensate), but, in a similar way, the scheme employs heat pumps to extract energy from a low-temperature source to produce district heating water at a suitable temperature.	
Criteria	Rating	Notes
Net annual average energy efficiency		The main benefit of this technique is flexibility, not energy efficiency. Although an overall analysis has not been performed, it is thought unlikely that drawing excess grid power to operate heat pumps is more energy-efficient than using surplus heat from a turbine bleed point.
Applicability		The applicability is restricted to a small number of district heating schemes.
Exclusion criteria	No	None noted.
TRL	9	There are one or two small-scale examples in Norway and Russia.

[90] Ricardo Energy & Environment.

Technique title:	Use of ilmenite as a bed material in a circulating fluidised bed (CFB) reactor	
Description	A new combustion concept has been developed by Chalmers University of Technology in Gothenburg, Sweden, developed from steel industry applications[91]. The principal of the new concept is to replace the inert silica sand bed material conventionally used in a CFB reactor with a metal oxide, ilmenite. Ilmenite is the titanium-iron oxide mineral with the formula $FeTiO_3$. Silica sand has one main purpose in a CFB reactor and that is to act as a heat carrier. Where metal oxide is used as a bed material, as well as carrying heat, the metal oxide carries oxygen for the combustion reaction and absorbs fly ash. The benefits of this concept are that it enables the input of up to 4% more heat energy to the boiler and, with better oxygen distribution, there is considerably less CO in the stack emissions. The concept has gone from lab-scale in 2013 to a commercial-scale demonstrator at the Handeloverket waste treatment plant in Sweden. This plant has a thermal input of 75MW. The cost of ilmenite will be higher than silica sand. No data has been provided on the operational costs to replenish the ilmenite bed material.	
Criteria	Rating	Notes
Net annual average energy efficiency		With the input of up to 4% more heat energy to the boiler, a small gain in plant energy output may be realised.
Applicability		CFB technology is not widely applied to the larger waste streams such as household waste but may treat prepared waste-derived fuels such as SRF and is well suited to waste wood. Therefore, the applicability is somewhat limited. Where pretreatment of mixed waste is required to produce SRF, this will require an additional energy input of approximately 1.7% of the waste input energy.
Exclusion criteria	No	None noted.
TRL	9	It has been demonstrated on a commercial scale in Sweden.

[91] Chalmers University of Technology, London EfW conference, 2016.

Technique title:	**Organic Rankine Cycle (ORC) turbine for low-grade heat utilisation**	
Description	Waste heat is often of a low temperature and it can be difficult to efficiently utilise the heat contained. In these cases, the ORC turbine can bring some additional benefit to raise the overall plant efficiency. The ORC turbine utilises this otherwise wasted energy and converts it into power. The Organic Rankine Cycle is named for its use of a working fluid with a boiling point occurring at a lower temperature than water/steam which is used in conventional Rankine Cycle turbine applications. The fluid allows the Rankine Cycle to recover energy as heat from lower temperature sources such as incinerator waste heat. The working fluid used is normally a refrigerant fluid which must conform to the requirements of the Montreal Protocol (non-ozone-depleting). The working principle of the ORC turbine is the same as that of a conventional turbine; the working fluid is evaporated using (low-grade) heat from the incineration process and passes through the turbine at pressure to produce mechanical energy. The fluid exits the turbine to a condenser heat exchanger where it is finally recondensed. Because of the low working temperatures of the ORC, heat transfer inefficiencies are highly prejudicial and result in a low overall energy efficiency. Suitable equipment is required to prevent any fires related to the working fluid.	
Criteria	Rating	Notes
Net annual average energy efficiency		The net average annual electrical efficiency of the ORC turbine is estimated to be around 19%[92]. This is mitigated by the fact that the ORC turbine can utilise low-grade heat which would otherwise be emitted to atmosphere. A conventional turbine can still recover high-grade heat at a higher efficiency in tandem with an ORC turbine.
Applicability		Most WtE plants recover waste low-grade heat which could be used to provide an energy source for an Organic Rankine Cycle turbine.
Exclusion criteria	No	None noted.
TRL	9	There are many commercial examples in operation but these are uncommon in WtE plants.

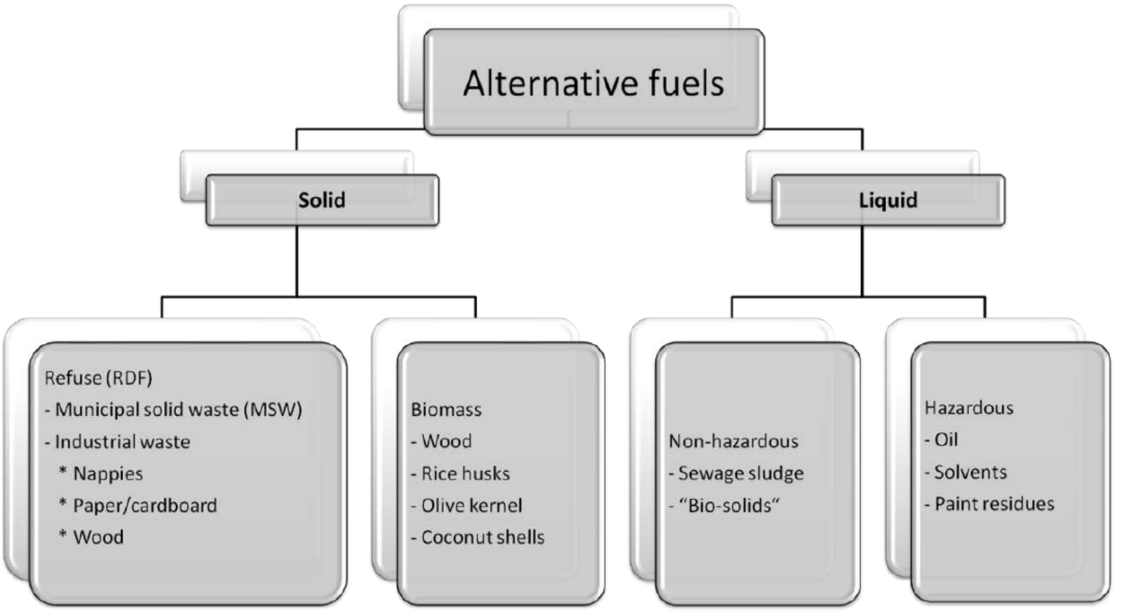
[92] http://www.energy.siemens.com/mx/pool/hq/power-generation/steam-turbines/downloads/brochure-orc-organic-rankine-cycle-technology_EN.pdf.

4.6 CL plants: Cement and lime production plants

This section considers techniques where waste is used as an alternative fuel (AF) in the production of cement and lime (CL). Of these two products, the production of cement using waste as an alternative fuel makes up the majority of plant capacity.

4.6.1 Overview of waste in CL applications

Co-firing of waste (such as tyres, oils and solvents, plastics, textiles and paper wastes) and biomass wastes (such as animal meal, sewage sludge, waste wood, sawdust) with fossil fuels is commonplace as an alternative fuel (AF) for firing CL plants. These AFs are shown in the illustration below:



Cement kilns (and other CL plants) require very large quantities of thermal energy so the use of waste-derived alternative fuels can help reduce high energy costs and environmental impact. Cement kilns have very exacting standards for waste-derived fuels to ensure the cement product will:

(a) conform to specification (as residual contamination from the waste fuel will be trapped in the cement clinker product); and

(b) guarantee that all cement plant emissions to air stay within permitted IED levels; the unique process and energy requirements of the cement industry enable the use of fuel mixes that would not be suitable for many other industries.

A second advantage of alternative fuel utilisation in cement kilns is that approximately 25% of the waste material content is recycled into production of the clinker, bringing together both energy recovery and material recycling (which is one step higher on the waste hierarchy). There is no residual bottom ash produced from the waste incineration process.

4.6.2 Energy efficiency

The most energy-efficient CL plants are characterised by the following features:

- the type of cement kiln - a modern cyclone preheater plant with a precalciner normally has higher energy efficiency than a long wet kiln or a kiln equipped with a grate preheater;
- additional features to utilise waste heat for useful purposes such as drying of residues.

The range of energy efficiency in cement kilns varies between 65% (for older installations) and 80% for newer plants with a current average of around 75%[93]. This is not subject to a heat load factor as cement manufacture is continuous. However, it has been calculated that 1.7% of the SRF input energy is also required for the pretreatment of MSW to produce SRF.

4.6.3 CL plants - Proven improvement techniques and evaluation

<table>
<tr><th>Technique title:</th><th colspan="2">Conversion of waste heat to power in cement kiln applications</th></tr>
<tr><td>Description</td><td colspan="2">Due to the high electric energy consumption of the clinker-burning process, Rohrdorfer Zement implemented a waste heat recovery system to reduce the total energy consumption and increase energy efficiency at their plant in Rohrdorf, Germany.

In order to use the waste heat of the rotary kiln (from the denitrification plant and the clinker cooler exhaust air), a waste heat power generation (WHPG) plant was installed in 2012. There, steam is generated which is used for driving a turbine and producing electricity. The operational experience gained with the waste heat recovery plant has shown that the total power demand of the Rohrdorf cement plant can be reduced by 4.5 to 5.5 MW_{el} with the new installation. As a consequence, this increase in energy efficiency decreases the annual CO_2 emissions by 16,000 tonnes per year based on the German power mix.

Although the technical feasibility of the technique was proven, the project was not commercially viable without financial support from the government. A similar project was implemented in Romania at the Fienei cement production plant where, again, a WHPG project was technically successful but needed a significant government subsidy and a long payback period.

A WHPG can be retrofitted to an existing cement kiln facility where space permits.

The Organic Rankine Cycle turbine may also be utilised in cement kiln applications to recover energy from low grade waste heat, this is discussed under waste incineration (pathway 2).</td></tr>
<tr><td>Criteria</td><td>Rating</td><td>Notes</td></tr>
<tr><td>Net annual average energy efficiency</td><td></td><td>As a CHP installation, the energy efficiency achieved will be high at over 75%. The pretreatment required to make SRF suitable for cement kiln applications will require energy input.</td></tr>
</table>

[93] Cembureau, 11 April 2016.

Technique title:		**Conversion of waste heat to power in cement kiln applications**
Applicability		The ability to retrofit waste heat energy recovery has been proven.
Exclusion criteria	No	None noted.
TRL	9+	At least two examples of this technique which were commissioned within the last five years have been cited by Cembureau[94].

[94] Cembureau, April 2016.

4.6.4 CL plant techniques - Technology to watch

In addition to the proven CL plant techniques discussed above, there are emerging techniques which are not currently ready for widespread deployment but have the potential to increase the energy recovered from waste in the future. These are listed in Table 2.56.

Table 2.56: List of emerging CL plant energy efficiency improvement techniques

#	Technique title
a	Use of waste-derived syngas as fuel for cement kiln burners
b	Use of hydrogen extracted from waste syngas as fuel for cement kiln burners

A full description of each emerging CL plant energy efficiency technique and the evaluation is provided below.

4.6.5 Cement kiln emerging energy efficiency improvement techniques evaluation

Technique title:	**Use of waste-derived syngas as fuel for cement kiln burners**	
Description	Syngas from the gasification of more homogeneous waste streams may be used as an alternative fuel in cement kiln applications[95]. Syngas can be produced by pretreating the waste prior to gasification. The syngas would need to be cooled and cleaned before being used as a fuel in a cement kiln, either in the main burner or in the calciner. The NCV of the syngas is much lower than that of natural gas (around 10MJ/Kg in comparison to natural gas at 47MJ/Kg). Cement manufacturers are however considering this route, as it would allow them to: • reduce the chlorine content in the fuel by cleaning up the syngas prior to combustion; they could then use high-chlorine wastes, which were previously not acceptable but have a better (higher) gate fee; • allow for use of alternative fuel in the main burner in very short kilns rather than in the precalciner only; • have a mixed power generator / alternative fuel syngas fuel in kiln operation; they could use part of the syngas to run reciprocating engines. Syngas from alternative fuels has been used as a fuel in clinker production since the mid-1990s at Rüddersdorf in Germany where a mix of RDF, wood and other fuels is gasified to produce a syngas[96]. The plant is still operating in 2016.	
Criteria	Rating	Notes
Net annual average energy efficiency		The pretreatment and gasification process will consume energy, but no assessment has yet been carried out as to whether this will be more energy-intensive than conventional SRF production processes. The syngas produced will be have a relatively low NCV

[95] Cembureau, April 2016.
[96] http://www.gasification-syngas.org/resources/world-gasification-database/rdersdorf-fuel-gas-plant/.

Technique title:		**Use of waste-derived syngas as fuel for cement kiln burners**
		in comparison to SRF.
Applicability		The gasification of mixed waste is unproven as a technique; only homogeneous waste streams could be used, although the technique would also allow high-chlorine wastes that are more difficult to treat
Exclusion criteria	No	None noted.
TRL	9	One commercial example has been noted.

Technique title:		**Use of hydrogen extracted from waste syngas as fuel for cement kiln burners**
Description	ECRA[97] considered the possibility of using hydrogen from syngas as a low-carbon fuel to fire cement kiln burners where the syngas was derived from fossil fuels. The same syngas could equally be derived from the gasification or pyrolysis of waste. This technology is unlikely to be adopted as there are a large number of drawbacks: • as syngas could only be used for clinker burning, CO_2 emissions originating from the energy-intensive calcination of limestone will remain unaffected; • due to its explosive properties, hydrogen cannot be used in existing cement kilns, but could be utilised after dilution with other gaseous fuels or inert gases like nitrogen or steam; • furthermore, the combustion and radiation properties of hydrogen differ significantly from those of the fuels being used today in the cement industry, meaning that - even if handling problems could be solved - the clinker burning process would have to be significantly modified and would necessitate new developments in burner and combustion technology. There are no accurate estimations of costs but, due to the aforementioned technical barriers, costs are unlikely to be irrelevant.	
Criteria	Rating	Notes
Net annual average energy efficiency		Energy efficiency is unknown due to the low TRL but it is unlikely to be better than in existing processes due to the complex syngas generation process.
Applicability		This technique cannot be retrofitted.
Exclusion criteria	Possible	The use of hydrogen may be incompatible with restrictions on dangerous substances and explosive atmospheres.
TRL	3	The technique only exists as a concept.

[97] ECRA, Development of state of the art techniques in cement manufacturing, February 2009.

4.7 Anaerobic digestion plants

This section considers anaerobic digestion (AD) processes to produce biogas from a waste feedstock.

4.7.1 Overview of anaerobic digestion

AD can be used to treat both the biodegradable fraction of mixed household MSW, typically as part of a mechanical biological treatment process (MBT), and source-segregated household and commercial organic waste which may contain animal by-product (ABP) materials such as food waste. The process is operated under controlled conditions with the anaerobic digestion taking place within sealed tanks. This is undertaken on a scale ranging from small farm-based AD plants to large industrial AD plants. The range of technology also varies from simple systems to very sophisticated and highly mechanised and automated systems.

The process has not always been deployed successfully for use in the treatment of 'black bag' mixed household MSW; emerging techniques for anaerobic digestion of the organic fraction of MSW are considered in Section 4.7.5.

Organic waste will be received at the site, inspected for compliance against waste codes and then treated to remove packaging and/or prepare it for the digestion process. Successful pretreatment systems exist for household biowaste and packaged food waste from stores. For wet AD processes, water will be added to create a slurry. The feedstock is anaerobically digested in a tank over a period of time, generating biogas. The biogas is captured and used to recover renewable electricity or heat. Following the completion of the digestion process, the digestate may be stored to allow stabilisation before being used either in liquid or dewatered form as a fertiliser or soil improver on agricultural land or for land restoration. The digestate is mechanically screened to the required size grade for final use and to remove any residual physical contamination such as plastic which was not removed at the pretreatment stage.

For a conventional AD plant, the electrical output based on the energy content of the organic feedstock is 18%[98].

A common variation on wet AD processes are dry AD processes. Dry AD processes are operated under controlled conditions with the anaerobic digestion being undertaken either in a 'tunnel' or 'box'. Due to the more capital-equipment-intensive nature of the dry AD process, it is typically undertaken at scales in excess of 25,000 tonnes per year. The process normally uses specialised machinery including shredders, and screens make the process more efficient, introduce greater process control and reduce costs through greater mechanisation. Waste is commonly fed into the digestion vessels using walking floors. The biogas and digestate produced by dry AD processes are used in the same way as for wet AD systems.

4.7.2 Energy efficiency

The energy output from an anaerobic digestion plant depends to a great extent on the biomethane potential of the feedstock. High-energy feedstocks such as glucose or kitchen waste will have much higher energy yields than feedstocks such as grass cuttings. Those organic feedstocks with the highest biomethane potential contain 10 times more energy than the lowest biomethane potential feedstocks, such as sewage sludge.

[98] ISWA CE Report 5, p. 25.

In terms of converting the available feedstock input energy into heat and power, the following characteristics distinguish a high-efficiency plant[99]:

- The overall net annual average energy efficiency of a mesophilic AD plant which operates at around 40°C will be better than that of a thermophilic AD plant which operates at higher temperatures of around 70°C, even though more biogas will be produced at higher temperatures.
- The highest waste energy utilisation can usually be obtained where the heat recovered by the combustion of the biogas can be supplied continuously to a heat consumer in combination with electricity generation. However, the adoption of this output is very dependent on plant location and the availability of a long-term user for the supplied energy.
- Where co-generation is not practical, high energy efficiency can be obtained by upgrading the biogas produced to biomethane and utilising this for transport fuels or by injecting the biomethane directly into the grid.
- From an operational point of view, the sooner that biowaste can be input into an AD plant, the better the energy yield will be as fresh matter has a higher biomethane potential.
- Basic anaerobic digestion leaves much of the energy content of the feedstock untapped. Advanced AD systems (which use a variety of techniques as described below) to extract more biomethane and residual energy from the waste will offer higher overall energy efficiency.
- Where AD digestate can be spread to land in lieu of manufactured fertilisers and the organic waste nutrient content is recycled, significant GHG savings can be made. Fertilisers derived from fossil fuel sources are energy-intensive in their manufacture and, when applied to land, emit nitrous oxide which as a greenhouse gas is almost 300 times more potent than CO_2 in its warming potential.

The range of energy efficiency (based on the organic waste energy input) in AD plants is shown below in Table 2.57[100].

Table 2.57: Net annual average efficiency of AD processes

Net annual average efficiency (%)		
Electricity only	**CHP mode (80% heat load factor)**	**Gas network / liquefaction to biofuel**
18 – 23[101]	36	> 40

Energy efficiency may be further increased by linking AD with other processes as described under emerging AD and biological techniques.

[99] EBA Interview, May 2016.

[100] ISWA CE Report 5, 2015.

[101] ISWA state an energy efficiency of 18% which applies to a typical AD food waste plant, the UK also estimates energy efficiency for a sewage sludge AD plant to be 16%. As food waste plants are more relevant to this study, the ISWA figure has been used. The upper figure reflects the most advanced AD plants such as AD with ITHP.

4.7.3 Anaerobic digestion - Proven improvement techniques

A list of proven AD techniques is provided below in Table 2.58.

Table 2.58: List of proven anaerobic digestion improvement techniques

#	Technique title
a	AD with biomethane injection to grid (gas-to-grid)
b	Sewage sludge advanced AD - THP
c	Sewage sludge advanced AD - ITHP
d	Vertical-flow dry AD
e	Micro anaerobic digestion
f	AD with liquefaction of biogas to liquefied biomethane (LBM)
g	AD with compression of biogas to compressed biomethane (CBM)

A full description of each proven AD technique and the evaluation is provided below.

4.7.4 Anaerobic digestion techniques evaluation

Technique title:	**AD with biomethane injection to grid (gas-to-grid)**	
Description	Biomethane produced from the anaerobic digestion (AD) of food waste and sewage sludge has the same composition as fossil-fuel-derived methane and therefore is suitable for use as a substitute for natural gas in a gas-to-grid network. In an AD process, micro-organisms in the feedstock break down organic waste in the absence of oxygen to produce methane-rich biogas. The biogas is upgraded to biomethane and impurities such as CO_2 and H_2S are removed by scrubbers and activated carbon filters. A small volume of propane is added to the methane, to ensure the gas has the same natural gas quality, and then fed in to the local gas distribution network. The 'upgrading' of biogas to meet quality standards necessary to permit the injection of gas into the natural gas network involves the following principal stages: • removal of hydrogen sulphide and carbon dioxide from the biogas; • enrichment using propane to meet calorific value and Wobbe Index requirements; • compression to meet network pressure requirements. A number of separation technologies exist for the removal of carbon dioxide but the most commonly used are membrane separation and 'water wash'. In 2014 the number of plants operating biomethane production stood at almost 400, with concentrations of plants in Germany, the Netherlands and Sweden. The overall energy efficiency of the AD - GtG process is 41% based on the energy content of the organic waste input versus the biomethane injected to grid[102]. The true carbon savings will depend on the final use of the gas by the consumer. The European Biogas Association predicts that GtG will be a more popular route for delivering biomethane to consumers than other more energy-intensive routes such as liquefaction and compression / trailer transport[103].	
Criteria	Rating	Notes
Net annual average energy efficiency		With the biomethane supplied to the grid, seasonal fluctuations are mostly eliminated. A net average annual energy efficiency of 41% is possible.
Applicability		It is considered that biogas plants and suitable biomethane injection points can be reasonably co-located. The biomethane can also be used in LCP applications.

[102] ISWA CE Report 5, p. 25.
[103] EBA interview, February 2016.

Technique title:		**AD with biomethane injection to grid (gas-to-grid)**
Exclusion criteria	No	None noted.
TRL	9+	There are now a large number of GtG installations across the EU.

<table>
<tr><th>Technique title:</th><th colspan="2">Sewage sludge advanced AD - THP</th></tr>
<tr><td>Description</td><td colspan="2">

The Thermal Hydrolysis Process (THP) first dewaters the incoming sludge stream to 16.5% dry solids (DS) before the dried biomass enters a pressure vessel. Steam is added to the pressure vessel at roughly 12bar, degrading the biomass before high-rate AD occurs. Conventional sewage sludge digestion achieves volatile solids destruction (VSD) of 40-50%, which yields 300-350m^3 of biogas per tonne of dry solids which translates to a 40% mass reduction.

Typical sites with the THP achieve 60% VSD and produce 450m^3 of biomass per tonne of dry solids, representing approximately a 30% increase in gross energy output. However, insufficient high-grade heat is recovered by the process through CHP to meet all the THP steam requirements, resulting in additional fuel (natural gas) being needed.

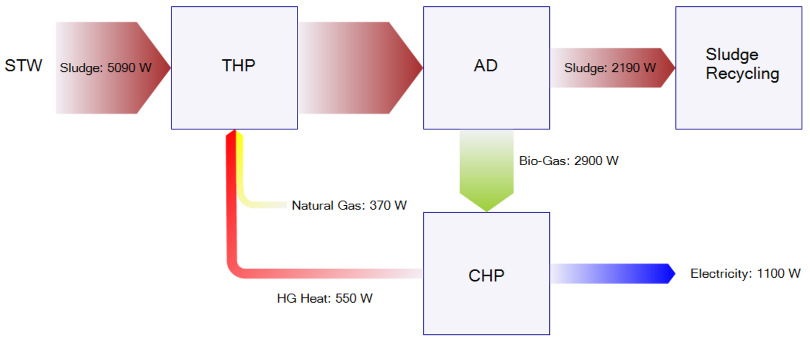
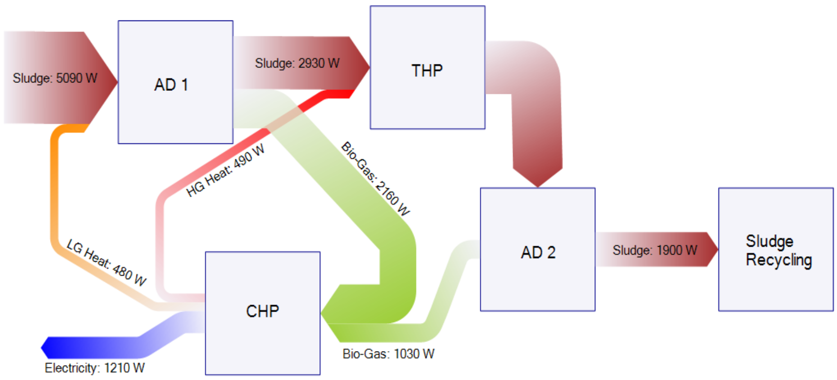


Image courtesy of DECC

There are a number of large THP plants successfully operating in Europe. The investment required for a new THP plant is significant. A number of basic AD plants have been upgraded to THP plants with commercially acceptable payback periods.

</td></tr>
<tr><td>Criteria</td><td>Rating</td><td>Notes</td></tr>
</table>

Net annual average energy efficiency		The net annual electrical efficiency is estimated at 22%[104] which is 6% higher than for conventional sewage sludge AD (16%).
Applicability		An existing sewage sludge plant can be economically upgraded to a more advanced THP facility with medium payback times.
Exclusion criteria	No	None noted.
TRL	9+	There are a large number of THP plants operating successfully across the EU.

Technique title:	**Sewage sludge advanced AD - ITHP**	
Description	The Intermediate Thermal Hydrolysis Process (ITHP) locates between two digestion stages. In the first stage of digestion, a conventional digester generates biogas and forms a residual sludge from the readily available organic matter. Digested and concentrated sludge is then hydrolysed in a plant which reduces its size. In the second-stage digester, which operates at a higher loading rate, more biogas is produced. The total biogas production of both phases is approximately 500m^3/t DS, representing an 11% improvement on the conventional THP. The final VSD is around 65%. Increased energy recovery and reduced THP size result in the process being self-sufficient in terms of heat when combined with a CHP unit.  Image courtesy of DECC There are a number of large ITHP plants successfully operating in Europe. The investment required for a new THP plant is significant. A number of basic AD plants have been upgraded to ITHP plants with commercially acceptable payback periods.	
Criteria	Rating	Notes
Net annual average		The net annual electrical efficiency is estimated at 23%[105] which is 7% higher than for conventional

[104] UK Department for Energy and Climate Change.

energy efficiency		sewage sludge AD (16%)
Applicability		An existing sewage sludge plant can be economically upgraded to a more advanced ITHP facility.
Exclusion criteria	No	None noted.
TRL	9+	There are a number of ITHP plants operating successfully across the EU.

Technique title:	**Vertical-flow dry AD**	
Description	This technique has been developed to enable a relatively wide range of organic wastes to be digested as it uses gravity to enable the flow of material through the process (as opposed to more common horizontal systems where the organic material needs to be wetter to enable it to flow through the process). Organic waste is pretreated to reduce its size to below 40mm. This enhances the quality of the end product and may reduce energy consumption and abrasion. The pretreated fraction is mixed with digested residue from the digester at a mixing ratio of typically 1 tonne of feedstock to 6-8 tonnes of digested residue. Small amounts of steam are added to raise the temperature to 35-50°C for mesophilic operation and 50-55°C for thermophilic operation. The resulting material is then pumped to the top of the digester through feeding tubes and is pushed out onto the top of the digesting mass in the digester. Once the material enters the main body of the digester, it takes a couple of days to reach the bottom, descending by gravity only. No mixing equipment or gas injection is needed in the inner part of the digester, with biogas rising and exiting through the roof, towards the gas storage and treatment. The process can operate at a total solids concentration of up to 45-50% going into the digester, with total solids concentrations of up to 45% for the digested residues. These highly concentrating operating conditions are due to the mass moving in a vertical direction. Dry AD systems with a horizontal mass through the digester require a higher level of flowability, with solids concentrations that are roughly 10-20% lower. The higher concentration of solids allows for higher biogas production rates of up to 10m^3 of biogas per m^3 of active digester volume per day. The process also requires no additional water input.	
Criteria	Rating	Notes
Net annual average energy efficiency		The vertical-flow dry AD system has a net electrical energy efficiency which is inferior to wet AD (~18%).

[105] UK Department for Energy and Climate Change.

Applicability		The main advantage of dry AD is its ability to accept a wider range of feedstocks than wet AD, such as green waste which would otherwise be composted with no energy recovery.
Exclusion criteria	No	None noted.
TRL	9+	There are a very large number of dry AD plants across the EU-28.

Technique title:	**Micro anaerobic digestion**	
Description	A containerised micro AD solution has been developed for treating organic waste which enables food waste to be processed near producers and the outputs (power, heat and digestate) to be made available. The technology is most applicable to larger commercial and municipal organisations producing kitchen food waste, used cooking oil, spent alcoholic drinks and garden waste. An 8kW combined heat and power (CHP) unit processes an average of 105 m^3/day of biogas providing approximately 57MWh of electricity per annum. Through the recovery of energy and the elimination of waste disposal costs, the unit is claimed to generate net energy revenues of around EUR 20,000 per annum.	
Criteria	Rating	Notes
Net annual average energy efficiency		The net annual average energy efficiency for an AD CHP unit is estimated at 36%[106] where 80% of the heat output is utilised annually. This would increase to 41% if the entire heat output was used, which may be possible depending on the particular installation such as a large hotel or hospital with a large constant demand for hot water, but is still much lower than for a CHP unit connected to a WI plant As the unit can be used locally, there is a reduction in the energy used to transport the feedstock and distribute the energy outputs which may be significant and therefore makes the technique somewhat more attractive.
Applicability		A degree of energy efficiency is only possible where both heat and power can be utilised by the food waste producer. This technique can be used in any location and as a containerised solution is easy to retrofit. It is restricted to organic wastes.

[106] ISWA CE report 5, p. 25 – The CHP heat output of 25% of the feedstock energy input is adjusted to 20% for annual average consumption at an 80% load factor plus the 16% net electrical power output.

Exclusion criteria	No	None noted.
TRL	9+	There are a number of examples operating around the EU-28.

Technique title:	**AD with liquefaction of biogas to liquefied biomethane (LBM)**	
Description	Prior to liquefaction, biogas generated from organic waste sources is upgraded to biomethane which involves removing the carbon dioxide and trace contaminant gases. A number of technologies can be used to remove carbon dioxide such as membrane separation, chemical scrubbing, water scrubbing and pressure swing adsorption. In liquefaction, the amount of moisture has to be carefully controlled otherwise ice will form during cooling which will block the flow of the gas produced. The resulting biomethane product (which is equivalent to natural gas) is converted to a liquid via a cooling process (normally using liquid nitrogen) and stored in large cryogenic insulated tanks prior to transportation. Due to the high capital costs, liquefaction of biomethane is only commercially viable on a relatively large scale; production of 20 tonnes/day of LBM requires roughly 1900m^3/hr from an AD plant. Liquefaction is therefore more suited to larger AD sites. An advantage of liquefaction is that the product can be effectively carried by road tanker, so there are few restrictions on the location of the biogas plant. A disadvantage is that the cooling process is energy-intensive so the energy efficiency of biogas conversion to LBM is lower than for gas-to-grid (GtG) injection (but GtG is slightly more constrained by location).	
Criteria	Rating	Notes
Net annual average energy efficiency		Although all the biogas energy output is recovered without seasonal variation, the plant's parasitic electrical consumption is high. It is estimated that liquefaction takes 10% of the waste input energy in comparison to 5% for GtG upgrading and pressurising[107]. The net annual average energy efficiency is therefore approximately 36%.
Applicability		LBM has the advantage that the plant location is wholly flexible and the liquefied biomethane can be transported by tanker to the required location for use.
Exclusion criteria	No	None noted.
TRL	9+	There are many LBM applications operating, particularly in Scandinavia.

[107] ISWA CE Report 5, Table 5.

Technique title:	**AD with compression of biogas to compressed biomethane (CBM)**	
Description	As per GtG, prior to compression, biogas generated from organic waste sources is upgraded to biomethane which involves removing the carbon dioxide and trace contaminant gases. A number of technologies can be used to remove carbon dioxide such as membrane separation, chemical scrubbing, water scrubbing and pressure swing adsorption. The resulting biomethane product (which is equivalent to natural gas) is compressed to 250bar for easier storage and distribution and can then be dispensed as CBM by: • direct supply through a dispensing station on the biogas-producing site; or • transfer to a trailer which transports the gas off site. To be commercially viable, a typically sized plant would need to produce around 10 tonnes of CBM per day. The option of an on-site filling station is likely to be dictated by the plant location. With commercial vehicles in particular, operators will not wish to make detours to refuel and dispensing stations would need to be close to main transport routes or depots. For transportation by trailer, a round trip of 100km is considered economically viable from the biogas production site to the CBM dispensing station. The amount of CBM product that can be transported in one 44-tonne truck load is quite low as the high pressures require very robust trailer construction; for a steel trailer, around 5 tonnes can be transported. For more costly carbon fibre trailers (which have a lower net weight than steel trailers), around 10 tonnes of CBM can be transported in one load. The compression process to 250 bar for transport applications is energy-intensive so the energy efficiency of biogas conversion to CBM is lower than for (lower pressure) gas-to-grid (GtG) injection (but GtG is more constrained by location).	
Criteria	Rating	Notes
Net annual average energy efficiency		All of the biogas energy output is recovered without seasonal variation. Upgrading and pressurising will require slightly more energy input than GtG as 250bar pressure has to be met rather than 10bar for grid injection. The marginal effort for the extra compression from 10bar to 250bar is not very significant however[108].
Applicability		CBM has the advantage that the plant location is completely flexible and the cooled and liquefied

[108] Ricardo Energy & Environment.

Technique title:		**AD with compression of biogas to compressed biomethane (CBM)**
		biomethane can be transported by tanker to the required location for use.
Exclusion criteria	No	None noted.
TRL	9+	There are many CBM applications operating within the EU-28.

4.7.5 Anaerobic digestion and biological techniques - Technology to watch

In addition to the proven AD techniques discussed above, there are emerging AD and biological techniques which are not currently ready for widespread deployment but have the potential to increase the energy recovered from waste in the future. These are listed in Table 2.59.

Table 2.59: List of emerging AD and biological improvement techniques

#	Technique title
a	Sewage sludge advanced AD with advanced energy recovery (gasification)
b	Sewage sludge advanced AD with advanced energy recovery (pyrolysis)
c	Enzymatic conversion of waste to biogas
d	Fermentation of packaged food waste
e	Bio-thermic digestion

A full description of each emerging AD technique and the evaluation is provided below.

4.7.6 AD and biological emerging techniques evaluation

Technique title:	**Sewage sludge advanced AD with advanced energy recovery (gasification)**	
Description	A similar process to sewage sludge advanced AD with advanced energy recovery (pyrolysis) with gasification replacing pyrolysis as the final stage of energy recovery from the sewage sludge stream (see also technique below). To sustain the conversion process, partial combustion of the syngas occurs during gasification of the dried biomass feedstock. The resulting syngas CV is lower than for pyrolysis, typically in the range of 4-8MJ/m^3 as nitrogen is introduced with air, diluting the syngas and some fuel. The gasification process is therefore not as efficient as the pyrolysis processes, with a 20% difference (reduction) in conversion efficiencies expected between the two approaches.	
Criteria	Rating	Notes
Net annual average energy efficiency		The net annual energy efficiency is estimated at 28%[109] which is 12% higher than for conventional sewage sludge AD (16%).
Applicability		An existing sewage sludge plant can be upgraded to a more advanced facility.
Exclusion criteria	No	None.
TRL	6	The concept has been demonstrated.

Technique title:	**Sewage sludge advanced AD with advanced energy recovery (pyrolysis)**
Description	A similar process to sewage sludge advanced AD with advanced energy recovery (gasification) with pyrolysis replacing gasification as the final stage of energy recovery from the sewage sludge stream. Before the pyrolysis process, a dryer produces a solid fuel feed using biomass from either a Thermal Hydrolysis Process (THP) sludge treatment process (as shown below) or an ITHP. The pyrolysis process has been shown to reduce the mass of the biomass solids by 90%, liberating a pyrolysis gas with a high CV of 11-20MJ/m^3 and leaving very little residual product for disposal. The fuel gas from the pyrolysis process is then utilised in a second gas engine (CHP2). CHP1 is a gas engine running on biogas from the AD process. Both CHP units recover heat which is split into high- and low-grade heat. The high-grade heat (200°C) is used to raise steam for THP and low-grade heat is used for sludge drying. Unlike other TH processes, there is no requirement for support fuel due to the

[109] UK Department for Energy and Climate Change.

	combination of CHP units raising all of the steam for THP. Pyrolysis shows the most potential as a form of advanced energy recovery.

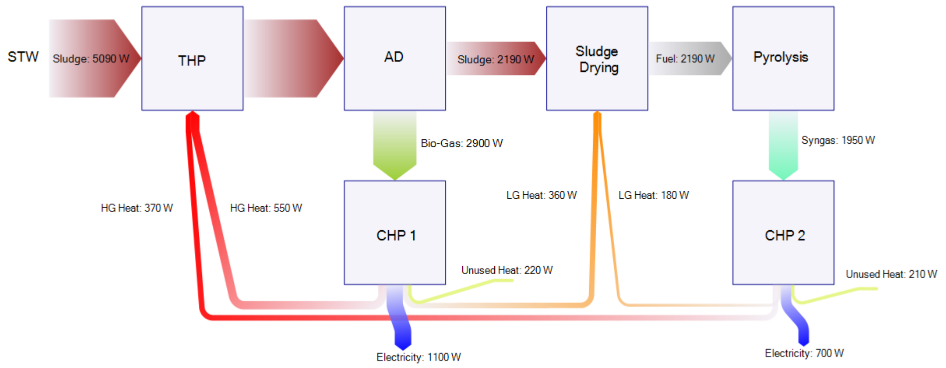


Image courtesy of DECC

Criteria	Rating	Notes
Net annual average energy efficiency		The net annual energy efficiency is estimated at 35%[110] which is 19% higher than for conventional sewage sludge AD (16%).
Applicability		An existing sewage sludge plant can be upgraded to a more advanced facility.
Exclusion criteria	No	None noted.
TRL	6	The concept has been demonstrated.

Technique title:	**Enzymatic conversion of waste to biogas**
Description	A process has been developed which involves solubilising the biodegradable organic fraction of unsorted MSW with enzymes. The resulting treated waste may then be refined to produce high-purity recyclates, RDF products as well as a bio-liquid suitable for anaerobic digestion. Anaerobic digestion of the bio-liquid produces a biogas which could then be used for energy recovery through conventional gas engines or injected to the gas network. The developer has been testing the technology at a demonstration plant since 2009 and is currently in the process of building a commercial-scale plant[111]. The net energy gain of the process may be limited as the processing system (including the various mechanical treatment steps, water treatment plant and enzyme reactor) may have significant energy requirements.

[110] UK Department for Energy and Climate Change (DECC).
[111] http://www.mrw.co.uk/news/worlds-first-bio-plant-set-for-uk/10003182.article

Criteria	Rating	Notes
Net annual average energy efficiency		This is not known, but it may be less than for conventional AD as the biogas produced needs to also power a highly complex plant.
Applicability		The process can take in a wide range of feedstocks including MSW.
Exclusion criteria	No	None noted.
TRL	8	The first commercial plant will begin operation in 2017, which will fully establish the performance of the process with actual MSW with all its inherent variations.

Technique title:	**Fermentation of packaged food waste**	
Description	Anaerobic digestion (AD) of food waste is often made more difficult by the presence of contaminants including food packaging. Large quantities of food waste are disposed of by large retailers; these are frequently sold in packaging containing plastics or aluminium, both of which are non-digestible and will either clog digesters or appear as contamination in the digestate product. Contamination in the digestate product is strictly controlled and, where limits are exceeded, application of the digestate to land will not be permitted. An alternative to AD of suitable types of food waste (particularly food waste which is not segregated from packaging) is to use fermentation[112]. The Fraunhofer Institute for Interfacial Engineering and Biotechnology in Germany has been operating a pilot plant since 2012 to develop the technique. Food waste contains a lot of water and has a very low lignocellulose content, making it highly suitable for rapid fermentation. The food waste and packaging feedstock are milled down to a maximum of 2 or 3 cm or until a pumpable slurry is formed. The slurry is fermented to release biogas from the organic fraction, and non-organics such as plastic are separated out from the residual sludge. The fermentation process takes two or three days which is a much shorter processing timeframe than AD which is typically 2 to 3 weeks. A key challenge for researchers is maintaining constant environmental conditions for the micro-organisms to perform effectively. To achieve this, a feedstock management system has been devised where food waste is held in several storage tanks, where a number of parameters are automatically calculated, including the pH value. The management system determines exactly how many litres of waste from which containers should be mixed together. In addition to using the biogas for conversion to biofuel, the contaminant fractions could be used for energy recovery and the fermentation sludge may be treated to recovery further biomethane.	
Criteria	Rating	Notes
Net annual average energy efficiency		Not known due to the low TRL.
Applicability		Fermentation offers a potential solution to some of the practical difficulties experienced with AD such as contamination. Packaging contamination is a very common issue and is problematic in terms of the digestate being allowed to be spread to land.
Exclusion criteria	No	None noted.

112 https://waste-management-world.com/a/rapid-food-waste-fermentation-developed-at-german-university.

TRL	6	The technique is at the early stages of development (pilot plant).

Technique title:	**Bio-thermic digestion (BTD)**	
Description	A process has been developed that will use extremophile bacteria harvested from deep ocean volcanos to reduce the organic content in trade and black bag waste[113]. The lowest temperature at which these bacteria will operate is 90°C. Because extremophile bacteria live in extreme conditions they are very voracious and consume the organic load very quickly. As the bacteria consume the organic load, they produce two by-products, which are heat and water. The process heat by-product helps limit the operating costs of the BTD process but some additional heat energy will need to be added. The main advantage of the technique (which is aerobic) is the much reduced digestion time (2 to 3 days). The process is designed to treat sorting residues rich in organic material from the recycling processes which may otherwise go straight to landfill. The process digests the organic content from drum fines, and removes odour, resulting in a discharge of water and an inert powdery residue. Trials in 2016 demonstrated that the organic content in the treated trommel fines was reduced by 87%. The resulting 13% residue is biologically inert and, with a dry NCV of around 12MJ/Kg, it could be utilised as a waste-derived fuel or added to biomass fuel.	
Criteria	Rating	Notes
Net annual average energy efficiency		No information is available on the net energy efficiency of the process or whether indeed biogas can be recovered as the process is aerobic. However, the higher operating temperatures would suggest the energy efficiency is lower than for conventional AD.
Applicability		BTD is a niche process for treating organic trommel fines and other organic wastes. Therefore applicability is somewhat limited in scale.
Exclusion criteria	No	None noted.
TRL	8	Some demonstration-scale trials have been completed during the past 8 years of research and a commercial-scale plant is in development.

[113] https://waste-management-world.com/a/advetec-bio-thermic-digester-to-cut-recycling-firms-costs-by-400k-pa.

4.8 Other waste-to-energy plants

This section considers other proven waste-to-energy techniques which make up the remainder of the WtE capacity in the EU-28 outside the four main pathways.

4.8.1 Overview of other waste-to-energy plants

The majority of waste is treated via one of the four pathways already examined, but there are a range of further WtE plants which treat other waste streams, often very different in nature both with regard to the used WtE technology and the input waste streams. The overview below provides a summary of the main proven techniques for those plants grouped under the common denominator 'other'.

Hazardous waste thermal treatment

Chemicals, solvents, clinical waste and other hazardous materials are commonly incinerated in high-temperature processes in accordance with IED requirements (1100°C with a minimum residence time of 2 seconds). In the case of low-NCV hazardous wastes, significant quantities of support fuel may be required to achieve this temperature. Where the waste disposal site also has a heat demand, a simple waste heat boiler is sometimes used to recover some of the thermal energy from the combustion process.

The most popular process for hazardous waste incineration is within a rotating kiln. More advanced processes for the plasma gasification of small quantities of hazardous waste are also established with around 80 reference plants worldwide. Following gasification, hazardous compounds are broken down by the intense heat of the plasma arc, with the residues trapped in a stable vitrified clinker which can be recycled.

Hazardous Waste Europe (HWE) have stated that energy recovery is considered by its sector to be of secondary importance to hazardous waste 'destruction' and, as a result, there is currently little research or development being conducted into new forms of energy conversion from hazardous waste[114].

Waste vegetable oils and fats conversion to biodiesel

There are a number of well-established processes for the conversion of waste vegetable oils and fats to biodiesel.

Used cooking oil (UCO) is composed of purified oils and fats used by restaurants, catering facilities and kitchens to cook food for human consumption. UCO is a waste that is no longer fit for purpose and can subsequently be used as a feedstock for the production of biofuels. Pretreatment of UCO is required to remove any solid matter followed by free fatty acid treatment. Transesterification then takes place, converting the UCO to short-chain alcohols suitable for the production of biodiesel. A restriction to this technique is that this form of fatty acid methyl ester (FAME) biodiesel can only be blended in small quantities with conventional biodiesel; European diesel standard EN590 restricts biodiesel content to a maximum of 7% by weight. The same technique can be used to produce biofuel from tallow (animal fats).

[114] HWE interview, April 2016.

4.8.2 Other WtE plants - Proven improvement techniques and evaluation

Technique title:	**Hydro treatment of oils and fats to produce renewable diesel (hydro-treated vegetable oil)**
Description	An alternative to the traditional FAME process for converting used cooking oil and animal fat waste streams to renewable diesel is to refine these feedstocks into renewable diesel using hydrogen. One of the benefits of biodiesel produced in this way is that it can be used directly in engines and fuel distribution systems (as a drop-in fuel, either neat (100%) or blended with fossil fuel with different ratios) as its composition is similar to fossil alternatives[115]. The hydro treatment process consists of three main process steps / reactors: 1) catalytic hydro treatment; 2) stripping; 3) isomerisation. This process is a continuous process during which the feedstock flows from one reactor to the next without intermediate storage. The reactors are fixed bed reactors specially designed to withstand the high pressure and temperatures needed for the process. Process conditions are: Pressure: min. 30 bar; Temperature: min. 265°C. Finland has also stated that over 1.6m tonnes of renewable diesel were produced in 2015 using this technique. Renewable diesel has the advantage that it provides lower NO_x emissions than conventional fossil diesel and can therefore assist with improving air quality in urban areas.

Criteria	Rating	Notes
Net annual average energy efficiency		The precise net annual energy efficiency has not been made publically available but is known to be in excess of 40%.
Applicability		The process is not location-dependent, but waste oils and fats are a relatively small waste stream. The process also utilises non-waste feedstock streams such as palm oil.
Exclusion criteria	No	
TRL	9+	There are at least five commercial-scale operational plants in Europe.

[115] Finnish Ministry of the Environment, April 2016.

4.8.3 Other WtE plants - Technology to watch

In addition to the 'other' proven WtE processes discussed above, there are emerging techniques which are not currently ready for widespread deployment but have the potential to increase the energy recovered from waste in the future. These are listed in Table 2.60.

Table 2.60: List of other emerging WtE improvement techniques

#	Technique title
Advanced thermal treatment	
a	Bubbling fluidised bed gasifier
b	Two-stage combustion
c	Two-stage combustion with plasma
d	High-efficiency CFB gasification
e	Plasma gasification
f	Direct melting systems
g	High-temperature gasification
h	Combined pyrolysis and gasification
i	Slow pyrolysis
j	Flash pyrolysis
k	Pyrolysis of waste tyres
l	Pyrolysis of paper sludge
m	Gas turbines
Waste to fuels and biofuels[116]	
a	Waste plastics to fuels
b	Fuels from MSW
c	Bioethanol from organic wastes and residues
d	Gasification with syngas methanation and conversion to biomethane
e	Direct liquefaction

4.8.3.1 Overview of other emerging WtE techniques – Advanced thermal treatment

Pyrolysis

Pyrolysis is the thermal degradation or decomposition (thermolysis) of organic materials by heat (and some inorganic materials such as tyres and plastic waste), without combustion, in either the complete absence of oxygen or where it is so limited that gasification does not occur to any appreciable extent. Conventional pyrolysis takes place at temperatures between 400 and 900°C and products include syngas, liquid and solid char. The liquid product is also known as pyrolysis oil, olefin, or bio-oil when processing biomass. Utilising pyrolysis for waste treatment is currently less well developed than gasification although there are some examples installed.

Pyrolysis is a mature technology in terms of its application to coal, peat and liquid fossil fuels, but there are examples of its application to waste-derived fuels too. There is some experience of slow pyrolysis of MSW, but this still tends to be in development

[116] The fraction of the fuel produced which can be considered 'biofuel' is dependent on the biogenic content of the waste feedstock.

stages and there are several examples of project failures. Successful examples of pyrolysis tend to be those plants using homogeneous waste streams such as tyres and wood chips and plastic waste. There are different configurations of pyrolysis equipment, including fluidised bed, moving bed and rotating cone equipment.

The design of the pyrolysis process will impact on the characteristics of the process outputs. For example, slow pyrolysis will produce charcoal, oil and gas, whereas fast pyrolysis is designed to maximise the production of pyrolysis oils in addition to the low-hydrocarbon gas that is a by-product. The pyrolysis process requires the input of energy to initiate and sustain the pyrolysis process (equivalent to 20-25% of the input energy). Whilst gasification systems can be designed to release some of the energy in the feedstock to sustain the gasification process, pyrolysis generally needs energy from an external source to sustain the process.

Gasification

Gasification is the thermal breakdown/partial oxidation of waste under a controlled oxygen atmosphere (the oxygen content is lower than necessary for combustion). The waste reacts chemically with steam or air at a high temperature (>750°C). The process is sustained by the heat recovered from the partial combustion of the feedstock. The syngas (primarily consisting of CO and H_2) produced by gasification has a lower calorific value than pyrolysis gas and is dependent upon the gasification process. The tar levels in the syngas are lower than for pyrolysis gas but depend on the actual gasification technology. Potential syngas uses are the same as for pyrolysis.

Successful examples of gasification also tend to be those plants using homogeneous waste streams such as tyres and wood chips; a large MSW gasification plant in the UK was abandoned in 2016 following over two years of effort to complete the commissioning process.

Plasma gasification

Plasma gasification is the term that applies to a range of technologies that involve the use of a plasma torch or arc. Plasma is an electrically conductive gas, such as nitrogen or argon, which is heated by an electrical current to very high temperatures. The reaction takes place within a chamber connected to a plasma torch, which is refractory-lined to withstand the high temperatures produced by the plasma torch.

The plasma torch can be applied directly to the feedstock, or to the syngas produced by a proceeding gasification process. Plasma gasification operates at temperatures as high as 7,000°C, resulting in rapid chemical reactions to break down the feedstock into gases. Inorganic materials are melted into a liquid slag, which is cooled into a solid.

The higher temperatures ensure that the syngas produced by the plasma process is cleaner than that of conventional combustion, as the higher temperatures allow for the breakdown of tars. Whilst the syngas can be used for energy utilisation, the plasma process itself has a high electric consumption. Syngas can be utilised to generate electricity via boilers, gas turbines or engines. Plasma gasification is a complex and expensive process and the technology is not considered proven yet. Significant energy input is required. Syngas cleaning is complex.

Plasma pyrolysis

Plasma pyrolysis is a process for converting high-calorific wastes, typically plastics, into a syngas by means of thermal plasma. The process uses temperatures of up to 6000°C in an oxygen-starved environment to decompose input plastic waste into a syngas, consisting of CO, H_2 and a small amount of higher hydrocarbons.

Hydrothermal carbonisation

The hydrothermal carbonisation process uses a combination of heat and pressure to chemically convert organic waste into a carbon-dense material which typically has a high energy value. The process is suitable for the pretreatment of both wet and dry biomass waste prior to energy recovery, including agricultural biowaste, municipal biowastes, waste wood, and sewage sludge.

4.8.3.2 Overview of other emerging WtE techniques - Waste to fuels

Catalytic direct liquefaction

The catalytic direct liquefaction process is one in which solid waste is converted into liquid carbohydrates in a single-stage process using catalysts. The resulting liquids have fuel-like properties and can be used as a diesel substitute.

Thermal depolymerisation

Thermal depolymerisation (TDP) is a despolymerisation process using hydrous pyrolysis for the reduction of complex organic materials (usually waste products of various sorts, often biomass and plastic) into light crude oil. Materials are subjected to high temperatures and pressure in the presence of water, resulting in a hydrous pyrolysis process. The high pressure and heat work to produce crude hydrocarbons and solid minerals which are then separated by distillation and oil refining techniques.

A full description of each other emerging WtE technique and the evaluation is provided below.

4.8.4 Other WtE emerging techniques evaluation

Advanced thermal treatment

Technique title:	**Bubbling fluidised bed gasification**	
Description	This is a gasification technology based on a bubbling fluidised bed reactor. The bubbling fluidised bed reactor enables flexibility in the types of waste that can be processed, because it achieves a better mixture between inert and combustible material due to its high heat transfer index, and because it reaches high heating speeds. Temperatures within the reactor reach in excess of 800ºC. The fluidisation air is supplied at the bottom of the reactor. The technique also uses mineral catalysts to accelerate the decomposition reactions in combustible materials, improving performance. Syngas leaves the reactor via a series of cyclones which remove particles in the gas stream. A further thermochemical treatment stage reduces the tars in the gas. The syngas gas leaves the reactor chamber at a temperature of around 600ºC and, in a second stage, part of its thermal energy is transferred to a heat recovery circuit that supplies other sections of the plant.	
Criteria	Rating	Notes
Net annual average energy efficiency		The technology is claimed to be able to deliver higher electric performance than other alternative technologies (from 26% to 34%)[117]. However, as the technology is at the demonstration scale, no independently verified data are yet available from commercial operations. Where pretreatment of mixed waste is required to produce SRF, this will require an additional energy input of approximately 1.7% of the waste input energy.
Applicability		Reasonable flexibility on waste types.
Exclusion criteria	No	None noted.
TRL	8	There are a number of small-scale (up to 5MW) demonstration plants operating throughout Europe on biomass or waste.

[117] EfW London Conference 2015, EQTEC.

<table>
<tr><th>Technique title:</th><th colspan="2">Two-stage combustion</th></tr>
<tr><td>Description</td><td colspan="2">Gasification sometimes consists of a two-stage combustion process, whereby thermal conversion is carried out in two stages:

• Stage one: gasification of waste into a syngas takes place in a primary chamber.
• Stage two: The syngas is oxidised at a high temperature in a secondary chamber.

Some of the facilities have been in operation for 10 years, but it is notable that most of the facilities are designed with relatively low steam parameters with no power output (only heat export), require waste pretreatment, and experience lower availability compared to moving-grate-fired plants.

Where power is recovered, the net electrical efficiency is around 20% which is lower than conventional combustion due to the relatively low steam conditions (20 bar, 350°C)[118]. The waste is first shredded and then fed into a primary gasification chamber, where it is used to produce a syngas.

This syngas is transferred to a secondary high-temperature oxidation chamber where it is fully combusted under tightly controlled conditions which results in very low emissions – this is the primary advantage of the technique. The resulting heat energy is used to produce steam, which can be used to supply renewable heat and/or generate renewable electricity based on the biogenic content of the waste.</td></tr>
<tr><td>Criteria</td><td>Rating</td><td>Notes</td></tr>
<tr><td rowspan="2">Net annual average energy efficiency</td><td></td><td>For power only, the electrical efficiency is lower than conventional combustion.</td></tr>
<tr><td></td><td>For heat only applications, a net annual energy efficiency of 80% is achievable and has been commercially demonstrated in Norway. The pretreatment required to make the waste suitable for gasification will require energy input.</td></tr>
<tr><td>Applicability</td><td></td><td>Independent of location, this technique is able to treat most wastes, subject to pretreatment requirements. There are higher subsidies for advanced thermal treatment in some Member States but these are subject to frequent change.</td></tr>
<tr><td>Exclusion criteria</td><td>No</td><td>None noted.</td></tr>
<tr><td>TRL</td><td>9+</td><td>There are several examples of plants across Europe. Plant performance with power export is considered much less well proven than for heat only which is considered a proven technique.</td></tr>
</table>

[118] ISWA, Alternative Waste Conversion Technologies, January 2013.

Technique title:	**Two-stage combustion with plasma**	
Description	This technique involves a two-stage combustion process which combines a gasification stage with a second plasma stage, i.e. the gasification of waste and biomass followed by the post-treatment of gasification products with plasma. Waste requires pretreatment, such as shredding and the removal of metals and inert waste, and is mixed to ensure a homogeneous fuel to optimise the process. The prepared fuel is fed into the gasification stage where it is converted to a syngas. The syngas obtained can be used for chemical applications or for electricity production.	
Criteria	Rating	Notes
Net annual average energy efficiency		The net electrical efficiency of such a system is stated as being able to reach 35-40%[119]. However, no independently verified data are available from commercial operations. Efficiency is also improved if heat is recovered. The pretreatment required to make the waste suitable for gasification will require energy input.
Applicability		Independent of location, this technique can be used on a wide range of waste streams.
Exclusion criteria	None	None noted.
TRL	8	There is a commercial-scale demonstration plant in France, with others in development.

[119] Performance analysis of RDF gasification in a two stage fluidized bed–plasma process, 2015, M. Materazzi et al.

Technique title:	**High-efficiency circulating fluidised bed gasification**	
Description	This technique is used for treating Solid Recovered Fuel (SRF). The SRF is conveyed into circulating fluidised bed (CFC) reactors. The gasifiers contain a medium such as hot sand and limestone that is fluidised with air blown from the bottom of the gasifier. The SRF is mixed with the fluidised bed at a temperature of 900°C. The fuel will not burn as there is insufficient oxygen, but instead is broken down into a gas. The hot gases rise to the top of the gasifier and then into a cooling system where the gas temperature falls to 400°C. The resulting gas is treated to remove corrosive alkali, heavy metal chlorides and sulphur compounds so that it can be considered equal to natural gas in terms of its purity and can be used in a boiler or other recovery applications. Efficient gas cleaning results in reduced levels of corrosion in the boiler. Therefore, the steam temperature and pressure are high and can provide highly efficient electricity generation. As well as stand-alone waste plants, the system also offers the potential to convert or co-fire fossil-fuel-powered boilers, if the syngas produced has end-of-waste status. Co-firing of gas from biomass/waste has been demonstrated to replace up to 40% of the coal energy input but 100% gas firing can be reached, as is done in new stand-alone plants.	
Criteria	Rating	Notes
Net annual average energy efficiency		If heat and power are recovered, an overall energy efficiency of 90% can be achieved. In power-only mode, electrical efficiency will also be high. Where pretreatment of mixed waste is required to produce SRF, this will require an additional energy input of approximately 1.7% of the waste input energy.
Applicability		High – the technique can be used as a stand-alone waste plant and to convert / co-fire fossil-fuel-fired boilers.
Exclusion criteria	No	None noted.
TRL	9+	Commercial-scale facilities are in operation.

Technique title:	**Plasma gasification**	
Description	Plasma gasification technology can be used to convert a wide range of waste streams in to syngas, including municipal solid waste, hazardous wastes and sewage sludge. Plasma gas is created by combining electricity and air to form a plasma torch. The process typically combines gasification and plasma technologies. The plasma gas reaches very high temperatures, 5000-8000°C, and is then directed into a gasifier chamber. The gasifier is starved of oxygen, and so, instead of combusting, heat from the plasma breaks the feedstock down into elements like hydrogen and simple compounds like carbon monoxide and water. The organic components from the waste are converted into syngas while the inorganic components such as glass/ metals are melted and converted into an inert slag which may be sold as an aggregate. The quantities of slag and syngas cleaning residues produced are dependent upon the input waste composition. The syngas produced in the plasma gasification process can be converted into electricity using gas turbines or reciprocating engines, heat and steam, and liquid fuels. In most cases, and when MSW is the feedstock, syngas clean-up will include the removal of particulates, acid gases and heavy metals.	
Criteria	Rating	Notes
Net annual average energy efficiency		The technique is claimed to be able to achieve between 25% and 33% net electrical efficiency. The pretreatment required to make the waste suitable for gasification will require some energy input. However, no independently verified data are available from commercial operations. ISWA[120] estimated that the overall net electrical efficiency is below 20%.
Applicability		There is some flexibility on waste types, subject to pretreatment. Application to MSW has not been proven.
Exclusion criteria	No	None.
TRL	8	Technology has historically been used for the destruction of hazardous wastes. However, there are a number of small-scale commercial plants in Europe which are used for energy recovery. A developer has recently reported to have abandoned the commissioning of a large plasma gasification facility with significant financial losses.

[120] ISWA, Alternative Waste Conversion Technologies, January 2013.

Technique title:	**Direct melting systems**	
Description	The direct melting system (DMS) will typically consist of a waste charging system, a gasifier, a combustion chamber, a boiler and a flue-gas cleaning system. One of the reported advantages of the DMS process is that no pretreatment of waste is required, unlike in other gasification technologies, such as a fluidised bed gasifier. The high-temperature gasification means that the technology is suited to a variety of wastes. The principle of the process is the treatment of waste in a fixed bed gasifier. Coke or limestone is added at 5-10%. Waste is loaded from above, together with the coke. The combustion in the lower part of the furnace (300-400°C) provides the energy for the subsequent gasification. Thermal decomposition takes place at 300-1000°C. Combustion occurs at 1000-1700°C, with melting finally taking place in the melting zone at 1700-1800°C. The syngas is drawn off at the top of the reactor, and is typically combusted in a separate combustion chamber and power generated in a steam turbine.	
Criteria	Rating	Notes
Net annual average energy efficiency		The addition of support fuel is also required in some cases, otherwise pretreatment of the waste is required to make it suitable for gasification; this will require energy input. The gross efficiency of the plant is 23%, at 400°C and 40 bar, and the net efficiency is estimated to be well below 20%[121].
Applicability		No pretreatment of waste is required with some forms of direct melting systems, and it is not considered to be location-dependent.
Exclusion criteria	No	None noted.
TRL	9	There are a large number of direct melting plants in Japan and Korea so the technique is well proven. Much progress has been made on improving energy efficiency but it is still lower than conventional combustion. However, there are as yet no direct melting plants operating in the EU, so some aspects of performance are still to be proven.

[121] ISWA, Alternative Waste Conversion Technologies, January 2013.

Technique title:	**High-temperature gasification**	
Description	High-temperature gasification occurs at a temperature of up to 2,000°C. The high gasification temperature is achieved by partial combustion with the addition of pure oxygen and natural gas. Metals and most minerals melt at this temperature and are quenched in water. The solidified iron is recycled, while the mineral fraction is used as synthetic gravel. The heat energy in the hot syngas is quenched away, and therefore lost, in a water bath and then passed through a scrubber-based gas cleaning system. The syngas produced is primarily used as the syngas in a steam boiler and, to a minor extent, as input for gas engines. The main reason for the limited usage in a gas engine is due to the significant costs of cleaning the syngas to a quality suitable for gas engines.	
Criteria	Rating	Notes
Net annual average energy efficiency		Limited operational data are available but ISWA estimated the net energy efficiency at below 20%[122].
Applicability		Advantage for use is vitrification as opposed to recovery of energy from waste. The technique is not commercially or technically proven in Europe.
Exclusion criteria	Yes	Reported high costs and technical challenges.
TRL	8	Widely demonstrated in Japan, but waste destruction and not energy recovery is the main priority, for example some plants are used to vitrify slag from WtE facilities. A developer abandoned the operation of a large facility in Germany in 2010 after 5 years of difficult operation with significant financial losses.

[122] ISWA, Alternative Waste Conversion Technologies, January 2013.

Technique title:	**Combined pyrolysis and gasification**	
Description	This technique uses a combination of pyrolysis and gasification to process a refuse-derived fuel (RDF)[123]. The RDF is first conveyed into a pyrolysis reactor, where, in the absence of oxygen, the RDF is heated and converted to a syngas and a carbon-rich char. The char is fed into a gasification reactor where it is heated using high-temperature steam with the controlled addition of oxygen. This converts the char into further gases. The gases from both the pyrolysis and gasification processes are combined. The high-temperature gas can be used to provide heat to the pyrolysis stage and to a conventional steam boiler. Some processes have been designed to accept a wide range of wastes from various processes, including MSW, auto shredder residue, industrial waste, medical waste, electronic waste, and oil and sewage sludge.	
Criteria	Rating	Notes
Net annual average energy efficiency		No operational data available to determine this. The pretreatment required to make the waste suitable for the process will require energy input.
Applicability		Reasonable flexibility on waste types, subject to pretreatment. The technique is modular and scalable.
Exclusion criteria	No	None noted.
TRL	9	This technology is being used in several fully operational plants on a commercial scale. However, it has been reported that the facilities using variations of this technique have all experienced operating difficulties.

[123] IEA Task 36 UK Workshop EfW Next Generation, 2014.

Technique title:	**Slow pyrolysis**	
Description	A criteria used to distinguish between different types of pyrolysis is the residence time of gas within the reactor. Slow pyrolysis takes place at medium to high temperatures and the longer residence times allow for the composition of liquid or solid reaction products. Char production through slow pyrolysis of waste wood and other biomass has been demonstrated. Finely diced waste is pyrolysed in either in a screw conveyor or reactor vessel that is indirectly heated. The slower heating rate favours char and liquid production over gas. The properties of the reaction products will depend on the waste composition. Processes taking a waste feedstock are considered unlikely to produce a solid char product, but instead to use char to recover additional energy for parasitic supply (e.g. for heat to dry waste) or dispose of char residue to landfill.	
Criteria	Rating	Notes
Net annual average energy efficiency		Limited operational data available to determine this.
Applicability		Mainly applicable to wood waste and other forms of biomass.
Exclusion criteria	Yes	Limited examples available.
TRL	6	The slow pyrolysis process is innovative in its conversion of the char for use in agriculture but is currently at the early stages of development.

Technique title:	**Flash pyrolysis**
Description	A criteria used to distinguish between different types of pyrolysis is the residence time of gas within the reactor. When input materials are rapidly heated, the process is called flash (or fast) pyrolysis. A higher yield of liquid products can be achieved, particularly where lower temperatures are used. Waste is injected into a fluidised bed of inert material operating at 500°C. The surface size of the spread fuel and the heat transfer characteristics of the fluidised bed ensure a very fast heating rate which maximises the production of vapour. The vapour is subsequently condensed as a liquid that contains approximately 70% of the energy value of the waste feedstock. The by-product char and gas are used in part to provide heat to drive the process. The liquid fuel has been successfully used to fire boilers and kilns. Trials have been undertaken in reciprocating engines and gas turbines. Excess char can be sold as a product for activated carbon manufacture or as a reducing agent in metal production. The

Technique title:	**Flash pyrolysis**	
	char can also be used as fuel either on its own or as a slurry with the pyrolysis liquids. The main use for fast pyrolysis processes at present is the manufacture of speciality chemicals and food additives although this is expected to change to energy use when further plants are developed. Other fuels include whole tree woodchips from short-rotation coppice, wood waste, and agricultural residues such as straw.	
Criteria	Rating	Notes
Net annual average energy efficiency		There is limited operational data available with which to confirm energy efficiency.
Applicability		The technique is mainly applicable to wood waste and other forms of biomass.
Exclusion criteria	Yes	Limited examples available.
TRL	5	Flash pyrolysis of waste has been in development for several decades at the laboratory scale but has not progressed.

Technique title:	**Pyrolysis of waste tyres**	
Description	A number of facilities have been developed for the pyrolysis of waste tyres[124]. Pyrolysis of tyres generates pyrolysis oil, char and syngas. The pyrolysis oil can be further processed into a fuel oil, and the syngas can be combusted to generate heat and/or power. The char can be recycled into carbon black which is a raw material in tyre production. However, there are challenges in achieving the quality requirements for the pyrolysis char to be able be used as a carbon black material in the manufacture of new tyres. The economics of some of these plants have not proved attractive and many have closed after 5 to 7 years of operation. There are currently only a few waste tyre pyrolysis plants in operation on an industrial scale in Europe. There are also plants in Japan. The technology pyrolyses rubber granules from tyres in the absence of oxygen at temperatures between 350-700°C. The technique developer claims that the residual carbon black char meets the highest quality standards and does not contain toxic or carcinogenic components in any significant concentration.	
Criteria	Rating	Notes
Net annual average energy efficiency		There is limited operational data available with which to confirm energy efficiency.

[124] ERTMA, 2016

Technique title:	**Pyrolysis of waste tyres**	
Applicability		This technique is specific to waste tyres only.
Exclusion criteria	No	None noted.
TRL	9	Although the process is well understood, the results have not been as expected, particularly with regard to recycling of the char as a raw material in tyre manufacture.

Technique title:	**Pyrolysis of paper sludge**	
Description	High-temperature pyrolysis is being developed to pyrolyse paper sludge to produce second generation biofuels and minerals including calcium carbonate and kaolinite. The technology is currently at the pilot scale. With a homogeneous feedstock, the pyrolysis process may be more successful than for other feedstocks trialled[125].	
Criteria	Rating	Notes
Net annual average energy efficiency		The net annual average energy efficiency is unknown due to the technique being at the early stages of development.
Applicability		Applicable to paper sludge only.
Exclusion criteria	No	None noted.
TRL	6	The process has been demonstrated on a very small scale.

Technique title:	**Gas turbines**
Description	In an Integrated Gasification Combined Cycle (IGCC) process, syngas can be combusted in gas turbines to generate electricity. Gas turbines used for this process are similar to natural gas combined-cycle gas turbines but will have been specially adapted for use with syngas. This is primarily due to the higher levels of hydrogen found in syngas. In an IGCC power plant, the gasification process will typically consist of one or more gas turbines and a steam turbine. The cleaned and conditioned syngas will be combusted in the gas turbine to generate electricity, with excess heat from the gas turbine being used as steam in a steam turbine to generate further power. There are examples of gas turbines being used with syngas, but work is ongoing to further develop this technology.

[125] CEPI, interview February 2016.

Technique title:	**Gas turbines**	
Criteria	Rating	Notes
Net annual average energy efficiency		The gas turbine could in theory provide higher energy efficiency than a steam turbine, but so far it has not been proven to work on syngas.
Applicability		There is potential for this technique to be retrofitted in some instances, but the quality and cleanliness of the syngas used will be critical to its successful operation.
Exclusion criteria	No	None noted.
TRL	8	The use of gas turbines for syngas has been demonstrated on a commercial basis but development is ongoing.

Waste to fuels and biofuels

Technique title:	**Waste plastics to fuels**	
Description	Pyrolysis technologies are being applied for the conversion of non-recyclable waste plastics into liquid hydrocarbon fuels. The technology effectively reverses the plastics production process, where hydrocarbons are used to create plastics. Instead, the process cracks the hydrocarbon chains within the plastics, to produce distilled fuels. The feedstock first needs to be chipped to produce a plastic flake. The material also needs to be washed to remove impurities, and then dried to remove moisture. The flakes are fed into a pyrolysis reaction chamber, in the absence of oxygen. The pyrolysis gases are then condensed into a distillate which is further refined into diesel-based products. Many plants in the EU and elsewhere are still operating at the demonstration scale only but there is at least one plant in Spain which is operating on a commercial scale and may be able to demonstrate a TRL of 9. PVC and PET plastics are difficult polymers for plastics-to-fuels plants to process; PVC causes corrosion (and can give rise to dioxin formation when heated) and PET plastic does not readily liquefy. However, the amount of PVC in mixed plastics waste streams is small and most PET (drinks bottles etc.) has value and is able to be recycled. The most effective plastics-to-fuel processes will be those that can deal with both PVC and PET and therefore do not require residual non-recyclable plastics to be extensively sorted prior to treatment.	
Criteria	Rating	Notes
Net annual average energy efficiency		Limited operational data are available, however the pyrolysis process will require heat input and the process plant will have a parasitic load. One developer of this type of process estimates that approximately 85% of the plastic energy content can be converted into useful fuel products. However, due to the early stage of development, this cannot be independently verified through commercial operation.
Applicability		The technique requires the separation of non-recyclable plastics from mixed waste streams. Commercial considerations mean that this can be a significant waste stream.
Exclusion criteria	Possible	This technique could be seen as preventing increased recycling of plastics. As the plastic feedstock is fossil-fuel-derived (with no biogenic content) the fuel will not be eligible for support under the Renewable Energy Directive or support implemented nationally by Member States. This policy may hold back the development of this technology.

Technique title:	**Waste plastics to fuels**	
		The UK is of the view that 'End of waste' (EoW) issues and compliance with the REACH Directive (where EoW status is granted) are potential barriers to implementation[126]. Other stakeholders are of the opinion that this is not an issue – this study can only conclude that more research is needed on this emerging topic.
TRL	7	The companies developing these processes are currently at the demonstration plant stage or have very small commercial plants. Commercial-scale plants are being developed from demonstration plant experience where the developers are resolving practical difficulties in scaling up production.

Technique title:	**Fuels from MSW**	
Description	There are a number of processes being developed which convert MSW to fuels and potentially other commodity chemicals[127]. The biofuel content of the fuel produced will be based on the biogenic content of the MSW input. An example of this is the conversion of pretreated waste to a syngas, which is subsequently then converted into fuels and commodity chemicals, using commercially available catalysts. The process will typically consist of feedstock preparation, gasification, cleaning and conditioning of the syngas, and finally synthesis of the syngas in the products, which can include methanol and ethanol. The process used for synthesis is a combination of chemical reactions which is used to convert syngas into liquid hydrocarbons. The syngas produced can also be used in boilers and engines or turbines. In addition to using syngas, products from gasification can be used in other applications. Syngas can be used to synthesise a range of liquid hydrocarbons including distillate fuels (including diesel fuel and kerosene), alcohols (methanol and ethanol) and fertilisers (ammonia).	
Criteria	Rating	Notes
Net annual average energy efficiency		There is no commercial data available to verify the performance claims from the developers, but some processes have been able to provide data which indicate that between 40% and 50% of the waste input energy can be converted into biofuels. The pretreatment required to make the waste suitable for gasification will require energy input.

[126] Feedback from the UK to the WtE background document, April 2016.
[127] London EfW Conference 2015, Enerkem.

Technique title:	**Fuels from MSW**	
Applicability		There is a reasonable flexibility on waste types (including MSW), dependent on effective pretreatment.
Exclusion criteria	No	None noted.
TRL	8	There are some commercial-scale process demonstration examples, with more in development.

Technique title:	**Bioethanol from organic wastes and residues**	
Description	A range of processes have been developed in Finland to produce bioethanol from second generation feedstock such as food industry process residues, household biowaste, cellulosic residues and waste[128]. The technique has been developed to enable cost-effective ethanol production by fermentation in distributed small plants so that the production plants can be built near the "source of waste" (e.g. brewery, enzyme production), which minimises the transport costs and emissions. The main product is bioethanol, which is used in high-blend ethanol fuels and as a bio-component in low-blend petrol. Other useful by-products obtained are: animal feed, fertilisers, chemicals, lignin, electricity and/or heat, and biogas. The precise nature of the by-products depends on raw material used.	
Criteria	Rating	Notes
Net annual average energy efficiency		The energy efficiency of the process is unknown but, to produce biofuels which are compliant with the Renewable Energy Directive, the process energy efficiency is likely to be high.
Applicability		The process is highly rated in terms of its ability to be co-located with waste production sites, but the waste stream quantities will still be relatively small and disaggregated.
Exclusion criteria	No	None noted.
TRL	9	Currently there are five operational plants in Finland. The sum of the production capacities of these five plants is 15 million litres of bioethanol per year. A new plant producing bioethanol from sawdust is under construction and should be started in 2016. This will increase the production capacity by 10 million litres.

[128] Finnish Ministry of the Environment.

Technique title:	**Gasification with syngas methanation and conversion to biomethane**	
Description	This technique is currently being developed to produce a syngas which is free from intractable levels of tar which can subsequently be treated by conventional technologies to allow its methanation. The biomethane produced by the process can be injected to the grid or used as a transport fuel[129]. The biofuel content of the methane produced will be based on the biogenic content of the waste input. The waste feedstock needs to be prepared to provide a homogeneous material such as SRF. Methanation requires the syngas to be free of contaminants, notably of condensed hydrocarbons, heavy metals, sulphur and halogens. The technology utilises a gasifier and plasma converter close-coupled to produce a suitably clean syngas reformed from the contaminants, allowing constituent sulphur and halogens to be removed by conventional techniques as well as heavy metals. The technology has been tested on a range of mixed and organic waste feedstocks. Key performance indicators were a carbon conversion efficiency of near to 100%, with cold gas conversion efficiencies of 75-90% depending on the feedstock. Depending on the feedstock, the gas' calorific value was 7-14MJ/Nm^3 with the system producing a consistent syngas. Measured tar levels by mass were below 0.05%, sulphur compounds below 0.02% and nitrogen compounds below 0.2%. Heavy metals contamination was below 6 parts per billion by mass. The syngas methanation process is well established with the technology using a combined high-temperature water-gas shift using an iron catalyst with methanation using a nickel catalyst. A by-product of the methanation process is CO_2 which is produced in large quantities. This CO_2 by-product would need to be utilised in order to achieve the desired GHG emission reduction level.	
Criteria	Rating	Notes
Net annual average energy efficiency	(green)	There is no commercial data available to verify the claimed performance, but data has been provided by the developer which indicates that the process net energy efficiency will be between 40% and 50%. The pretreatment required to make the waste suitable for gasification will require energy input.
Applicability	(amber)	The process has the potential to use a wide range of feedstocks but extensive pretreatment is required to achieve sufficient homogeneity.
Exclusion criteria	No	None noted.
TRL	6	The technique is not yet operating commercially, but a demonstration-scale plant is currently being developed.

[129] UK Department for Transport.

Technique title:	**Direct liquefaction**	
Description	This technique involves liquefying high-molecular substances of an organic origin. It is a single-stage process (direct liquefaction) that differs from other processes in that the liquid energy carriers are derived not as distillate but by means of Fischer-Tropsch synthesis subsequent to gasification/carbonisation. Unlike other methods of direct liquefaction, the process does not require high pressure, high temperature or the addition of hydrogen. The process results in distillates which can be used as a fuel or as a material for further processing.	
Criteria	Rating	Notes
Net annual average energy efficiency		The net annual average energy efficiency is not known.
Applicability		The technique is only applicable to pretreated waste, i.e. refuse-derived fuels.
Exclusion criteria	No	None noted.
TRL	6	The technique is only implemented in demonstration plants.

4.9 Detailed analysis of selected techniques

The following techniques have been selected for a more detailed analysis based on the net annual average energy efficiency and applicability evaluation. The techniques with the best evaluation outcomes (i.e. more greens or ambers) have been selected below and at least one technique has been selected for each pathway group. These are mostly proven techniques; the emerging techniques analysed are marked as (E).

Combustion plants

1 High-efficiency circulating fluidised bed gasification and co-firing of syngas in the combustion plant

2 Feeding of secondary fuels into a fluidised bed combustion plant

Waste incineration plants

3 High steam parameters for boilers and superheaters

4 Flue-gas condensation and component cooling

5 Heat pumps

6 District cooling (100% load)

7 4th generation heat networks

Cement and lime plants

8 Conversion of waste heat to power in cement kiln applications

Anaerobic digestion

9 Sewage sludge advanced AD - Thermal Hydrolysis Process (THP)

10 AD with biogas injection to grid (GtG)

11 Sewage sludge advanced AD with advanced energy recovery (Pyrolysis) (E)

Other WtE plants

12 Biodiesel from hydro treatment of waste edible oils and fats

13 Two-stage combustion with plasma (E)

14 Fuels from MSW (E)

Combustion plants

	Title: **High-efficiency circulating fluidised bed gasification and co-firing of syngas in the combustion plant - Item 1**
1	***Technical description*** This technique is used for generating electricity from Solid Recovered Fuel (SRF). SRF is materials produced from a mechanical waste treatment process, where metals, compostable waste and other materials are separated from the waste stream for material recovery. No other treatment is needed for the material before it is used as a fuel in the circulating fluidised bed gasification process. The SRF is conveyed into circulating fluidised bed (CFB) reactor. The gasifiers contain a medium such as hot sand and limestone that is fluidised with air blown from the bottom of the gasifier. The SRF is mixed with the fluidised bed at a temperature of 900°C. The fuel will not burn as there is insufficient oxygen, but instead is broken down into a syngas. The hot gases rise to the top of the gasifier and then through a cyclone, after which they leave the reactor into a cooling system where the gas temperature falls to around 400°C. At this lower temperature, impurities in the gas, such as alkali chlorides, Pb and Zn, turn to a solid form and can be removed in a filter system operating at that temperature. Ceramic filters within the cooling chambers will collect unwanted particles, whilst allowing the gas to flow through. A nitrogen pulse will regularly eject collected dust, which falls to the chamber floor for removal. The resulting gas is clean following the removal of corrosive components and therefore it is possible to achieve efficient energy recovery as electricity by using high steam temperature and pressure. If both heat and power are recovered, an overall energy efficiency of 90% can be achieved. In power-only mode, electrical efficiency will also be high (30% +). By using reheating in the boiler/steam cycle it may be possible to further improve electrical efficiency to close to 35% net, even when the electricity consumed in the pretreatment and sorting required to make the waste suitable for gasification are taken into account. The pretreatment and sorting required to make the waste suitable for gasification will require energy input. As well as stand-alone waste plants, the technique also offers the potential to convert or co-fire fossil-fuel-powered boilers. This technique will be most feasible if the syngas produced has end-of-waste status; otherwise a waste incineration permit is needed for both the gasifier and for the existing boiler. Co-firing of gas from biomass/waste could replace up to 40% of coal energy input but 100% gas firing can be reached in new stand-alone plants. The gas resulting from the CFB gasifier and gas cleaning is injected into the existing combustion plant boiler where it is co-fired with coal to generate steam and power through a turbo generator set. Due to the efficient gas cleaning process, there are few impurities to cause corrosion in the combustion plant boiler. Therefore, the steam operating temperature and pressure are high, as is the resulting electricity generation - and can provide efficient electricity generation. Typically this will be between 36% and 40% for a coal combustion plant.
2	***Costs*** The capex for a 250,000 t/yr stand-alone plant utilising this technique is estimated at EUR 240-260 million, which is comparable to a conventional incineration plant of a similar capacity. It is likely that the capex associated with this technique will be reduced further as follow-on plants benefit from the learning and experience gained with the first

	Title: **High-efficiency circulating fluidised bed gasification and co-firing of syngas in the combustion plant - Item 1**
	commercial plants. The conversion of old plants will result in a capex of 30-40% of a similar size new incineration plant. This is due to the fact that a major part of the existing infrastructure (boiler, turbogenerator and balance of plant equipment) can be reused. There is no publicly available data on the technique's opex costs.
3	***Achieved economic benefits*** The direct displacement of coal in existing power stations by a syngas generated from waste can be an attractive environmental and economic option.
4	***Operational data*** A co-firing gasification plant, Kymijärvi I, is operated in Lahti, Finland, where refuse-derived fuel and biomass are gasified and the resulting syngas co-fired in an existing coal-fired plant to recover power and heat for the city. [1] The plant entered operation in 1998, and includes a 60 MWth fluidised bed gasifier. The technique developer has also recently published updated operational data for its stand-alone demonstration plant at Kymijärvi. This plant is operated on waste (e.g. SRF and wood waste) only, and was developed to commercially demonstrate the high efficiencies that can be achieved. This facility has been operating successfully for over three years, with a reported net electrical efficiency of 30%; the developer plans to increase this efficiency further in the next generation of plants. It is also reported that the operation of a high-temperature steam boiler on waste-derived syngas is achievable without significant corrosion. The plant has operated for more than 25,000 hours since its commissioning in 2012 [3]. In 2014, the plant reported [4]: <table><tr><td>Operational hours</td><td>6967</td></tr><tr><td>Availability</td><td>88.8%</td></tr><tr><td>Electricity</td><td>241 GWh</td></tr><tr><td>District heating</td><td>514 GWh</td></tr></table>
5	***Environmental and/or human health benefits and drawbacks*** The reported high energy efficiency and displacement of fossil fuels have clear environmental and carbon reduction benefits.
6	***Technical considerations relevant to applicability*** The technique can be used in the form of a stand-alone installation or can be applied to convert / co-fire fossil-fuel-fired boilers. It therefore has wide applicability. The gas quality enables the gas to be co-fired in existing boilers, therefore there is potential for retrofitting this technique with minimum boiler alterations across EU Member States. Existing fossil fuel power plant infrastructure can be utilised. Effective gas cleaning can ensure that corrosive and harmful compounds are removed from the gases, enabling the syngas to potentially have a wider number of uses beyond combustion.

	***Title:* High-efficiency circulating fluidised bed gasification and co-firing of syngas in the combustion plant - Item 1**
7	***Driving forces or barriers for implementation including feedstock availability*** Drivers: • Higher efficiencies can be achieved by avoiding or minimising corrosion-related issues in conventional waste-fired boilers. Corrosion in the boiler will limit the temperature of the steam, therefore reducing the efficiency of energy recovery as electricity. Converting the waste into a gas, which is subsequently cleaned and upgraded prior to use in a boiler, can limit corrosion, and thereby increase efficiency. Barriers: • For co-firing of syngas in a combustion plant, the facility will need to be compliant with the Industrial Emissions Directive (formerly the Waste Incineration Directive) or be able to demonstrate that end-of-waste status has been achieved. Operators of combustion plants may not wish to pursue either option. • The age, condition and regulatory issues could present a barrier for the conversion of some combustion plants to co-fire syngas.
8	***Residual risks*** As indicated above, it may not be possible for a wide number of existing combustion plant facilities to be converted. There are other competing uses of SRF which can be run directly and without gasification, i.e. in cement kilns.
9	***Example plants or TRL*** In addition to the facilities named above, a further example includes a 30MW waste wood gasifier in Amercentrale, Holland which was supplied and commissioned in 2000. The syngas is used as a coal replacement in the original coal-fired boiler.

TRL		9	Commercial-scale facilities are in operation.

10 ***References***

	Reference	**Strength of Evidence**
[1]	Valmet Gasification of Waste Technology Review, Fichtner Consulting Engineers, 2015	80%
[2]	Valmet	80%
[3]	https://waste-management-world.com/a/all-good-as-140-mw-finnish-waste-gasification-plant-passes-25-000-hours	70%
[4]	Kymijärvi II Waste Gasification Power Plant, published by Valmet.	90%

	Title: Feeding of secondary fuels into a fluidised bed combustion plant - Item 2
1	***Technical description*** This technique description is focused on the partial substitution of biomass by SRF in biomass-fired fluidised bed combustion plants. However, other combinations of primary and secondary fuel combustion in a fluidised bed combustion plant (such as coal and sewage sludge) are also possible. There are a number of operational biomass co-incineration plants which in some cases are able to successfully increase the ratio of SRF co-firing to over 50% (whereas waste substitution ratios in coal-fired plants are much more restricted). For co-firing in a fluidised bed boiler, it has been demonstrated that careful feeding of the primary and secondary fuels is one of the most important factors for good operation. One of the benefits of SRF co-incineration is that some biomass fuel sources are of relatively low quality with a high moisture content of up to 60%. This can result in a low net calorific value (NCV) fuel typically between 5 and 15 MJ/kg. SRF is a fast-burning material and has a high NCV typically of between 15 and 25 MJ/kg and an oxygen content of close to zero. CO_2 emission factors are ~25% lower than that of coal. Thus, SRF can operate as a support fuel to biomass, assisting in ignition and supporting a more stable combustion and better burning of low-grade biomass. In a modern biomass fluidised bed combustion plant, the net annual average electrical efficiency will be around 28% to 30%. In older plant designs, the net electrical efficiency will be nearer to 20%. Energy input will also be required to sort and pretreat the waste feedstock to provide a suitable SRF.
2	***Costs*** To co-fire SRF, a number of modifications would be required to the combustion plant. These include: • storage of the waste feedstock; • a suitable system to screen out or crush unsuitable particles of waste in the SRF; • a system to either mix the waste with primary fuel prior to combustion or a separate feed system for the waste; and • there may be a requirement for enhanced abatement measures to control emissions from the SRF fraction of the fuel. Costs would be dependent on the scale of the combustion plant being considered for co-firing. There would also be administrative costs associated with the process of obtaining an environmental permit to co-fire waste and maintaining IED compliance through annual testing and certification.
3	***Achieved economic benefits*** The key economic benefit of this technique is to replace biomass which would be supplied at a cost to the combustion plant of approximately EUR 154 per tonne [1] with SRF which could provide a revenue to the combustion plant. A gate fee of around EUR 60 per tonne may be charged for SRF depending on the composition of the fuel.

	Title: Feeding of secondary fuels into a fluidised bed combustion plant - Item 2
4	***Operational data*** Operations have shown that correct mixing of the primary and secondary fuels is key to operational success in a fluidised bed boiler. Fuels should either be thoroughly mixed before being fed into the boiler or a separate feeding system should be used which can be carefully controlled; although SRF is reasonably homogeneous (as a prepared fuel), it is still a waste and subject to more variation than a primary fuel. Therefore the in-feed of the SRF needs careful monitoring, where unwanted material can be removed quickly. Early trials in Finland raised some issues with chemical interactions between compounds in biomass and SRF which gave rise to boiler fouling, but these are now reported to be resolved [2].
5	***Environmental and/or human health benefits and drawbacks*** The substitution of biomass with SRF may help avoid sustainability issues associated with the consumption of virgin biomass. SRF incineration needs to be performed in compliance with the IED to minimise the impact on the environment; any co-incineration activity needs to be monitored by the relevant national authority. Extensive pretreatment of waste is required to manufacture high-quality SRF. If the SRF used has a high fossil fuel content (for example a high plastics content), it will provide reduced benefits in terms of GHG emissions savings compared to biomass. SRF will need to be stored such that no deleterious effects from odour or leachate are observed.
6	***Technical considerations relevant to applicability*** SRF and biomass co-firing has been proven at ratios of up to 50:50. [3]
7	***Driving forces or barriers for implementation including feedstock availability*** Drivers: • The key driver for this technique is cost reduction for combustion plants, where a gate fee can be charged for SRF. Barriers: • Any combustion plants co-firing waste need to be permitted and be IED-compliant. Feedstock availability: • Task 1 has shown that feedstock availability is high where HSW, sorting residues and mixed wastes can all be processed to manufacture SRF.
8	***Residual risks*** The technique has been commercially proven in many plants but there is a small residual risk that combustion plant performance may be reduced through the introduction of a waste feedstock (from boiler fouling etc.) and operators will need to remain vigilant that emissions from a combustion plant are in full compliance with the IED.

	Title: Feeding of secondary fuels into a fluidised bed combustion plant - Item 2		
9	***Example plants or TRL***		
	TRL	9+	Over 15 operational examples of biomass and waste co-firing plants have been provided for the current WI BREF update work [4].
10	***References***		

	Reference	Strength of Evidence
[1]	http://www.biomassenergycentre.org.uk /portal/page?_pageid=75,59188&_dad=portal	90
[2]	Finnish Ministry of the Environment	70
[3]	Finnish Ministry of the Environment	90
[4]	Finnish Ministry of the Environment	90

Waste incineration plants

	Title: **High steam parameters for boilers and superheaters – Item 3**
1	***Technical description*** Compared to fossil-fuel-fired LCP boilers, waste-fuelled boilers have lower electrical generation efficiency. This is primarily because of the severe corrosive environment created by waste incineration which limits steam temperatures and pressures to around 425°C and 50 bar. However, numerous techniques have been developed to help boost the energy efficiency of conventional incineration to above 30%. These include external superheaters, radiant pass superheaters and the reheating of turbine steam. • External superheaters - An innovative solution is to provide an external superheater which is powered by the gasification of a cleaner and more homogeneous fuel such as waste wood, which is proven. This additional, cleaner heat source can raise the steam generated by the waste-fired 'base plant' to temperatures of over 500°C without risking early failure of superheater tubes. This technique is offered commercially, the most suitable application would be where a WI plant and a biomass combustion plant are in the same location. [1] • Radiant pass superheaters - A number of technology providers have fitted superheaters in the radiant or first pass area of the boiler. This is where flue-gases are hottest, the radiant section of the boiler is normally lined with refractory with the boiler tubes located behind the refractory wall. As the boiler tubes do not come into direct contact with the flue-gases, the energy transfer is considered to be radiant. Unprotected steel components would not be able to withstand the intense heat of this section of the boiler and would rapidly corrode. Some plants with this boiler arrangement experience a superheated life of under one year. To overcome this, a radiant superheater can be fitted where it is coated with silicone carbide (SiC) tiles. The radiant superheater operates in combination with the conventional downstream convection superheater bundles. A radiant superheater can raise steam temperatures by between 40°C and 80°C which corresponds to an increase in electrical energy efficiency of around 3%. [2] • Turbine steam reheating – Utility-scale power plants using biomass and fossil fuels as a feedstock commonly employ reheating of turbine steam after its first passage through the turbine to increase electrical efficiency. For this application, the steam temperature is limited to 400°C, but the steam pressure increases considerably. After the first passage through the high-pressure section of the turbine, the resulting steam is superheated again and subsequently used in the turbine's medium and low-pressure sections. Usually after expanding in the high-pressure turbine, the steam has lower pressure (typically 20 % of the pressure on entry) and is reheated with flue-gas in the boiler to the same temperature. Achieved benefits are increased electrical efficiency by approximately 3 percentage points to reach 30% net electrical efficiency. In order to gain the maximum effect from this set-up, the steam pressure has to be increased to at least

	Title: **High steam parameters for boilers and superheaters – Item 3**
	120 bar. However, with the corrosive elements present in waste-fuel-derived flue-gases, at this temperature level there is a high risk of corrosion, even if Inconel cladding is used for boiler tube protection. The Amsterdam AEB plant in the Netherlands employs a steam reheat system through an intermediate superheater and operates at steam conditions of 480°C and 130 bar [3]. The superheaters are designed to be removed easily and, due to rapid corrosion, need replacement around every two years. In a very large plant such as AEB Amsterdam, the revenues from increased electrical production outweigh the cost of superheater replacement. In most WI plants, this is not the case and the superheater life needs to be at least five years to replacement.
2	***Costs*** Such high efficiency requires both high capex and opex and hence is particularly suited for the largest plants where large amounts of power are exported.
3	***Achieved economic benefits*** High steam parameters can bring increased power revenues.
4	***Operational data*** Operational data from AEB Amsterdam indicate a net electrical efficiency of 33%.
5	***Environmental and/or human health benefits and drawbacks*** Increased electrical efficiency from waste feedstocks enables a greater reduction in fossil fuel use.
6	***Technical considerations relevant to applicability*** High steam parameters offer year-round net electrical efficiencies of up to 33%. Net electrical efficiencies of 35% are being targeted by developers but have not yet been achieved.
7	***Driving forces or barriers for implementation including feedstock availability*** This technique becomes more effective as the price of electrical power increases.
8	***Residual risks*** Higher steam pressures with or without higher superheating temperatures will result in increased corrosion risks, especially in the superheaters, and thus a risk of reduced plant availability and increased maintenance costs. Higher steam parameters will also result in a higher capital investment cost, partially due to additional corrosion protection measures.
9	***Example plants or TRL*** Due primarily to cost/benefit, there are only a few commercial examples of the highest steam parameters which currently provide a net electrical efficiency of over 33%.

	Title: High steam parameters for boilers and superheaters – Item 3		
	TRL	9+	There are a limited number of examples operating on a commercial basis

10 ***References***

	Reference	Strength of Evidence
[1]	Volund technical papers	70%
[2]	Volund technical papers	70%
[3]	AEB Amsterdam	90%

	Title: **Flue-gas condensation and component cooling - Item 4**
1	***Technical description*** Flue-gas condensation (FGC) is a technique to recover further energy from the flue-gases produced during combustion. The flue-gases still contain water vapour following clean-up which can be condensed to a liquid form to enable additional low-grade heat to be recovered. FGC can be a cost-effective method of recovering energy for a district or local heating grid. As a rough guide, a flue-gas condensation installation can increase heat energy recovery by up to 15% [1]. There is a small decrease in electrical energy efficiency associated with this. The technique works by cooling the water in the flue-gas below its water dew point. The heat that is released by the resulting condensation of the water is recovered as low-temperature heat. The flue-gas can be cooled either directly via a heat exchanger, or indirectly via a condensing scrubber. The heat that is recovered can then be distributed via a district heating network. Flue-gas condensing in a scrubber will comprise [2]: • cooling of the flue-gas to dew point, by injecting water if not already saturated; • the gas is then passed through a scrubber which is cooled by a heat exchanger on the recirculating scrubber liquid; • the heated water from the scrubber is then pumped through a heat exchanger and recirculated; • the condensate is removed from the scrubber circuit and can be further used as process water or discharged as waste water; • the cooled flue-gas is then passed to the stack. Smaller amounts of useful heat can also be recovered from water-cooled plant components which generate large amounts of waste heat such as water-cooled grates and HV transformers.
2	***Costs*** A feasibility study [3] conducted within an operational WI plant into increasing efficiency by the use of heat pumps (combined with flue-gas condensing) concluded that energy recovery for district heating increased by 9.4MWth through the use of a 2.3 MW_{el} heat pump combined with flue-gas condensing; an estimated investment cost of EUR 6 million including EUR 3 million for the heat pump was required. Flue-gas temperatures on exit were reduced from 60°C to 37°C; reductions to as low as 30°C may be possible.
3	***Achieved economic benefits*** Greater quantities of heat can be extracted from the flue-gases, resulting in higher heat sale revenues. Reducing the flue-gas temperature has the effect of reducing the overall gas flow. This reduces the power demand of the induced draft (ID) fan, therefore resulting in a parasitic load saving.
4	***Operational data*** There will be a small impact on electrical power production from FGC (around

	Title: **Flue-gas condensation and component cooling - Item 4**
	0.5% to 1% reduction) but, where heat is exported, the overall energy efficiency will increase considerably. The CHP net annual average efficiency is estimated to rise from 76% to 88% with the addition of FGC for the most advanced plants [4].
5	***Environmental and/or human health benefits and drawbacks*** Plume visibility may increase due to an increased droplet precipitation due to the lower stack gas exit temperatures. This may have a potential visual impact but will not impact on health. This issue can be overcome by reheating the flue-gas, however this would then impact on the net efficiency gains of the flue-gas condensation.
6	***Technical considerations relevant to applicability*** Full benefits of FGC will only be realised where the plant exports heat, ideally to a district heating network which has suitable low return temperatures. Otherwise the energy recovered by FGC can only be used for boiler feed water preheating, which is limited.
7	***Driving forces or barriers for implementation including feedstock availability*** The potential to recover heat by flue-gas condensation is highest for high-moisture-content fuels, including biomass and municipal waste. The potential is also increased where heat is useful at the lowest possible temperatures, for example in district heating or an industrial user of low-grade heat.
8	***Residual risks*** The high level of condensate can be corrosive.
9	***Example plants or TRL***

TRL	9+	The latest installations of waste incineration plants employ FGC, particularly in Scandinavia.

10 ***References***

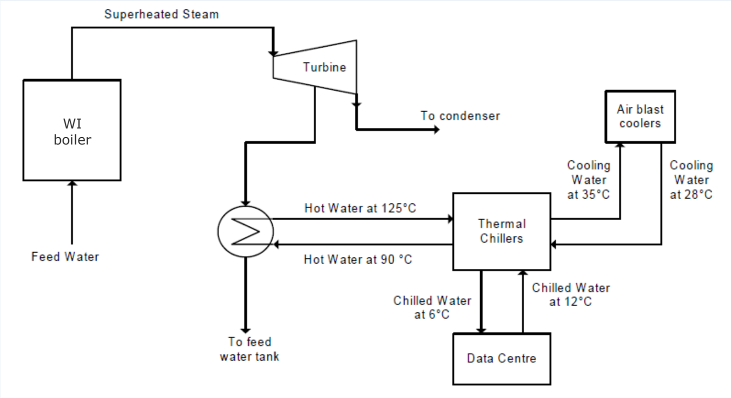
	Reference	Strength of Evidence
[1]	ISWA CE Report 5, 2015	90%
[2]	NLWA Flue Gas Treatment Technology Options Consultation	90%
[3]	Statkraft, Norway – A case study of Trondheim WtE plant	70%
[4]	Calculation by Ricardo Energy & Environment based on efficiencies presented in ISWA CE Report 5, 2015, Appendix 1.	90%

	Title: **Heat pumps - Item 5**
1	***Technical description*** The principle of a heat pump is to upgrade a low-temperature waste heat flow to a useful high-temperature heat. There are many different types of heat pumps, including compressor heat pumps (using electricity) or absorption heat pumps (using heat from steam, hot water or flue-gas). In compressor heat pumps, the main components are the compressor, expansion valve, and two heat exchangers in the form of an evaporator and condenser. A working fluid known as a refrigerant passes through all components of the system. In the evaporator, the working fluid is heated by the transfer of heat from the heat source, i.e. flue-gases, which causes the evaporation of the working fluid. This vapour is then compressed to a higher pressure and temperature. The hot vapour then enters the condenser, and, as the vapour condenses, heat is released which can then be used. The condensed working fluid is then expanded in the expansion valve and is returned to the evaporator where the cycle starts again. Absorption heat pumps are driven thermally as opposed to mechanically. They work on the principle of the ability of liquids or salt to absorb vapour. For example, commonly paired working fluids and absorbents include water and lithium bromide, and ammonia and water. An absorption heat pump consists of an absorber, a solvent pump, a thermal compressor and an expansion valve. Vapour is produced in the evaporator, at low pressure, which is then absorbed in the absorber and produces heat. The solution is then pressurised in the compressor, where the working fluid then evaporates. The vapour is then condensed, and the absorbent returned to the absorber via the expansion valve. Heat is recovered from the heat source in the evaporator. Large absorption heat pumps are increasingly being used to recover heat from flue-gas condensation.
2	***Costs*** A feasibility study [1] conducted within an operational WI plant into increasing efficiency by the use of heat pumps (combined with flue-gas condensing) concluded that energy recovery for district heating increased by 9.4MWth through the use of a 2.3 MW_{el} heat pump combined with flue-gas condensing; an estimated investment cost of EUR 6 million including EUR 3 million for the heat pump was required. Flue-gas temperatures on exit were reduced from 60°C to 37°C; reductions to as low as 30°C may be possible.
3	***Achieved economic benefits*** Greater quantities of heat can be extracted from the flue-gases, resulting in higher heat sale revenues.
4	***Operational data*** In the EC-JRC study on Best Available Technologies for the heat and cooling market, [2], large absorption heat pumps using flue-gas condensation in connection with MSW are reported to raise district heating temperatures from 40–60°C to about 80°C. A flue-gas condensation installation can increase heat energy recovery by up to 15% of the furnace energy output but, in tandem with a heat pump installation, this figure increases by a further 5% to just over 20% [3]. The CHP net annual average efficiency is estimated to rise from 76% to over 88% with the addition of heat pumps in tandem with FGC for the most advanced plants. [4]
5	***Environmental and/or human health benefits and drawbacks*** Heat pump technologies have low CO_2 emissions.

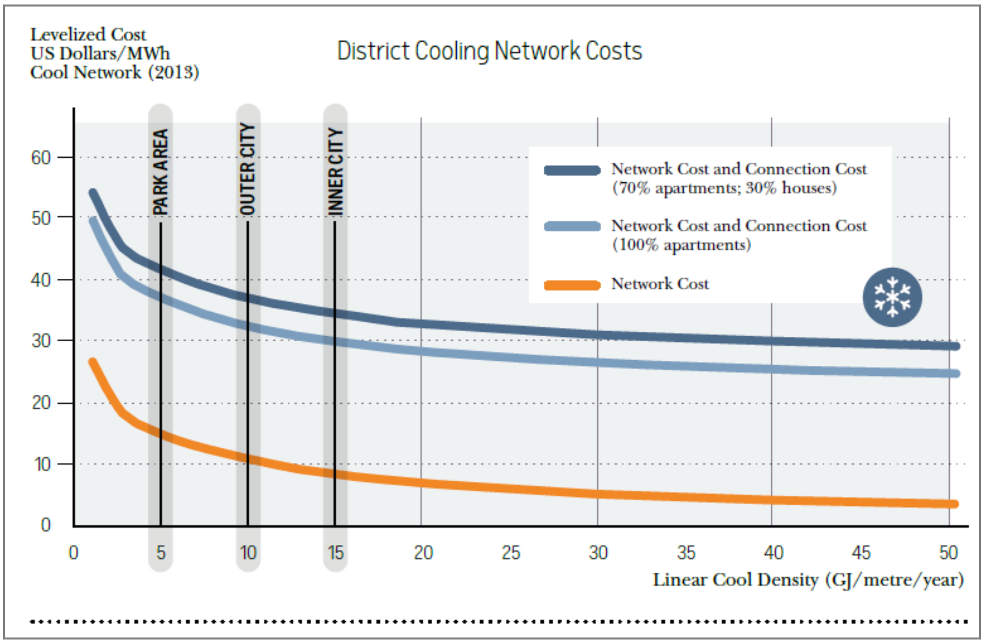
	Title: **Heat pumps - Item 5**
6	***Technical considerations relevant to applicability*** Full benefits will only be realised where the plant exports heat in the form of district heating or steam. The technique can be used to recover heat from flue-gases from incineration of MSW, biomass and other wastes.
7	***Driving forces or barriers for implementation including feedstock availability*** An advantage of heat pumps is that they can utilise waste heat that would have otherwise been lost, by transforming it to a higher temperature. However, the pump itself will need energy to facilitate the transformation from low to high temperature, either in the form of electricity or a further high-temperature heat source. The driver for installation of this technology will be dependent on the availability of a heat user or the presence of a district heating network.
8	***Residual risks*** Residual risks are small, investment is dependent on the security of the heat user (i.e. that a long-term heat offtake agreement is in place).
9	***Example plants or TRL*** Examples of plants with heat pumps are as follows: • Öresundskraft Filborna WTE, plant, Helsingborg, Sweden – This 70MW facility was opened in 2012. The plant's energy recovery process is designed to maximise energy output via a heat pump system. The plant was installed with a two-stage condensing system, where in the first stage the flue-gas is cooled by the return district heating water and in the second stage by an absorption heat pump [5]. • Vestforbrænding waste-to-energy plant, Copenhagen, Denmark – This plant was upgraded in 2006 by the installation of a flue-gas condensation and integrated absorption heat pump. The flue-gases are cooled by a circulating cooling water system. The temperature of the heat recovered from the flue-gases is lower than the district heating return temperature and is therefore raised to the required temperature by two steam-driven heat pumps in series, increasing the district heating temperature from 60ºC to 80ºC [6].
	TRL | 9+ | Many of the latest generation of WI plants incorporate FGC and heat pumps working in tandem.
10	***References***

	Reference	**Strength of Evidence**
[1]	Statkraft, Norway – A case study of Trondheim WtE plant	70%
[2]	European Commission, Joint Research Centre, Institute for Energy and Transport, Best available technologies for the heat and cooling market in the European Union, 2012.	90%
[3]	ISWA CE Report 5, 2015	90%
[4]	Calculation by Ricardo based on efficiencies presented in ISWA CE Report 5, 2015, Appendix 1.	90%
[5]	Götavergen Miljö Reference Case Study, Filborna WTE, plant, Helsingborg, Sweden	90%

***Title:* Heat pumps - Item 5**			
	[6]	Götavergen Miljö Reference Case Study, Vestforbrænding waste-to-energy plant, Copenhagen, Denmark	90%

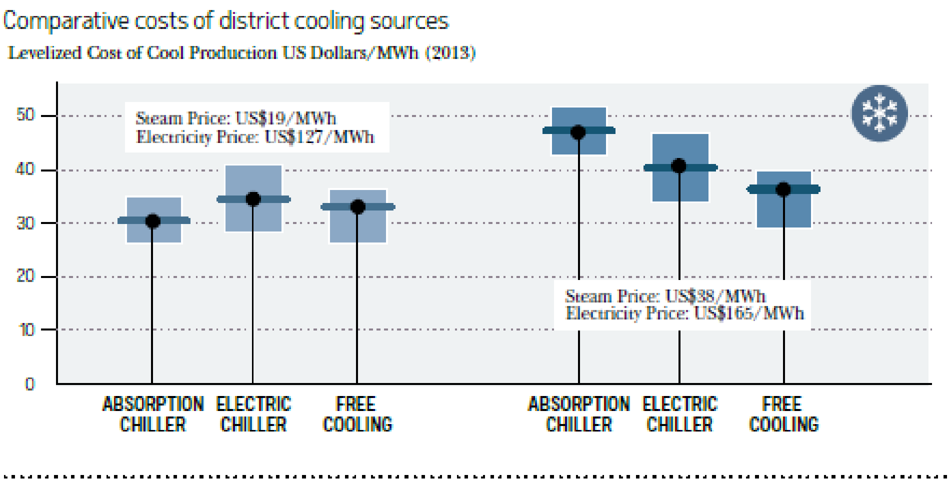
	***Title:* District cooling - Item 6**
1	***Technical description***
	This refers to the use of heat from a WI plant to provide chilled water for air conditioning and other cooling applications. One option is to use steam from the WI plant to drive the compressor for a vapour compression refrigeration system. However, a more commonplace option is to use lower-grade heat (e.g. low-pressure steam or hot water) within an absorption refrigeration system. Absorption-based chiller systems are more widely used on account of their ability to use lower-grade heat, thereby reducing the penalty on the electrical output of the WI plant. The overall energy efficiency of cooling systems is less than that of a system delivering heat energy, particularly refrigeration absorption. The performance of the chiller system is expressed in terms of its coefficient of performance (CoP, the ratio of cooling output to heat input). Steam-based absorption systems can achieve CoPs in the order of 1.2 while hot water systems achieve CoPs of 0.6. On account of the absorption thermodynamic cycle, in comparison to district heating which typically has a heat energy efficiency of 65%, district cooling energy efficiency is typically around 42% (both these efficiency figures are for the heat / cooling energy only). Backup facilities are normally required to provide for WI supply outages. This will typically be provided by electrically powered vapour compression chiller systems. Such systems will also often be allied with sources of free cooling such as bodies of water, which are more capable of providing cooling services in winter. Applications are currently limited to a small number of schemes (e.g. Districlima in Barcelona, Spain). However, one area of potential growth is the provision of cooling services to data centres, which have constant and very high cooling requirements. A schematic is shown below. 
2	***Costs***
	Levelised costs for district cooling networks are given in the following figure.

***Title:* District cooling - Item 6**



(Source: UNEP [1])

Levelised costs for district cooling sources are given in the following figure.



(Source: UNEP [1])

3 ***Achieved economic benefits***

Cooling effort requires the input of primary (electrical) energy and is therefore more highly valued than heat energy and should attract more revenue.

Because heat demand is seasonal and will be lower during summer, utilising waste heat for district cooling provides an additional revenue source.

If supplying 100% load to a cooling user such as a data centre, both efficiencies and revenues will be greater.

	Title: **District cooling - Item 6**
4	***Operational data*** Only very limited examples of operating data for district cooling systems were available. One example (where data are available) is the 2015 annual report for HOFOR P/S[2], who own and operate one of the main district heating and cooling networks serving Copenhagen, Denmark. HOFOR P/S reported the following details regarding its District Cooling Business area during 2015: • the company has 54 cooling customers; • the total cooling capacity for the system is 50MW_{th}; • the overall district cooling network length is 17km; • annual cooling supplied was 15 GWh; • net sales (including other operating income) was DKK 38.3 million (EUR 5.15 million); • operating expenses (excluding raw materials and consumables) were DKK 6.4 million (EUR 0.86 million); • raw materials and consumables costs were DKK 3 million (EUR 0.4 million).
5	***Environmental and/or human health benefits and drawbacks*** District cooling using waste heat from the incineration of waste will potentially have lower CO_2 emissions and use less energy than alternative systems. Absorption chillers such as those used to convert waste heat into cold water for district heating do not use refrigerants which can be considered environmentally damaging.
6	***Technical considerations relevant to applicability*** Where district cooling is linked to a consumer such as a data centre, year-round cooling is required. In these cases, the net annual average energy efficiency is estimated at 68% (in a **combined cooling and power** configuration), even for the most efficient systems. Otherwise, where cooling is assumed to be required only 80% of the year due to seasonal demand, a net annual average energy efficiency of 60% can be expected, even for the most efficient systems. Better annual energy efficiency is dependent on being connected to large cooling energy consumers such as hospitals or data centres. Hot climates within the EU-28 will also offer seasonal demand.
7	***Driving forces or barriers for implementation including feedstock availability*** The driving force for district cooling is more aligned with cooling demand, as opposed to feedstock availability. The technique is particularly relevant for hot countries. Alternatively, users with constant cooling demands such as data centres are a potential market.
8	***Residual risks*** Many of the risks match those associated with district heating networks, namely the need to secure a stable, long-term demand (in this case for cooling) to justify the significant capital investment. There therefore exists a risk of the distribution network becoming stranded in the event of there being a collapse in network demand.

	Title: **District cooling - Item 6**
	The decentralised technology alternatives for district cooling (namely electrically driven air conditioning) can be installed relatively easily. As such, there would be a greater risk compared to heat networks of individual users switching away from cooling networks in the event that cooling prices to customers do not remain competitive (e.g. due to a fall in electricity prices).
9	***Example plants or TRL*** The technology is slowly building traction in some countries because of its ability to alleviate demand on power systems. Some examples include the following: • San Adrià de Besòs waste-to-energy plant, Barcelona/Spain [3]. This plant provides cooling power via two 4.5MW absorption chillers. Cooling is distributed (along with heating) by Districlima. Cooling temperatures are 5.5°C, with a return temperature of 14°C. The plant also has a 20MW electrically driven chiller and 10.4MW of chilling capacity in the form of a 5,000m^3 chilled water tank. • Adelgade District Cooling, Copenhagen/Denmark [4]. The system provides chilled water to nearby users including banks, hotels, museums, offices and a mint. The capacity of the cooling centre is 15 MW_{th} and comprises a combination of free cooling using water from the nearby Nyhavn canal as well as a steam-driven absorption chiller. The capacity of the absorption chiller is 3.5 MW_{th} and is driven using heat from the local district heating network. Water from the canal is also used for heat rejection, eliminating the need for cooling towers.

TRL	9+	All technology is proven but uptake and examples remain limited due to commercial reasons.

10 ***References***

	Reference	**Strength of Evidence**
[1]	*District Energy in Cities: Unlocking the Potential of Energy Efficiency and Renewable Energy,* UNEP, 2015	90%
[2]	Hofor Forsyning P/S Annual Report 2015 [In Danish]	80%
[3]	Hitachi Zosen Innova presentation, European Union Sustainable Energy Week, 2011	90%
[4]	Thermax Europe Website, *http://www.thermax-europe.com/district-cooling.aspx,*	70%

	***Title:* 4th generation heat networks - Item 7**
1	***Technical description***
	The evolution of district heating can be said to have evolved through three generations since its first introduction [1], the 1st generation being steam-based systems, the 2nd generation being high network supply temperatures (above 100°C) and the 3rd generation referring to district heating networks (DHN) using medium supply temperatures (between 80°C and 100°C). The 4th generation of heat networks therefore refers to emerging new systems which use low-temperature district heating (LTDH). In general, 4th generation heat networks refer to the technological and institutional concepts to broaden the suitability of district heating and cooling networks beyond their current areas of greatest suitability (densely populated areas located within cold climates). These concepts seek to reduce the minimum heat demand density required to make a network commercially viable. This allows networks to continue to be appropriate in areas where heat demand density is lower, either through lower dwelling density or a reduced heat demand as a result of energy efficiency improvements. The four main features of 4th generation heat networks are as follows : 1. Ability to supply low-temperature district heating for space heating and hot water. This concerns the use of heat delivery temperatures below 50°C, compared to 100° for current generations. 2. Ability to distribute heat in networks with low grid losses. 3. Ability to utilise renewable heat and recycled heat from low-temperature sources. This includes waste heat from power generation (including WtE) as well as heat from other renewable sources (e.g. geothermal and solar thermal). 4. Ability to form an integral part of smart energy systems (e.g. through intelligent control of demand and supply through demand-side response and thermal storage). The deployment of 4th Generation Heat Networks would make district heating viable in a greater number of situations, increasing the potential for heat networks to be developed in areas in the vicinity of WI plants. This would enable these plants to operate in a co-generation mode and, as a consequence, increase their energy efficiency. In addition, the use of lower operating temperatures would enable WI plants to supply the necessary heat with less impact on their power output, leading to higher power to heat ratios. Examples of 4th Generation Heat Networks are available. However, these are currently limited to small-scale networks such as the 5MW_{th} system installed at Stadsoevers in the Netherlands. It is reported that the delivery of heat has no reducting effect on electricity production. Hot water is delivered at 40°C and may be raised to 65°C locally using heat pumps, so power consumption from the grid will be required. [1]
2	***Costs***

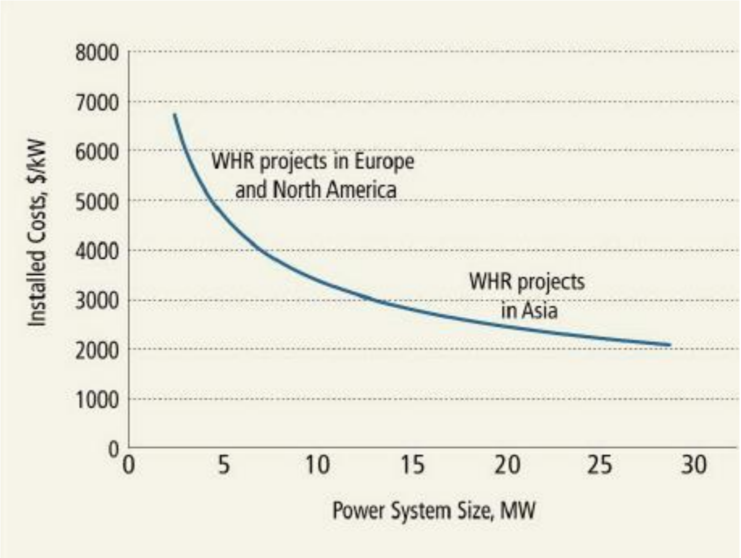
	Title: 4th generation heat networks - Item 7
	Cost data are limited. However, work by the IEA [2] analyses a series of seven LTDH case studies and identifies investment costs in the range of EUR 115 - 206 per metre network length and distribution costs of EUR 3.2 – 13.7 per GJ of heat delivered. The study explains that the wide variation in costs is due to the case studies covering a wide range of different LTDH design approaches.
3	***Achieved economic benefits*** In the case of utilising heat from waste-to-energy, the use of LTDH enables higher heat utilisation from flue-gas condensation. The low return temperature from the system also makes direct flue-gas condensation from combustion flue-gases possible. This is due to the high moisture content in the feedstock. In addition, LTDH makes the use of heat pumps as a form of heat recovery more financially competitive, as both pressure and temperature can be lower in the heat pump condenser, therefore using less energy and giving a higher coefficient of performance. It is also possible to achieve a higher utilisation of low-temperature sources, such as component cooling.
4	***Operational data*** Low supply temperatures means turbine electrical generation losses in the WI plant are minimal. Where this is true, the net annual average energy efficiency is estimated to rise from 76% to 82% for the most advanced plants.
5	***Environmental and/or human health benefits and drawbacks*** The principal benefits are the additional carbon emissions savings brought about by increased thermal efficiency and reduced network losses. In addition, as with previous generations of district heating, there will be local air quality benefits brought about by removing the need for a local heat-generating plant. This will be particularly marked where the incumbent heat recovery is based on solid or liquid fuel.
6	***Technical considerations relevant to applicability*** Heat pumps may be required to raise water supply temperatures locally for some applications and these will require additional energy input. The network design must be compatible with lower temperatures.
7	***Driving forces or barriers for implementation including feedstock availability*** Advantages of LTDH are reduced heat losses and an improved synchronisation between heat supply and heat demand temperatures. This has the added benefit of reducing thermal stresses in pipework, offers the potential to use alternative pipe materials, and reduces the risk of the water boiling and the risk of scalding. 4th generation networks still require a local energy user but the technology will help to expand the applicability of district heating and cooling. A further barrier is that LTDH will not be able to supply high-temperature heat demands.
8	***Residual risks*** There is a risk of legionella growth at low hot-water temperatures. The transition from current DH systems to the next generation DH system

	Title: **4th generation heat networks - Item 7**
	requires coordinated efforts for building energy reduction [2]. With increasing building energy efficiency, heat networks will have to go further distances to access the same heat demand to make the system viable. This could in time restrict the applicability of LTDH.
9	***Example plants or TRL*** IEA[2] identify the following case studies for LTDH: i. Kirsehir, Turkey; ii. Ringgården 34, Lystrup, Denmark; iii. Drake Landing, Okotoks, Canada; iv. Söndrum, Halmstad; v. Herting, Falkenberg; vi. Ackermannbogen, Munich, Germany; vii. Greenwatt Way, Slough, UK. None of the case studies identified were configured to directly utilise WI as a heat source.
	TRL | 9 | The only applications operating to date are relatively small-scale.
10	***References***

	Reference	Strength of Evidence
[1]	SUEZ Environment, Showcase for WtE efficiency, London, February 2015	70%
[2]	IEA DHC CHP, Toward 4th Generation District Heating: Experience and Potential of Low-Temperature District Heating, 2014	90%

Cement and lime plants

	***Title:* Conversion of waste heat to power in cement kilns - Item 8**
1	***Technical description*** The use of waste-derived fuels in cement kilns is well established and well documented. The fuel is co-combusted with fossil fuels in the kiln, in order that the required temperatures are achieved for the production of clinker from raw mineral materials. The waste is fully combusted within the kiln. Previously, waste heat from the process was used to preheat incoming materials, or is otherwise emitted to atmosphere. To increase the efficiency of this process, developments are being made to convert waste heat into power. Heat is recovered from exhaust gases and can either be used to provide low-temperature heating within the process or can be used to generate electricity. *Direct heat recovery to the process [1]* This method utilises heat that is directly in contact with incoming cooler materials, or air. Heat is transferred from the higher to lower temperature medium, effectively preheating the temperature of inputs to the kiln. This results in an increase in the efficiency of the kiln or preheater. *Waste heat boilers [1]* A further waste heat recovery (WHR) method is to use waste heat in a boiler. A waste heat boiler will consist of a series of tubes, similar to a conventional boiler. In this case, the boiler will raise steam by the water in the boiler being heated by waste heat from exhaust gases. This system can be used to provide further steam or hot water to the process. *Waste heat power generation [1]* Power can be generated using a Waste Heat Recovery Power Generation (WHRPG) system, which typically consists of a low-parameter steam turbine. The turbine is powered by steam generated from the waste heat, in turn producing electricity. There are several different ways in which power can be generated. A traditional steam Rankine cycle is the most efficient option for recovery of heat from exhaust gases when gas temperatures are in the range of 340°C–370°C *[1]*. When gas temperatures are lower, an organic Rankine cycle (ORC) or Kalina cycle is a more efficient option as they use working fluids with lower boiling temperatures. *Waste heat for district heating [2]* A further example of waste heat recovery from cement kilns is the use of heat for district heating networks. Heat is extracted via heat exchangers from the flue-gas of the cement kilns.
2	***Costs*** The capital costs of each waste heat recovery project will be dependent on site-specific and project-specific factors. For example, the amount of heat available, and the temperature of the exhaust gases will determine the size of the equipment required and the overall generation efficiency that can be achieved. WHRPG systems can be complex installations, consisting of boilers or heat exchangers, a steam turbine, gearbox, generator, condenser, and associated piping, lubrication, water treatment system and electrical equipment and controls. [3] Capex is closely correlated with size, with smaller systems incurring a higher

	Title: **Conversion of waste heat to power in cement kilns - Item 8**
	cost per kW of output, see figure below [3]. 
3	***Achieved economic benefits*** • Reduced use of fossil fuels through the generation of power on site, and reduction in heat demand when heat is reused in the process. • Potential sale of district heating. • Project payback is directly linked to the price of the electricity that the WHRPG is replacing.
4	***Operational data*** A selection of operational data is summarised in the table below [5].

Company	Country	Facility	Production capacity	WHR tech used	Output (kW)	Date of install
Yingde CONCH Cement	China	Yingde	15,000 tonnes/day	AWC/PH*	27,000	2007
Siam Cement	Thailand	Kaeng Khoi	5,500 tonnes/day	AWC/PH*	9,100	2008
Aalborg Portland	Denmark	Aalborg	1.8 million tonnes/year	District Heating	1,200,000 (GJ)	1998

*Air Quenching Chamber boiler (recovers heat from exhaust gases).

** Preheater boiler (recovers heat from preheat system).

5	***Environmental and/or human health benefits and drawbacks*** • Increases efficiency of the cement plant. • Reduces fossil fuel usage and associated carbon emissions. • CO_2 emissions to the environment are also reduced by lowering the temperature of the exhaust gases.
6	***Technical considerations relevant to applicability*** The suitability of heat recovery from exhaust gases is impacted by the moisture content of the raw materials. Materials with a high moisture content can limit the

	Title: **Conversion of waste heat to power in cement kilns - Item 8**
	potential for waste heat recovery as the temperature and amount of exhaust gases will be reduced. Retrofitting to existing cement kilns to improve their efficiency is possible and therefore this technique is applicable to all Member States which have cement kilns. In terms of applicability to waste streams, cement kilns are able to accept a wide range of waste-derived fuels, including Solid Recovered Fuel, tyres, dried sewage sludge, animal wastes, spent solvents, and plastic wastes.
7	***Driving forces or barriers for implementation including feedstock availability*** Drivers: • Can contribute up to 30% of a CL plant's power demand. • Technology can contribute to sustainability and carbon reduction targets for the sector. Barriers: • The moisture content of the input material can impact on the potential for heat recovery from exhaust gases. • High capital costs can make payback periods too long for developers.
8	***Residual risks*** • Supplying heat when the plant is in shutdown. • Financial benefits dependent on energy markets. • Cement industry output can be impacted on by national economic downturns. • Technology is widely deployed in China, India and the US, but there are currently fewer examples in the EU.
9	***Example plants or TRL*** There are >700 plants in China, with other plants located in Asia, and a smaller number in the Middle East, the US and Europe.
10	***References***

TRL	9+	Technology widely demonstrated outside Europe, particularly in China.

	Reference	**Strength of Evidence**
[1]	Amiri, A, Vaseghi M R, Waste Heat Recovery Power Generation Systems for Cement Production Process, 2014	80%
[2]	Aalborg Portland Case Study	80%*
[3]	International Finance Corporation, World Bank, Waste Heat Recovery for the Cement Sector: market and supplier analysis, 2014	80%
[4]	Information provided by Cembureau	80%
[5]	Waste Heat Recovery Power Plant in Cement Plants, Kawasaki Plant Systems Ltd	60%

Anaerobic digestion plants

	***Title:* Sewage sludge advanced AD – Thermal Hydrolysis Process (THP) – Item 9**
1	***Technical description***

Thermal hydrolysis technology pretreats sewage sludge in a two-stage process, which combines the medium-pressure boiling of sludge with a rapid decompression. This effectively sterilises the sludge and means that it is more suitable for anaerobic digestion and increases the production of biomethane. The sterilisation process destroys pathogens in the sludge, ensuring it is suitable for subsequent use in agriculture.

The Thermal Hydrolysis Process (THP) first dewaters the incoming sludge stream to 16.5% dry solids (DS) before the dried biomass enters a pressure vessel. Steam is added to the pressure vessel at roughly 12bar, degrading the biomass before high-rate AD occurs. Conventional sewage sludge digestion achieves volatile solids destruction (VSD) of 40-50% which yields 300-350m^3 of biogas per tonne of dry solids which translates to a 40% mass reduction.

Typical sites with the THP achieve 60% VSD and produce 450m^3 of biomass per tonne of dry solids, representing approximately a 30% increase in gross energy output. However, insufficient high-grade heat is recovered by the process through CHP to meet all the THP steam requirements, resulting in additional fuel (natural gas) being needed.

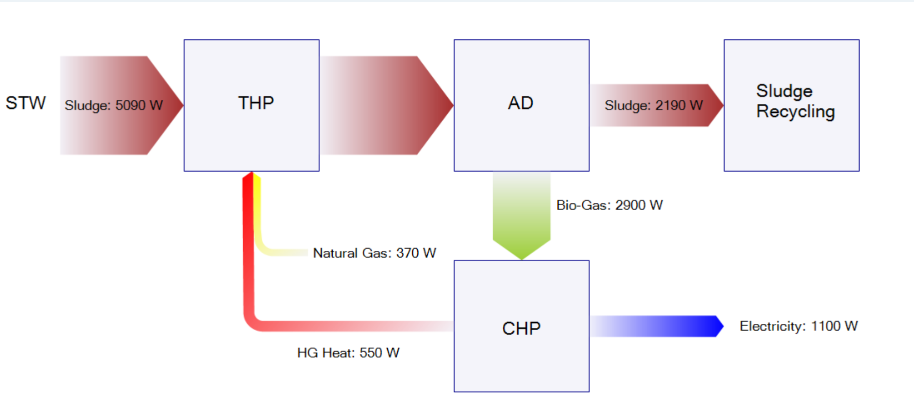


Image courtesy of DECC

2 ***Costs***

The investment required for a new THP plant is significant. A number of basic AD plants have been upgraded to THP plants with commercially acceptable payback periods. The estimated costs of a large sewage treatment plant (100 tonne dry matter per day) for conventional AD and in comparison to THP [1]:

	Conventional AD plant	Advanced AD and advanced energy recovery plant
Capex new build (million EUR)	70	73
Power output	3.5MW	4.9MW
Capex to retrofit advanced AD and energy recovery to a conventional AD plant (million EUR)	46	-

It can be seen that the predicted investment costs of a THP plant are broadly

	Title: **Sewage sludge advanced AD – Thermal Hydrolysis Process (THP) – Item 9**
	similar to those of a conventional AD plant, but the revenues from power output will be higher due to the higher net energy efficiency.
3	***Achieved economic benefits*** Higher biogas yields will increase power generation income.
4	***Operational data*** The net annual electrical efficiency is estimated at 22% which is 6% higher than for conventional sewage sludge AD (16%). [1]
5	***Environmental and/or human health benefits and drawbacks*** The technique is reported to have a low environmental impact, especially in relation to odour. [2]
6	***Technical considerations relevant to applicability*** The high investment costs and planning and permitting restrictions limit the application of this process to large organic waste treatment facilities (capacity of >50 t DS/day). The technique is most applicable to sewage sludge. It may also be able to be applied to other organic waste streams which have a high moisture content.
7	***Driving forces or barriers for implementation including feedstock availability*** Drivers: • The technology can result in increased biogas yields and increased volatile solids destruction. Landspreading of residual sewage sludge is becoming less accepted so a process which minimises the quantity of residual by-product is positive. • The reduction in mass is greater when compared with conventional digestion. • Transport costs can be reduced through enhance dewatering. • The effective destruction of pathogens ensures a high-quality marketable digestate. Barriers • Whilst biogas increases, the requirement for an input of high-grade heat does not necessarily result in an overall net increase in energy yield, with many first generation plants requiring a support fuel, typically natural gas, to support the process. [3] However, second generation THP plants do not require support fuel and are able to recover sufficient heat from the process to be self-sufficient. [4]
8	***Residual risks*** Residual risks are considered to be low as this is a well-established technique.
9	***Example plants or TRL*** Since the first installation in Hamar, Norway in 1996, there are now estimated to

***Title:* Sewage sludge advanced AD – Thermal Hydrolysis Process (THP) – Item 9**

be over 30 AD plants incorporating thermal hydrolysis globally. [5]

TRL	9+	There are a number of large THP plants successfully operating in Europe.

10 ***References***

	Reference	Strength of Evidence
[1]	UK Department of Energy and Climate Change and UK Water Industry. Cost in GBP converted to EUR at 1:1.4.	50%
[2]	Treating organic waste with Cambi THP, Wojtech.Sargalski, Odd Egil Solheim, Carsten Fjordside Cambi AS.	80%
[3]	Mills, N, et al, Life Cycle Assessment Of Advanced Anaerobic Digestion Process Configurations For Sewage Sludge - A UK Perspective	80%
[4]	UK Department of Energy and Climate Change and UK Water Industry.	50%
[5]	Beckton & Crossness Thermal Hydrolysis Plants advanced sludge digestion facility (ESDF) Case Study, Andre Le Roux & Andrew Bowen	90%

	Title: **AD with biomethane injection to grid - Item 10**
1	***Technical description*** Anaerobic digestion (AD) is a biological process through which micro-organisms break down organic material in an enclosed system without the presence of oxygen. As the material is digested, it is converted to biogas, a mixture of methane and carbon dioxide. The biogas can be combusted in an engine to recover electricity and heat. However, the biogas produced has the same composition as fossil-fuel-derived methane and therefore is also suitable for use as a substitute for natural gas via a gas-to-grid network. The methane-rich biogas is upgraded to biomethane by the removal of impurities such as CO_2 and H_2S, which are removed by scrubbers and activated carbon filters. A small volume of propane is added to the methane to ensure the gas has the same natural gas quality. The biomethane is continuously analysed under strict quality control procedures prior to being fed into the local gas distribution network. In summary, the 'upgrading' of biogas to meet quality standards necessary to permit the injection of gas into the natural gas network involves the following principal stages: • removal of hydrogen sulphide and carbon dioxide from the biogas; • enrichment using propane to meet calorific value and Wobbe Index requirements; • compression to meet network pressure requirements. A number of separation technologies exist for the removal of carbon dioxide but the most commonly used are membrane separation and 'water wash'. The overall energy efficiency of the AD - GtG process is 41%, based on the energy content of the organic waste input versus the biomethane injected to the grid [1]. The European Biogas Association predicts that GtG will be a more popular route of delivering biomethane to consumers than other more energy-intensive routes such as liquefaction and compression / trailer transport [2].
2	***Costs*** Costs for development of a biomethane gas-to-grid project will be site-specific, and will depend on the complexities of each site, and also the degree of civil engineering work required. The capex required for biogas upgrading equipment is over and above that required for standard AD, but this is offset as no gas engine purchase is required. An estimation of the capex for an AD plant injecting 10 tonnes per day of biomethane to the grid is shown below in comparison to an equivalent power-only plant (with 2MW power export) [4].

***Title:* AD with biomethane injection to grid - Item 10**

		Cost item	GtG	Power export
Capacity	tpd	Biomethane to fuels tpd	10	10
	MW	MW biomethane to biofuels	5.70	-
	MW	MW power export	-	2.0
Capex	Eur(,000)	Development costs	1,603	1,229
		Grid connection import only	123	
		Other infrastructure	657	565
		Civil Works	2,405	1,844
		AD Plant	11,410	11,410
		Upgrading	2,520	
		H2S/VOC capex	882	882
		Injection plant	812	
		Gas grid connection	406	
		Grid connection for import & export		922
		Gas engines		2,709
		Total Capex	**20,818**	**19,562**

There is some evidence that the cost of gas grid connections is reducing, as the technology becomes more widely deployed.

3 ***Achieved economic benefits***

In terms of opex, injecting the gas (as biomethane) into a gas grid, the biomethane producer can charge domestic gas use tariffs which offer a much higher revenue when compared to other biogas applications. [3]

Biomethane is often exempt of tax and can be eligible for other financial incentives, for example biomethane injection to grid in the UK is eligible for special tariffs under the Renewable Heat Incentive.

4 ***Operational data***

There are approximately 200 plants across Europe that upgrade biogas to biomethane for injection to grid, and this number is growing. Example operational data of the Rainbarrow Farm biomethane grid injection facility opened in Poundbury, UK in 2012 is included below [5].

Feedstock	4,000 tonnes potato waste, 26,000 tonnes maize silage, 4,000 tonnes grass silage, and 7000 tonnes food waste
Annual raw gas production	7,450,000 m^3
Grid injection	400m^3/hr, Annual biomethane injected to grid – 3,500,000 m^3
Gas composition	Methane content in raw biogas – 53% Methane content in product gas – 96%
Target CV of gas grid	39.5 MJ/m^3

5 ***Environmental and/or human health benefits and drawbacks***

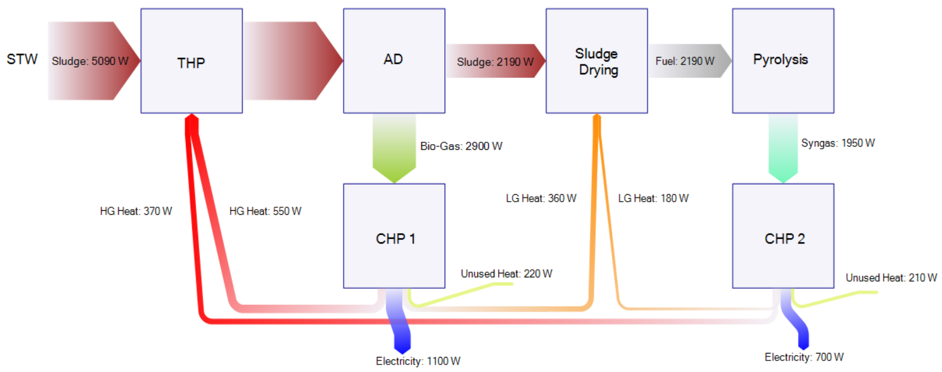
There are clear environmental benefits from utilising organic waste to produce biomethane for gas-to-grid injection. Waste-derived biomethane can be used in energy-efficient installations such as domestic heating and cooking facilities or to feed CCGT combustion plants.

	***Title:* AD with biomethane injection to grid - Item 10**
6	***Technical considerations relevant to applicability*** The level of biogas clean-up is more significant for injection of gas to grid than the gas purity levels needed for use in CHP engines. Connections to the local gas network can be complex and may require a long lead time.
7	***Driving forces or barriers for implementation including feedstock availability*** Drivers: • This technology is applicable to a wide range of waste feedstocks, including food waste from households, agricultural waste, commerce and industry, industrial effluents and sewage sludge. • Biomethane has a higher energy density than biogas and can increase overall net efficiency. • Contribution to renewable energy targets. Barriers • Degree of upgrading can add substantially to the cost and energy requirements. • Limited financial incentives or subsidies. • Distance of AD plants to gas distribution network.
8	***Residual risks*** • Ability to meet gas quality standards which differ across Member States. • Acceptance by, and capacity of, local grid.
9	***Example plants or TRL*** The European Biogas Association reports that there are in the region of 200 biogas plants which are injecting biomethane to the gas grid.

TRL	9+	Biomethane injection to grid in 200 biogas plants across 16 Member States

10 ***References***

	Reference	**Strength of Evidence**
[1]	ISWA CE Report 5, p. 25	
[2]	EBA interview, February 2016	90%
[3]	Department of Energy & Climate Change, UK, Biomethane in to the Gas Network – A Guide for producers, 2009	90%
[4]	UK Department for Transport / Ricardo, 2015	90%
[5]	EU GreenGasGrids Best Practice Example – Rainbarrow Farm, Poundbury	100%

	Title: Sewage sludge advanced AD with advanced energy recovery (pyrolysis) – Item 11
1	***Technical description (Emerging technique)*** This technique incorporates sewage sludge advanced AD with advanced energy recovery (pyrolysis) as the final stage of energy recovery from the sewage sludge stream. Before the pyrolysis process, a dryer produces a solid fuel feed using biomass from either a THP sludge treatment process (as shown below) or an ITHP. The pyrolysis process has been shown to reduce the mass of the biomass solids by 90%, liberating a pyrolysis gas with a high CV of 11 - 20MJ/m^3 and leaving very little residual product for disposal. The fuel gas from the pyrolysis process is then utilised in a second gas engine (CHP2). CHP1 is a gas engine running on biogas from the AD process. Both CHP units recover heat which is split into a high- and low-grade heat. The high-grade heat (200°C) is used to raise steam for THP and the low-grade heat is used for sludge drying. Unlike other TH processes, there is no requirement for support fuel due to the combination of CHP units raising all of the steam for THP. Pyrolysis shows the most potential as a form of advanced energy recovery.  *Image courtesy of DECC*
2	***Costs*** The estimated costs of a large sewage treatment plant (100tpd DM) for conventional AD and in comparison to an advanced energy recovery plant are shown below [1]:

	Conventional AD plant	Advanced AD and advanced energy recovery plant
Capex new build (million EUR)	70	73
Power output	3.5MW	8.5MW
Capex to retrofit advanced AD and energy recovery to a conventional AD plant (million EUR)	84	-

It can be seen that the predicted investment costs of an advanced plant are significantly more than for a conventional AD plant, but the revenues from power output will be higher and by-product disposal costs will be reduced due to there being lower quantities.

As it is an advanced process, some Member States may also offer financial incentives.

	Title: **Sewage sludge advanced AD with advanced energy recovery (pyrolysis) – Item 11**
3	***Achieved economic benefits*** This technique greatly reduces the amount of residual by-product following treatment of sewage sludge. The volume reduction is 96% compared to 40% for conventional AD. Spreading of sludge to land is not always possible (about 60% of the sludge produced is spread to land on average) and may come at a cost so minimising the quantity of residual by-product is financially advantageous. The high net electrical efficiency of the process can generate increased power sales revenue. The net annual average efficiency is estimated at 35% which is 19% higher than for conventional AD (16%) [2].
4	***Operational data*** As an emerging process with a low TRL, there is no operational data available.
5	***Environmental and/or human health benefits and drawbacks*** Alternative methods of treating sewage sludge have been developed as restrictions on the disposal of sewage sludge have gradually tightened across the EU-28.
6	***Technical considerations relevant to applicability*** The high investment costs and planning and permitting restrictions limit the application of this process to large sewage works (capacity of >50 t DS/day). Although this technique has been developed for sewage sludge, other organic feedstocks could potentially be used which would broaden the applicability of the technique.
7	***Driving forces or barriers for implementation including feedstock availability*** Drivers: • The Renewable Energy Directive requires a 15% reduction in carbon emissions by 2020 in all EU-28 Member States. This is driving the development of low-carbon energy production. • The technology can result in increased biogas yields and increased volatile solids destruction. Landspreading of residual sewage sludge is becoming less accepted so a process which minimises the quantity of residual by-product is positive. Feedstock availability • Task 1 has shown that feedstock availability is reasonable with approximately 10 million tonne per year of municipal sewage sludge (dry matter) being available.
8	***Residual risks*** • Pyrolysis has been shown in trials to be more effective on homogeneous waste streams such as biomass or paper sludge [3] but the process has not been proven on these feedstocks or dried sewage / sludge cake as is proposed in this technique. The most difficult aspect remains the combustion of the pyrolysis syngas in a reciprocating gas engine. This is

	Title: **Sewage sludge advanced AD with advanced energy recovery (pyrolysis) – Item 11**
	due to the presence of contaminants in the syngas such as tars which clog valves and other moving parts.
9	***Example plants or TRL*** The pyrolysis aspect of the technique as a whole is at an early stage of development; the advanced AD element is however commercially proven.
	TRL / 5 / Only pilot studies have been completed for the whole end-to-end process.
10	***References***

	Reference	Strength of Evidence
[1]	UK Department of Energy and Climate Change and UK Water Industry. Cost in GBP converted to EUR at 1:1.4.	50%
[2]	UK Department of Energy and Climate Change and UK Water Industry	50%
[3]	CEPI, study expert workshop, March 2016	50%

Other WtE plants

	Title: **Hydro treatment of waste edible oils and fats to produce renewable diesel – Item 12**
1	***Technical description***

An alternative to the traditional fatty acid methyl ester process for converting used cooking oil and animal fat waste streams to renewable diesel is to refine these feedstocks into renewable diesel using hydrogen. One of the benefits of renewable diesel produced in this way is that it can be used directly in engines and fuel distribution systems (as a drop-in fuel, either neat (100%) or blended with fossil fuel with different ratios) as its composition is similar to fossil diesel alternatives, i.e. C_nH_{2n+2} [1]. The process is reported to be compatible with existing fuel distribution systems and engines and meets manufacturer quality requirements.

Following bleaching pretreatment (using acids precipitating out as a salt) to remove impurities from the feedstock, the hydro treatment process consists of three main process steps / reactors:

1) catalytic hydro treatment;
2) stripping;
3) isomerisation.

This process is a continuous process during which the feedstock flows from one reactor to the next without intermediate storage. The reactors are fixed bed reactors specially designed to withstand the high pressure and temperatures needed for the process. Process conditions are:

Pressure: min. 30 bar;

	***Title:* Hydro treatment of waste edible oils and fats to produce renewable diesel – Item 12**
	Temperature: min. 265°C. The process requires the production and use of both hydrogen and steam.
2	***Costs*** The most recent plant constructed utilising this technique in Rotterdam in 2011 has an output capacity of 1 million tonne per year of biodiesel (using both waste and non-waste feedstock). This extremely large plant had an investment cost of approximately EUR 670 million [2].
3	***Achieved economic benefits*** Much of the global market for biofuels is driven by demand in the United States (in particular California) where EISA legislation requires minimum volumes of biofuels to be supplied to the US market otherwise a waiver fee is applicable. This is a significant export opportunity for European companies. In Europe, incentives are being offered in Member States for the production and sale of renewable transport fuels.
4	***Operational data*** Operational data has been provided for a plant in Singapore producing renewable diesel [3]: ***Feedstock and consumables***: 1.21 million tonne per year waste animal fats, waste edible oil (e.g. used cooking oil) (30,000 tonne per year rejects) 3,800 tonne per year hydrogen ***Annual production***: 1 million tonne per year renewable diesel Smaller quantities of naphtha and propane-rich off-gas There are also production plants in Finland, the Netherlands, Italy and Sweden.
5	***Environmental and/or human health benefits and drawbacks*** Renewable diesel has the advantage that it provides lower NO_x and particulate emissions than conventional fossil diesel and can therefore assist with improving air quality in urban areas. Renewable diesel produced using this process is demonstrated to provide a reduction of up to 85% in greenhouse gas emissions as calculated in accordance with the Renewable Energy Directive. This form of technique can also utilise crop-based feedstocks. This needs to be monitored to ensure waste feedstock is used where possible and any crop feedstocks added are from environmentally certified sources. Animal by-products feedstock (Category 2 and 3) has been approved as a safe feedstock. Category 1 by-products are not yet approved for use.
6	***Technical considerations relevant to applicability*** Traditional renewable diesel is limited in applicability as it is strictly limited in the quantity that manufacturers will permit for use within internal combustion engines. Where renewable diesel from hydro treatment can be used as a direct

	Title: **Hydro treatment of waste edible oils and fats to produce renewable diesel – Item 12**
	replacement for fossil diesel, this will enhance the applicability of the product.
7	***Driving forces or barriers for implementation including feedstock availability*** Drivers: • The Renewable Energy Directive requires a 10% reduction in carbon emissions by 2020 in all EU-28 Member States. This is driving the development of low-carbon biofuels processes. • As this technique can produce a jet fuel, this is a key advantage as there are currently no alternative means of jet propulsion other than the combustion of fuel in a jet engine (i.e. road vehicles can be run on electric power or hydrogen fuel cells). Barriers • From feedstock availability data presented in Task 1, it was estimated that 500,000 tonnes of edible oil and fats waste were collected in the EU-28 and an equivalent amount of biodiesel was produced. This is only 1% of the total available waste in the EU-28 so there is therefore quite a limited feedstock. The process can also utilise non-wastes such as palm oil as feedstock but this is not the preferred option.
8	***Residual risks*** • With many large plants providing significant quantities of biofuel, the residual technology risks are considered low.
9	***Example plants or TRL*** There are many large plants globally with a total capacity of 3.5 million tonnes provided by a number of suppliers. TRL: 9+
10	***References***

	Reference	**Strength of Evidence**
[1]	Finnish Ministry of the Environment, April 2016	90%
[2]	Neste, March 2016	90%
[3]	Finnish Ministry of the Environment, April 2016	90%

	Title: **Two-stage combustion with plasma – Item 13**
1	***Technical description (Emerging technique)*** Plasma is the term that applies to a range of technologies that involve the use of a plasma torch or arc. Waste is exposed to extremely high temperatures (over 5,000°C / 10,000°F) in the presence of controlled amounts of steam, air and oxygen. Waste is converted to syngas, composed primarily of carbon monoxide (CO), hydrogen (H_2) and other gaseous constituents. The syngas can then be cleaned and used within gas engines for electrical and heat energy recovery. Materials which are not gasified are vitrified leaving the bottom of the gasifier as an inert glass-like slag.

	***Title:* Two-stage combustion with plasma – Item 13**
	Plasma arc processing has been used for many years for the treatment of waste, in particular hazardous waste, such as incinerator fly ash and chemical weapons, and to convert it into non-hazardous slag. Plasma gasification is still an emerging technology in terms of its application to mixed waste streams, but there are a number of examples of the technology being utilised to convert municipal solid waste to energy, with the potential to achieve higher efficiencies than other energy from waste systems. High efficiencies are attributed to the high temperatures involved, in addition to the high heat density and almost complete conversion of the carbon-based materials to syngas, and the conversion of inorganic materials to slag. The two-stage combustion with plasma process has several steps. The first step will typically be to pretreat the feedstock to ensure it is homogeneous and dry, and also to remove recyclable materials. The second step is to gasify the waste, where the carbon in the waste streams will be broken down into gases, and the inorganic materials will melt into a liquid slag. The slag will be tapped off and cooled. The third stage is to treat the syngas further with a plasma torch, which results in a polished, high-quality syngas. A demonstration plant has been constructed in Morcenx, 100km south of Bordeaux, which utilises 50,000t/yr of commercial and industrial waste plus 7000t/yr waste wood fuel and 30,000t/yr of solid recovered fuel (8t/hour). The Solid Recovered Fuel is produced on site from commercial and industrial waste. Waste is shredded and inerts and metals removed. If necessary, waste is dried using heat from the process. All fuels are mixed to ensure a homogeneous fuel to optimise the process. The prepared fuel is fed into the gasification where it is converted to a syngas. The gas is then refined using a patented Turboplasma process. The plasma torch uses 10MW, which is maintained for approximately 1 second. This heats the syngas to 1200°C which thermally cracks the syngas. The Turboplasma technology acts to polish the syngas, in that it reduces the amount of tar formed during the gasification reaction. The syngas obtained can then be used for chemical applications or for electricity production. In the Morcenx facility, the syngas is then cooled, its heat recovered, then filtered. At this stage, the syngas is of commercial quality. The syngas is injected into gas engines to produce electricity. Heat from both the gasification process and the gas engines is used to raise steam in a turbine, generating 11MWel of power. 18MWth of heat is used deliver heat to a wood dryer which is used to dry wood chips to <20% moisture content and there are plans to also supply heat to a greenhouse. The electrical efficiency of the CHO Power system is stated as being able to reach 35-40%. Other companies have also developed two-stage processes which combine fluidised bed gasification with plasma technology [3]. Such processes use a bubbling fluidised bed gasifier. The syngas produced is then treated in a direct current (DC) plasma converter that polishes the gas by removing the organic contaminants and collects the inorganic material in an inert, molten slag. This technology is currently at the demonstration stage.
2	***Costs*** The capital costs for this technology are likely to be higher than those of conventional combustion as the immaturity of the technology, when applied to municipal waste, is not sufficient to secure as much investor confidence or for competition amongst suppliers to drive down equipment costs [1].

	Title: **Two-stage combustion with plasma – Item 13**
3	***Achieved economic benefits*** The economic benefits of this technology include: • income from gate fees for incoming waste; • income from sale of recyclables; • income from sale of power – electricity, or liquid fuels and other chemical commodities that can be derived from the syngas.
4	***Operational data*** Due to the low TRL, there is no publically available operational data.
5	***Environmental and/or human health benefits and drawbacks*** Some operators claim high efficiencies when compared to conventional combustion [2]. A further environmental benefit is that the syngas can be cleaned, via the plasma torch polishing, and therefore flue-gases should require less clean-up, and this should be at a lower cost than the post-combustion cleaning of conventional combustion flue-gases.
6	***Technical considerations relevant to applicability*** Refuse-derived fuel such as that used in combustion or gasification can contain a high quantity of ash and volatile materials [3]. These can decrease the thermal output in the combustion or gasification process, resulting in high ash clinkering, and increasing the emission of tars and CO_2. This in turn can affect the potential for achieving clean syngas for further industrial use. This technical issue can be addressed by using the two-stage process which separates the primary gasification from the plasma torch polishing which can remove the organic contaminants from the gas.
7	***Driving forces or barriers for implementation including feedstock availability*** Drivers: • Potential to utilise higher efficiency energy recovery systems. • Processing of organic waste into combustible syngas for electric power and thermal energy. • The plasma torch process results in a polished, high-quality syngas which can be used in gas engines or further upgraded or synthesised to other products. • Can be used for the reliable destruction of hazardous wastes. Barriers: • Requires pretreatment or specific feedstocks. • Large initial investment costs.
8	***Residual risks*** • Limited commercial-scale examples. • A number of plasma processes have experienced difficulty in achieving commercial viability, where technical issues have caused low availability. • High capital costs.
9	***Example plants or TRL***

TRL	8	There is a commercial-scale

	Title: **Two-stage combustion with plasma – Item 13**		
			demonstration plant in France, with other plants in development using similar plasma technology.

10 ***References***

	Reference	**Strength of Evidence**
[1]	Ducharme, C, Technical and economic analysis of Plasma-assisted waste-to-energy processes, Thesis, 2010	80%
[2]	CHO Power brochure	60%
[3]	Materazzi, M., et al. Performance analysis of RDF gasification in a two stage fluidized bed–plasma process. Waste Management, 2015	90%

***Title:* Fuels from MSW – Item 14**

1 ***Technical description (Emerging technique)***

In addition to being used directly to generate heat and power, municipal waste and other carbon containing wastes can be converted into intermediate liquid and gaseous fuels, including ethanol. The biofuel content of the fuel produced will be based on the biogenic content of the MSW input.

Ethanol is traditionally produced either through the fermentation of sugar and starch or through the hydrolysis and fermentation of cellulosic material. Bioethanol is produced mainly from sugar- or starch-rich food crops. However, ethanol can also be produced by treating a certain range of organic fractions of waste. Different technologies exist, each of which involves separate stages for hydrolysis (by enzymatic treatment), fermentation (by use of micro-organisms) and distillation.

An example of this is the conversion of pretreated waste to a syngas, which is subsequently then converted into fuels and commodity chemicals, using commercially available catalysts. The process will typically consist of feedstock preparation, gasification, cleaning and conditioning of the syngas, and finally synthesis of the syngas in the products, which can include methanol and ethanol. The Fischer-Tropsch process used for synthesis is a combination of chemical reactions which is used to convert syngas into liquids hydrocarbons.

The syngas produced can be used in boilers and engines or turbines, or can be used to synthesise a range of liquid hydrocarbons including distillate fuels (including diesel fuel and kerosene), alcohols (methanol and ethanol) and fertilisers (ammonia).

Waste-based ethanol can be refined from a number of industrial and municipal sources of waste. There are three main techniques for the conversion of waste to ethanol: [1]

- *Biochemical ethanol processing:* This process uses enzymes to break cellulose in the waste into simple sugars, such as glucose. These are then pretreated with an acid, alkali or steam, before the enzymic conversion in to ethanol.
- *Gasification and Fischer-Tropsch*: This process first gasifies the feedstock in a gasification chamber, at temperatures in excess of 700°C and in the presence of limited oxygen and/or steam. The syngas is then converted into diesel by the addition of catalysts, and at temperatures of 150-300°C.

	Title: **Fuels from MSW – Item 14**
	• *Pyrolysis:* Unlike gasification, pyrolysis of waste takes place at high temperatures but in the absence of oxygen. Waste is converted in to oil, char and syngas. The oil can be upgraded by to diesel. Ethanol can be used as a transport fuel as an alternative to replace petrol or diesel, in power generation by thermal combustion, as a fuel in co-generation systems and as a feedstock in the chemicals industry.
2	***Costs*** The conversion of wastes to bioethanol is understood to be possible at a lower cost than traditional crop-based feedstocks as the feedstock is available at a low cost, or can be subject to a gate-fee income, as opposed to the cost of cultivating crop-based feedstocks. However, the capex and opex costs are likely to be higher than for crop-based ethanol due to the feedstock preparation required, and other technical factors associated with using a less homogeneous feedstock.
3	***Achieved economic benefits*** Economic benefits are linked to oil prices as this also determines the production cost of competitors to biofuel, i.e. fossil transport fuels. The production costs of agricultural commodities are also dependent on the movement of oil prices. Therefore the economics of the production of bioethanol from wastes, and in particular municipal solid wastes, can be an important driver.
4	***Operational data*** The majority of advanced biofuel plants currently producing ethanol from second generation feedstock (which excludes feedstock such waste edible oils) are relatively small-scale. For example, there are currently five operational plants in Finland using one variant of biochemical ethanol processing. The sum of the production capacities of these five plants is 15 million litres of bioethanol per year which represents an average output of 3 million litres (approx. 2,400 tonnes). A new plant producing bioethanol from sawdust is under construction and should be started in 2016. This will add to the production capacity by 10 million litres.
5	***Environmental and/or human health benefits and drawbacks*** Life-cycle CO_2 costs are lower than for fossil fuels or crop-based biofuels [2]. In many parts of Europe where municipal solid waste is still predominantly landfilled, its conversion to biofuels would provide significant GHG savings. The displacement of GHG emissions for ethanol from municipal solid waste is estimated at -225g CO_2e/MJ [1].
6	***Technical considerations relevant to applicability*** Whilst waste offers a stable and cost-effective feedstock for ethanol production, the technology for conversion of wastes to biofuels is less proven than crop-based and other first generation conversion technologies. A further technical consideration is that municipal solid waste may require extensive pretreatment, i.e. a Solid Recovered Fuel may need to be produced, as opposed to raw residual waste. However, the technique is applicable to a wide range of organic wastes.
7	***Driving forces or barriers for implementation including feedstock***

	Title: **Fuels from MSW – Item 14**
	availability Drivers: • The use of waste-derived bioethanol can contribute to mitigating climate change, and deliver additional benefits such as reducing land competition between energy and food crops. • There are potential economic benefits achievable from using low-value feedstocks. • The technology could be applicable to the on-site conversion of some specific organic waste streams that are difficult to economically transport for disposal or treatment, i.e. liquid waste streams from food and beverage processing. • Potential to increase the value of high-value utilisation of low-value waste streams, improving revenue for the industries that produce and process these residue streams. • Some conversion processes can convert over 40% of the waste input energy into biofuel. Where heat use is not possible, this is a potential route to increase the energy efficiency of WtE. Barriers: • Competing uses of waste feedstocks could be a barrier in some locations. • The collection of organic waste feedstocks may not be widely deployed in some Member States. • Technologies could still be considered immature, with investors lacking confidence. • There is a call for more policy support and incentives, including increasing targets for the use of biofuels in transport.
8	***Residual risks*** • Limited commercially. • Competition with other proven energy from waste technologies, impacting on feedstock cost and security of supply. • Price volatility of competing products.
9	***Example plants or TRL*** Example plants include the following: Edmonton [3] – The Edmonton plant uses patented technology which chemically recycles the carbon molecules contained in post-sorted municipal solid waste (after recycling and composting) by converting these first into a syngas, which is then converted into fuels and commodity chemicals, using commercially available catalysts. The thermochemical process consists of four steps: feedstock preparation, gasification, cleaning and conditioning of syngas, and catalytic synthesis. In this technique, waste feedstocks are converted into methanol, ethanol or other chemicals Finland and Sweden [4] - There are five plants which convert sugar- and starch-rich waste streams from bakeries, breweries and potato processing factories into ethanol. They also have a plant which converts the biological fractions of municipal solid waste.

	Title: **Fuels from MSW – Item 14**		
	TRL	9	Some commercial-scale process demonstration examples, with more in development.
10	***References***		

	Reference	**Strength of Evidence**
[1]	Wasted: Europe's Untapped Resource – An Assessment of Advanced Biofuels from Waste & Residues	90%
[2]	Recreate: Policy Brief No. 2, November 2015, Producing Bio-ethanol from residues and wastes	90%
[3]	Information provided by Enerkem	60%
[4]	St1 Biofuels White Paper: Creating New Business from Waste-Based Advanced Ethanol – www.st1biofuels.com	70%

4.10 Discussion

4.10.1 Threats and opportunities for full deployment of proven techniques

As technology progresses, the landscape in which WtE operates is subject to constant change. The table below presents some of the threats and opportunities for proven WtE technologies such as incineration, CL plants and anaerobic digestion.

Opportunities	Threats
Greater support from authorities for the deployment of district heating and cooling. This will provide additional revenues for WtE plants where heat is able to be exported.	Continued poor public perception of incineration, principally due to emissions.
Residue treatment to reduce operational cost (please also refer to Section 4.10.3 for more detail).	Lack of grid access priority for WtE. Where intermittent renewable power sources such as wind and solar can feed into the grid at periods of peak energy production, baseload power from WtE plants may not be able to be sold at a good price. If WtE power was prioritised by the grid, power revenues would be higher and more stable.
Bottom ash is highly recyclable (please also refer to Section 4.10.3 for more detail)	Unforeseeable changes in WtE treatment capacity required due to poor implementation of the waste hierarchy. In recent years this has affected northern Europe, where over-capacity exists as EU recycling targets have increased.
Firmer application of landfill diversion targets will divert more non-recyclable waste to energy recovery.	Lack of good waste data (especially C&I data) makes capacity planning more difficult.
Potential for landfill bans for certain materials such as organics will hugely benefit anaerobic digestion.	Planning and permitting remains a significant burden on developers.
Firmer application of existing legislation associated with the Landfill Directive to avoid premixing (dilution) of hazardous waste. This would encourage more incineration of hazardous waste with energy recovery.	AD digestate can be difficult to utilise on land depending on: • seasonal constraints on spreading; • restrictions due to nitrogen-sensitive zones; • any plastic contamination in the fertiliser product which is contained in the feedstock and cannot be removed during the process.

Opportunities	Threats
Regulatory standards for both refuse-derived fuels (RDF) and Solid Recovered Fuels (SRF) can help to improve the quality of feedstock. Currently the standard of RDF can be highly variable.	As utility-scale power generation moves away from carbon (e.g. coal- and lignite-fired power stations are replaced by solar, wind, nuclear, tidal), WtE will lose its current low-carbon advantage. This shift is probably a number of decades away where utility-scale generation carbon intensity drops below 50% (where the biogenic content of waste utilised in WI plants is around 50%).
Mandatory requirements for source-separated collection of organic waste from households would hugely benefit anaerobic digestion.	Some emerging techniques produce a syngas which is able to be processed into a number of products such as fuels/biofuels and polymers, not just power and heat. If emerging techniques can progress to commercial viability producing large quantities of heat and power, then this could be a threat to proven WI plants.
Minimum standards for energy conversion efficiency (R1) are made mandatory by EU-28 national governments (or local authorities in municipalities) or incentivised by improving connections to heating or cooling networks.	

4.10.2 Threats and opportunities for full deployment of emerging techniques

For emerging techniques which produce syngas and biofuels, there are further opportunities and threats which are specific to these technologies.

Opportunities	Threats
Renewable Energy Directive (RED) requiring more renewable transport fuels such as those produced from biogenic waste. Emerging WtE techniques can help fulfil this role.	Lack of support for non-biogenic wastes such as plastic, which can be processed into fuels.
Government financial incentives for emerging technology can support the development and commercialisation of emerging techniques	Changes in government financial incentives for emerging technology have occurred frequently in past decades, which causes uncertainty for investors and therefore prevents long-term investment and development
Versatility of syngas to produce not only heat and power, but also useful products.	Lack of a market for waste-derived CO_2. Many potential users are sensitive to using waste-derived products in food

Opportunities	Threats
	products.
	Advanced processes can be highly sensitive to waste feedstock variation.
	Oil price volatility hinders long-term investment and development in emerging processes which produce fuels.
	High-profile ACT failures damage confidence in emerging technologies for both developers and investors.

4.10.3 Ancillary WtE techniques to help address threats and opportunities to WtE

There are a number of mature and emerging techniques which are ancillary to the main energy recovery techniques already discussed within this study which nonetheless are key in helping address the threats and opportunities associated with the wider deployment of WtE.

4.10.3.1 WtE residues

A key issue for WtE is the disposal of residues. The disposal of residues can be very costly for an operator and incorrect disposal can cause environmental harm. For waste incineration, there are two main residues which require disposal; these are Incinerator Bottom Ash (IBA) and Air Pollution Control Residues (APCr).

Incinerator Bottom Ash

IBA is an inert material and there are opportunities to recycle both the post-burn metals and the ash itself. The ability to recycle IBA is important in establishing the environmental credentials of waste incineration.

Although very common in some EU Member States (e.g. Denmark, the Netherlands and Germany), recycling of IBA is not fully established in Europe and is therefore a mature but developing technique. Recovery of IBA as a secondary aggregate has three main steps of crushing, maturation/weathering and screening/separation:

- Crushing is a general pretreatment technique to refine particle size for the use of IBA in construction materials. During crushing, IBA can sometimes be washed with a leachate to remove heavy metal components.
- Maturation or weathering exposes IBA to the atmosphere for an extended period, after which it is ready for processing. Exposure to the atmosphere aids in stabilising the material through hydration and carbonation which reduces the pH and removes soluble salts.
- The weathered IBA is then processed by a series of screens and conveyors, coupled with magnets and eddy current separators. Recovered metals are collected for recycling and grading of material sorted by particle size. Through the process small reject materials or fines will commonly be disposed of to landfill. However, more advanced processes are able to extract metals from the fines and retain the fine

aggregate fraction for recovery. The separated grades of aggregate are then stockpiled for collection and use.

IBA exhibits similar properties to natural aggregates and its use can give significant environmental and social benefits. Such examples of these benefits are: reducing the quarrying of primary aggregates and associated processing; additional recovery of recyclable material through ferrous and non-ferrous metals extraction; IBA landfill reduction; and a lower carbon footprint compared to primary aggregates.

Air Pollution Control Residues

APCr is classed as hazardous waste. The most common disposal route is currently pH neutralisation prior to disposal in hazardous landfill. However, APCr requires a derogation to enable this disposal route as the concentration of contaminants is up to three times above the upper permissible limit. It is widely acknowledged that this derogation is likely to be withdrawn in the coming years and therefore alternative treatment methods will be required.

Some examples of emerging APCr treatment routes to avoid disposal to hazardous landfill are as follows:

- Vitrification which involves the melting of APCr and a glass precursor (silica) at high temperatures to form an amorphous glassy clinker and bind/encapsulate the residue. The high temperatures effectively destroy dioxins, furans and other toxic organic compounds. This treatment allows for the reuse of a melted slag as a resource. APCr vitrification is integral to high-temperature gasification and melting technologies.
- Accelerated Carbonation Technology involves a controlled, accelerated version of the naturally occurring carbonation reaction. When CO_2 reacts with lime and calcium compounds in APCr, limestone is formed. As a result, the chemical and physical properties of treated materials are improved, including neutralised pH and reduced leachability of heavy metals. The finished aggregate is used as a replacement raw material for virgin aggregate in lightweight concrete blocks. Chlorides in APCr act as an accelerant and are beneficial to the block making process
- Cement production: APCr contains calcium oxide (CaO), silica (SiO_2), iron oxide (Fe_2O_3) and alumina (Al_2O_3), similar to the composition of raw materials for cement production, and can be used to replace limestone dependent on the quality of the final product and market acceptability. A potential application for APCr is low-energy cements, also called calcium sulphoaluminate cements, which can be synthesised at low temperatures and present high strength and rapid hardening. APCr provides a source of both alumina, for the formation of calcium sulphoaluminates, and silica, for the formation of calcium silicates.
- Concrete is a construction material that consists of cement, aggregate, water and admixtures. It solidifies and hardens after mixing and placement due to a chemical process known as hydration and the reactions that occur are the basis of the stabilisation and solidification (S/S) process. The S/S process is applied worldwide for the treatment of hazardous waste. Since the size of APCr particles is small (<150μm), they become encapsulated inside the concrete matrix. The main disadvantages are that the physical integrity of the product may deteriorate over time and that APCr mass and volume increases with treatment.

4.11 Task 2 - Conclusions on technical improvement potential of WtE

The main conclusion to be drawn from Task 2 of this study is ‘what are the key energy efficiency improvement techniques which will be able to change the landscape of WtE throughout the EU-28, particularly in the short term?' This has been examined for each of the five WtE pathways.

4.11.1 Combustion plants co-incinerating waste

A number of proven improvement techniques are available that would allow waste to be co-incinerated with primary combustion fuels at a relatively high net electrical efficiency. The main drawbacks to some of these techniques are that some are strictly limited in terms of the quantities of waste that can be co-fired (without causing deleterious effects to the combustion plant) and, as there are no thresholds for WID compliance, all combustion plants co-firing waste need to be permitted by the relevant national Environment Agency and meet EU-wide IED emissions standards.

The most promising of the improvement techniques examined in this group are:

- The production of gas products from waste which can be fired in high-efficiency combustion plants and at a relatively high substitution rate. Syngas produced from waste can be fired in coal-fired plants with a net electrical efficiency of between 36% and 40% and at a substation rate of up to 40%. Biomethane produced from waste which is of a similar standard to natural gas can be fired in CCGT power stations with an electrical efficiency of over 50%.
- Biomass and prepared fuels such as SRF can be co-fired in fluidised bed units at an electrical efficiency of around 30%.

4.11.2 Waste incineration

Waste incineration has traditionally struggled to achieve high energy efficiency as the waste feedstock is not homogeneous and contains pollutants which cause rapid corrosion to boiler systems at the high steam temperatures and pressures required to achieve high electrical efficiency. This is despite major advances in steel corrosion protection such as nickel-based coatings.

The most promising of the improvement techniques examined in this group are:

- innovative ways of superheating steam without serious corrosion effects;
- extracting low-grade energy from flue-gases;
- although district heating is very much an established technique, it is the most ready-to-use opportunity to increase the energy potential of the sector.

It is possible that the net electrical efficiency of waste incineration can rise from a current average of around 25% to around 33% through the application of these techniques.

4.11.3 Cement and lime production

Cement kilns are able to both use the energy and recycle a proportion of the material content of waste. In this respect they are a valuable pathway for waste-to-energy. Most of the gains in energy efficiency have been from incremental changes in detailed design which have increased energy efficiency from 66% several decades ago to the latest designs which offer 85% energy efficiency.

It is also noted that the levels of waste substitution (alternative fuels in lieu of fossil fuels) could rise from current average levels of around 40% to a realistic target of 70%. This would increase the total energy derived from waste in the EU-28, but does not change the energy efficiency of the technique.

Cement kilns do require waste feedstock to be pretreated to a high standard of quality which also requires energy input, estimated at 1.7%.

4.11.4 Anaerobic digestion

Anaerobic digestion (AD) has been a steadily growing pathway for energy recovery from organic wastes with a high moisture content (up to 95%) which in their natural form do not have sufficient calorific value for combustion. Anaerobic digestion in its basic form will only ever convert around 50% of the energy content of the feedstock into a useable form as biogas, which then must be converted into energy. Traditionally, gas engines have been utilised to produce power, which extract approximately 40% of the biogas energy as electrical power, reducing the overall process electrical efficiency to below 20% once parasitic loads have been accounted for.

The most promising of the improvement techniques examined in this group are the following:

- Improvement techniques such as gas-to-grid and more advanced forms of AD which offer the potential to improve the energy efficiency performance, with the potential to extract up to 40% of the feedstock energy input as useful energy. Some techniques such as gas-to-grid are quite location-dependent (which impacts on the technique applicability) but biomethane compression or liquefaction can help overcome this issue, albeit with slightly less overall energy efficiency.
- There are more advanced emerging techniques which can further process sewage sludge and other organic feedstocks to more completely extract the available energy and also reduce the amount of by-product for disposal. Although the digestate by-product from AD can have value as a soil improver, replacing energy- and greenhouse-gas-intensive manufactured fertilisers (with particular regard to nitrous oxide emissions), distribution to land can be problematic depending on demand from agricultural outlets.

4.11.5 Other WtE processes

This category has focused on emerging WtE improvement techniques which have attracted a great deal of attention in recent years.

Pyrolysis and gasification of homogeneous waste streams such as waste wood, tyres and plastic appear to have had some success in terms of commercial applications. Gasification and pyrolysis of MSW and other mixed wastes has not been commercially proven to date, even with extensive pretreatment of the waste to achieve better homogeneity. There have been many costly failures of MSW gasification and pyrolysis plants throughout the EU-28 Member States in the past decades. A number of successful demonstration-scale plants using emerging techniques have also failed to make the jump to commercial scale.

Considering the requirement for extensive waste pretreatment and the production of combustion support materials such as oxygen or steam, gasification and pyrolysis technologies (where the syngas produced is combusted in a boiler or gas engine) are unlikely to achieve higher overall net electrical efficiencies than conventional combustion plants. Conventional combustion plants have been proven to reach net electrical efficiencies of well over 30% through the application of improvement techniques.

The most promising of the improvement techniques examined in this group are the following:

- The production of syngas, where the gas is cooled and extensively cleaned before being combusted in a high-efficiency boiler. These plants have been operating for over five years and the data provided by Finland has shown steady progress towards commercially viable performance[130].

- As the combustion of syngas in a gas engine or boiler has proved to be limited in terms of both energy efficiency and reliability, the highest potential for emerging WtE processes may be those techniques which are able to convert cool, clean syngas to biomethane, fuels or biofuels. If these technologies can be commercially proven, over 40% of the waste input energy content may be recoverable.

[130] https://waste-management-world.com/a/all-good-as-140-mw-finnish-waste-gasification-plant-passes-25-000-hours.

5 Task 3 - Outlook on developments in the waste-to-energy landscape

This chapter aims to explore how the waste-to-energy landscape may evolve in the coming years. Issues with data quality highlighted in Task 1, as well as significant uncertainties on how waste generation and management may develop in individual Member States, complicate the calculation of precise forecasts or scenarios. Nonetheless, based on past evolutions and considering the waste hierarchy, the following developments may be possible in the short to medium term:

- Where landfill still represents a considerable share in the existing waste management strategy for one or more waste streams in a given Member State, this will be reduced substantially in the future through better waste prevention, more reuse, increased recycling and more incineration, in this order of preference according to the waste hierarchy. Member States with low landfill levels can help provide an indication of what is already practically achievable today for the different waste streams, although it depends on whether the alternative waste management options applied in those countries are already in line with the waste hierarchy.
- The generated amounts of mixed streams such as household and similar waste, mixed and undifferentiated materials and sorting residues are expected to decrease thanks to better and more widespread source-separated collection of waste in the future.
- The energy efficiency figures of existing and new waste-to-energy plants are likely to experience an increase towards those of the best plants encountered in each category, thanks to the technical improvements that are available today and that will be in the near future.

With these elements in mind, the waste-to-energy landscape evolutions are assessed in two steps in this task:

- What role may waste-to-energy play for the different waste streams in the future?
- What will be the expected changes in energy recovered from waste sent to waste-to-energy?

It should be stressed that the sections below provide a very simplified assessment of the possible future evolutions in the waste-to-energy landscape, which does not take into account the following elements:

- demographic and economic evolutions that influence the total and per capita amounts and types of waste produced;
- evolutions of carbon, energy and raw material prices, which may in turn influence the demand for raw materials and energy from waste;
- possible changes in waste exports, imports and level of treatment of generated waste;
- new legislation at national and EU level that may come into force in the coming years;
- National Waste Management Plans of individual Member States and their level of implementation.

5.1 Possible future role of waste-to-energy for the different waste streams

In this section, a tentative outlook is provided on how waste-to-energy figures could change in the near to medium future, taking into account:

- the existing quality of the statistical data, as discussed in Task 1;
- the existing waste management options for a given waste stream across the different Member States, in particular for streams with currently high overall landfill and/or incineration shares for the EU-28;
- possibilities to change generation patterns of the different waste streams, through better and more widespread source-separated collection and recycling.

It should be noted that the statistical data discussed in Task 1 mainly provide direct information on waste-to-energy processes that are linked to incineration (R1 & D10 figures). Whereas incineration and co-incineration activities represent the majority of waste-to-energy operations today, the waste-to-energy spectrum is obviously broader than (co-)incineration alone. As discussed in Task 1, anaerobic digestion also has an important share in today's recovery of energy from wastes, whereas other waste-to-energy processes currently play a minor role. However, anaerobic digestion falls under the definition of 'recovery other than energy recovery' as it recovers both energy and useful materials (digestate fertiliser). Nonetheless, for the waste streams discussed in Task 1 and evaluated in this section as well, anaerobic digestion is only relevant for anaerobically degradable materials, and thus mainly for animal and vegetal wastes (A&VW) and sewage sludge. Whereas anaerobically degradable materials may be present as minor fractions or impurities in other streams (e.g. food waste in HSW), AD processes are not suited to efficiently treating such other waste streams. Therefore, the following subsections will focus on incineration (R1 & D10) when discussing potential future developments in the waste-to-energy landscape, with the exception of A&VW and sewage sludge, for which AD is discussed.

5.1.1 Wood waste

Landfill, incineration (D10 & R1) and 'recovery other than energy recovery' for wood waste represented, respectively, 0.9%, 53% and 46% of the waste treatment and disposal options on average for the EU-28 in 2012.

Task 1 highlighted some minor issues with the reporting of wood waste (e.g. in Finland), due to the different forms of wood used for production processes and for energy recovery processes. Moreover, it was stated that some of the wood waste is hazardous, which may hamper recycling or impose restrictions on incineration, although hazardous wood wastes only accounted for a few per cent of the total reported wood waste data.

While landfilling figures are very low for wood waste in most Member States, Annex 6 reveals that incineration and 'recovery other than energy recovery' figures differ quite substantially between Member States. Many Member States are already achieving high 'recovery other than energy recovery' rates, up to 100%, whereas others still send large fractions of wood waste to incineration. Given the overall reported low share of hazardous material and the various material recovery possibilities, it may therefore be possible that incineration will further decrease moderately to substantially for this waste stream in the future, in line with the waste hierarchy.

5.1.2 Plastic waste

Landfill, incineration (D10 & R1) and 'recovery other than energy recovery' for plastic waste represented, respectively, 11%, 13% and 75% of the waste treatment and disposal options on average for the EU-28 in 2012.

Task 1 clarified that the Eurostat definition of plastic waste only covers non-hazardous waste. Moreover, mixed packaging, which may contain a large plastic fraction, falls within the category of 'mixed and undifferentiated materials'. Hence the amounts of generated plastic waste reported by Eurostat (17 million tonnes in 2012) are lower than the overall figures for post-consumer plastics reported by Plastics Europe (25 million tonnes in 2012).

Given this definition of a non-hazardous stream excluding mixed materials, it is not surprising that high 'recovery other than energy recovery' rates are already achieved in most Member States, as can be seen from the data in Annex 6. It should be possible that current landfill figures will continue to decline in favour of more recycling, with the existing moderate incineration figures remaining relatively stable or even experiencing a further moderate decline.

5.1.3 Paper waste

Landfill, incineration (D10 & R1) and 'recovery other than energy recovery' for paper waste represented, respectively, 0.5%, 0.9% and 99% of the waste treatment and disposal options on average for the EU-28 in 2012.

Given the very low landfill and incineration rates, as well as very high 'recovery other than energy recovery' rates already encountered across the Member States, little change in incineration is expected for this easily recyclable, non-hazardous waste category.

5.1.4 Textile waste

Landfill, incineration (D10 & R1) and 'recovery other than energy recovery' for textile waste represented, respectively, 6%, 6% and 88% of the waste treatment and disposal options on average for the EU-28 in 2012.

Task 1 clarified that the Eurostat definition of textile waste only covers non-hazardous waste. Taking into account the reuse and material recovery possibilities for this waste stream, as well as the already low landfill and incineration rates, it is possible that incineration remains relatively stable or even experiences a further moderate decline in the future.

5.1.5 Waste tyres

Landfill, incineration[131] (D10 & R1) and 'recovery other than energy recovery' for waste tyres represented, respectively, 3%, 48% and 49% of the waste treatment and disposal options on average for the EU-28 in 2012.

Task 1 showed that there were substantial issues with Eurostat data on amounts (in particular from Portugal) and treatment methods (in particular on landfilling). For this reason, ETRMA data were used instead in the analysis in this study.

Data presented in Annex 6 demonstrate that five Member States already feature 'recovery other than energy recovery' figures of more than 80% for waste tyres.

[131] Including co-incineration in cement kilns whereby non-combustible parts of the tyres are incorporated in the produced materials.

Taking into account the reuse and material recovery possibilities for this waste stream, and the already low landfill rates, it seems possible that incineration of waste tyres will experience a moderate to substantial decline in the future.

5.1.6 Waste solvents

Landfill, incineration (D10 & R1) and 'recovery other than energy recovery' for waste solvents represented, respectively, 0.8%, 60% and 39% of the waste treatment and disposal options on average for the EU-28 in 2012.

Task 1 clarified that the Eurostat definition of waste solvents only covers non-hazardous waste.

While landfilling figures are very low for waste solvents in most Member States, Annex 6 reveals that incineration and 'recovery other than energy recovery' figures differ quite substantially between Member States. Some Member States are achieving high 'recovery other than energy recovery' rates, up to 100%, whereas others send large fractions of waste solvents to incineration. These figures seem to suggest that there is still room for lowering the share of incineration, but it is unclear at present to what extent genuine non-energy recovery is feasible, depending on what falls under the reported category of waste solvents in the different Member States.

In conclusion, the potential for waste-to-energy development for this waste stream can be expected to be anywhere between stable and a substantial decrease.

5.1.7 Waste oils

Due to the lack of relevant data, as discussed in Task 1, no figures on waste management options can be provided for this waste stream.

5.1.8 Chemical waste

Landfill, incineration (D10 & R1) and 'recovery other than energy recovery' for chemical waste represented, respectively, 13%, 37% and 51% of the waste treatment and disposal options on average for the EU-28 in 2012.

Task 1 revealed that the definition of chemical waste covers a wide range of materials. This may also explain the diverging figures encountered across Member States for 'recovery other than energy recovery', as shown in Task 1 and Annex 6. Therefore, it remains unclear to what extent the share of 'recovery other than energy recovery' can grow in the future to further divert waste from landfill and to what extent it can be a feasible alternative for incineration, higher up the waste hierarchy.

In conclusion, the potential for waste-to-energy development for this waste stream can be expected to be anywhere between stable and a substantial decrease.

5.1.9 Household and similar waste (HSW)

Landfill, incineration (D10 & R1) and 'recovery other than energy recovery' for HSW represented, respectively, 50%, 38% and 12% of the waste treatment and disposal options on average for the EU-28 in 2012.

Data presented in Annex 6 show the large discrepancies between Member States regarding the amounts of HSW treated per capita. While the EU average stands at 274 kg/person, values range from 104 to 453 kg/person, with the 20th percentile value at 213 kg/person and the 80th percentile value at 361 kg/person. These divergent figures may partially be explained by different interpretations of the definition of HSW across the Member States. Nonetheless, of the five countries having the lowest landfill rates

(Germany, Sweden, Austria, the Netherlands and Belgium), four have HSW treated/capita values below the average of 274 kg/person. These data suggest that there is still room for decreasing the generation of such waste, through prevention and source separation. Based on the existing distribution of per capita treated HSW figures across Member States, a decrease of 20% and more of the EU average may seem realistic.

Further data presented in Task 1 and Annex 6 show that most countries with low landfill rates rely heavily on incineration for HSW, with incineration figures often around or even above 90%. In contrast, a small number of countries exhibit considerable shares of 'recovery other than energy recovery' for this stream. They include Italy, Poland, Cyprus and Portugal. However, as pointed out in Task 1, 'recovery other than energy recovery' figures may in many cases reflect waste entering Mechanical Biological Treatment (MBT) plants, rather than waste actually being recovered in ways other than energy recovery, according to expert opinions. This may reveal an important issue for this waste stream, namely that once HSW as a mixed stream has been generated, limited genuine non-energy recovery options remain available.

In conclusion, it can be expected that, in the future, the generation of the mixed stream HSW could decrease, by 20% and more, through more prevention of waste generation and better and more widespread source-separated collection of waste. Notwithstanding lower possible generation figures, the low recyclability of this stream will mean that energy recovery will constitute the main feasible alternative to landfilling. Therefore, it can be expected that incineration will experience a substantial overall increase for this waste stream. Finally, the further exclusion of wet biodegradable materials, which can be sent to AD or composting, as well as of recyclable materials with zero to low calorific value (e.g. metals or glass) from mixed HSW streams may also help increase their calorific value in the future.

5.1.10 Mixed and undifferentiated materials (M&UM)

Landfill, incineration (D10 & R1) and 'recovery other than energy recovery' for M&UM represented, respectively, 28%, 35% and 38% of the waste treatment and disposal options on average for the EU-28 in 2012.

Data presented in Annex 6 show the large discrepancies between Member States regarding the amounts of M&UM treated per capita. While the EU average stands at 66 kg/person, values range from 2 to 341 kg/person, with the 20th percentile value at 13 kg/person and the 80th percentile value at 86 kg/person. These divergent figures may partially be explained by different interpretations of the definition of M&UM across the Member States, and the generation of country-specific waste streams.

Further data presented in Task 1 and Annex 6 show that countries with low landfill rates exhibit very large differences in their shares of incineration and 'recovery other than energy recovery'. Therefore, it remains unclear to what extent the share of 'recovery other than energy recovery' can grow in the future to further divert M&UM waste from landfilling and to what extent it can be a genuinely feasible alternative for incineration, higher up the waste hierarchy.

Nonetheless, M&UM also contains materials that may be good candidates for source-separated collection, e.g. the mixed packaging waste. Hence, the main expected strategy for these materials, as for the mixed stream of HSW, is possibly to reduce the amounts that end up in this category through better waste generation prevention and better source-separated collection of waste. However, taking into account the wide distribution in current per capita generation figures across Member States, it is unclear what reduction in generation is truly feasible.

In conclusion, the outlook for waste-to-energy development for this waste stream can be expected to be anywhere between a substantial increase - in the case of low possible reductions in the amounts generated and low genuine recyclability - and a substantial decrease - in the case of considerable possible reductions in the amounts generated and good recyclability.

5.1.11 Sorting residues

Landfill, incineration (D10 & R1) and 'recovery other than energy recovery' for sorting residues represented, respectively, 52%, 35% and 13% of the waste treatment and disposal options on average for the EU-28 in 2012.

Data presented in Annex 6 show the large discrepancies between Member States regarding the amounts of sorting residues treated per capita. While the EU average stands at 125 kg/person, values range from 1 to 192 kg/person, with the 20th percentile value at 27 kg/person and the 80th percentile value at 137 kg/person.

Further data presented in Annex 6 for Member States with low landfilling rates of sorting residues suggest limited real growth potential for 'recovery other than energy recovery' for this waste stream. Hence, efforts to divert from landfill will mainly have to come from increased incineration.

On the other hand, as outlined in Task 1, more widespread and better source-separated collection is expected to lower the generated amounts of sorting residues. However, it is unlikely that this reduction in generation will be able to fully offset the large amounts that will be diverted from landfill.

In conclusion, it is possible that incineration will experience a moderate to substantial increase in the future for this waste stream.

5.1.12 Animal and vegetal waste (A&VW)

Landfill, incineration (D10 & R1) and 'recovery other than energy recovery' for A&VW waste represented, respectively, 9%, 6% and 86% of the waste treatment and disposal options on average for the EU-28 in 2012.

Given the low landfill and incineration rates, as well as high 'recovery other than energy recovery' rates already encountered across the Member States, it is expected that 'recovery other than energy recovery' will further grow in the future. The latter category also includes anaerobic digestion (AD), which is very important for this waste stream and which actually constitutes a recovery of both materials and energy.

Better and more widespread source-separated collection of waste will probably lead to a better exclusion of the wet biodegradable fraction from other waste fractions, in particular from mixed streams, resulting in an increase in the amounts of A&VW generated. Therefore, anaerobic digestion will likely continue to grow as a 'recovery other than energy recovery' treatment method.

Therefore it is expected that landfill can further decline and that incineration can stabilise or experience a moderate decline. Anaerobic digestion could probably experience a moderate to substantial increase.

5.1.13 Dried municipal sewage sludge

Landfill, incineration (D10 & R1) and 'recovery other than energy recovery' for these waste sludges represented, respectively, 8%, 27% and 65% of the waste treatment and disposal options on average for the EU-28 in 2012.

Data presented in Annex 6 reveal that 90% or more sewage sludge is already destined for 'recovery other than energy recovery' in nine Member States. This often involves a treatment method in which nutrients from sludge are brought back to the soil, through direct spreading of sludge or application of a sludge-derived material (e.g. sewage sludge compost). Other countries rely heavily on incineration, which in some cases is explained by concerns about possible pollution from sludge application to land.

Taking into account the already relatively low overall landfill rates and the unclear growth possibilities for 'recovery other than energy recovery' in Member States with high current incineration figures, the potential for sludge incineration may be situated between stable and a substantial decline.

As explained in Task 1, there is no data on AD of sewage sludge as Eurostat data on waste treatment refers only to the final treatment and AD of sewage sludge is only pretreated before the residues (digestate) are incinerated, put on farmland or landfilled. This lack of data makes it impossible to assess the possible growth of the amount of sewage sludge sent to anaerobic digestion.

5.1.14 Summary overview for the various waste streams

Table 3.61 provides a schematic overview of the state of play and the potential in waste-to-energy development, based on the discussions provided above for the different waste streams.

- The flame symbols represent the annual amounts of waste incinerated per capita on average in the EU-28 (combined R1 and D10 figures from 2012), using a logarithmic scale.
- The arrow symbols represent the potential shifts in incinerated amounts of waste relative to the total amounts of waste treated today for a given waste stream. In most cases, a range is provided, to reflect the uncertainty about the expected evolution.

This way of representing the data allows comparison of the future potential of waste-to-energy for a given waste stream to its role today in the overall waste management strategy for that same waste stream. Therefore, it provides an indication of the possible evolution of the waste-to-energy option. For instance, a future potential increase in incineration of a waste stream being diverted from landfill may be offset by a decrease in the overall amount of that waste stream generated through better prevention and source-separated collection. In such a case, the role of waste-to-energy over time will remain relatively stable.

It is important to stress that, due to the uncertainties and approximations used in the assessments of every individual waste stream, the present methodology does not allow the provision of an assessment of the overall evolution in the waste-to-energy landscape for all waste streams combined.

For the sake of completeness, it should also be noted that the expected better and more widespread source-separated collection of waste in the future will not only reduce the amounts of mixed streams being produced (e.g. HSW, M&UM and sorting residues), but will also increase the generated amounts of other types of non-combustible waste (e.g. glass or metals) and combustible waste (e.g. paper or plastics), due to a shift in waste materials from one waste category to another. However, in line with the waste hierarchy, it is unlikely that the material shifts to the new categories would result in higher amounts of waste being landfilled or incinerated from these categories. Instead, the new additions of source-separated materials in the new categories will most likely contribute to higher amounts of materials sent for 'recovery other than energy recovery', including recycling, and reuse.

Table 3.61: Summary overview of the state of play and likely trends in waste-to-energy development for different waste streams. The flame symbols represent the annual amounts of waste incinerated per capita on average in the EU-28 (combined R1 and D10 figures from 2012). The arrow symbols represent the expected shifts in incinerated amounts of waste relative to the total amounts of waste treated today for a given waste stream.

Waste stream	EU average amount incinerated /capita (R1+D10)	Potential for waste-to-energy development
Wood wastes	🔥🔥🔥	↓ to ↓↓
Plastic wastes	🔥🔥	≈ to ↓
Paper wastes	🔥	≈
Textile wastes	🔥	≈ to ↓
Waste tyres	🔥🔥	↓ to ↓↓
Waste solvents	🔥🔥	≈ to ↓↓
Chemical waste	🔥🔥	≈ to ↓↓
Household and similar wastes	🔥🔥🔥🔥	↑↑
Mixed and undifferentiated materials	🔥🔥🔥	↑↑ to ↓↓
Sorting residues	🔥🔥🔥	↑ to ↑↑
Animal and vegetal wastes	🔥🔥	≈ to ↓*
Dried municipal sewage sludge	🔥🔥	≈ to ↓↓

* Data refers to incineration only, the large fractions of A&VW treated by anaerobic digestion fall under 'recovery other than energy recovery'. Anaerobic digestion could probably experience a moderate to substantial increase.

Legend:

🔥 : incinerated annual amounts below 1 kg/capita.

🔥🔥 : incinerated annual amounts above 1 kg/capita and below 10 kg/capita.

🔥🔥🔥 : incinerated annual amounts above 10 kg/capita and below 100 kg/capita.

🔥🔥🔥🔥 : incinerated annual amounts above 100 kg/capita.

↑↑ : substantial increase of multiple tens of percentage points.
↑ : moderate increase of multiple percentage points.
≈ : relatively stable situation with possible upward or downward change of a few percentage points.
↓ : moderate decrease of multiple percentage points.
↓↓ : substantial decrease of multiple tens of percentage points.

5.1.15 Waste-derived fuels

Waste-derived fuels are not waste streams themselves but have been derived from waste streams. Today, biogas constitutes the most important waste-derived fuel in terms of total energy amounts recovered from waste, followed by biodiesel from waste.

It can be expected that the importance of biogas will increase, most likely substantially, in the near future. The main driver will be better and more source-separated collection of wastes, leading to the exclusion of wet biodegradable wastes from HSW and other streams, which can then be sent to anaerobic digestion to produce biogas. Another factor that may play a role is the growing trend towards production of renewable fuels, especially from waste materials to minimise issues with deforestation or competition with food crops.

The lack of data made it impossible to conduct a specific analysis on the potential of SRF for waste-derived energy production. On the one hand, country-specific waste management regulations such as a landfill ban, and source-separated collection of wet biodegradable waste (which increases the quality and LHV of remaining wastes) could lead to an increase in the production of SRF. On the other hand, more and better source-separated collection of wastes could lead to an increase in recycling and less wastes being transformed into SRF.

5.2 What will be the expected changes in energy recovered from waste sent to waste-to-energy?

In this second step, the improvement techniques have been applied to the available waste streams. This section focuses on proven improvement techniques which can be implemented in the short term and, for this application, an assessment of the total technical improvement potential in PJ has been calculated.

It is recognised that emerging improvement techniques may be able to make a contribution to the technical potential of WtE in the longer term, but this contribution is not able to be reliably quantified at this time.

In Task 1, it was established that the energy contents in the thirteen waste streams analysed in detail within this study are as shown below in Table 3.62.

Table 3.62: Amounts and corresponding energy content of waste streams sent for incineration in the EU-28

	LHV (MJ/kg)	Incineration R1 & D10 (in kt)	Incineration R1 & D10 (in PJ)
		Baseline	Baseline
HSW	9	52,180	470
M&UM	13	11,476	149
Sort Residues	15	22,281	334
Wood	13	27,965	375
Plastics	36	1,705	61
A&VW[1]	15	4,850	77

	LHV (MJ/kg)	Incineration R1 & D10 (in kt)	Incineration R1 & D10 (in PJ)
		Baseline	Baseline
Chemical	25	3,714	92
Paper	17	341	6
Textiles	17	134	2
Solvents	28	1,075	30
Sludge	10	2,306	22
Tyres	29	1,195	35
Total		**129,223**	**1 653**
1 – The average LHV for A&VW is calculated based on the LHV and the amount of waste sent to incineration for the 3 waste streams considered under A&VW.			

In Task 2, it was established that the net annual average energy efficiencies could move from the current average efficiencies to the optimised efficiencies if improvement techniques were implemented. This is shown again in Table 3.63.

Table 3.63: Summary of current and optimised energy efficiency for each of the five pathways

	Energy recovered as electricity efficiency [1]		Energy recovered as heat efficiency [2]		CHP recovery efficiency [3]				Energy recovery to fuel	
	Avg. %	Opt. %	Avg. %	Opt. %	Avg. %		Opt. %		Avg. %	Opt. %
					Electric	Heat	Electric	Heat		
Combustion plants [4]	36	40	-	-	-	-	-	-	-	-
WI plants	22 [5]	33 [6]	72 [7]	80 [8]	17 [9]	51 [9]	27 [10]	66 [10]	-	-
					Total 68		Total 93			
CL plants [11]	-	-	75	80	-	-	-	-	-	-
AD plants	18 [12]	23 [13]	-	-	18 [14]	18 [14]	-	-	-	41 [15]
					Total 36					
Others	20 [16]	35 [17]	75 [16]	80 [8]	-	-	-	-	-	40 [18]

Net annual average efficiency:
[1] 100% electrical load.
[2] 100% heat load.
[3] CHP - 80% of heat sold annually, 100% electrical load.
References:
[4] LCP BREF, coal / lignite pulverised combustion
[5] ISWA CE report 2015, gross existing plant efficiency corrected to net efficiency
[6] AEB Amsterdam / Martin GmBH statistics, refer also *High Steam Parameters for Boilers and Superheaters* proven technique

[7] CEWEP
[8] Ricardo estimate based on known boiler efficiencies
[9] Annual average efficiency based ISWA CE report 2015 existing CHP plant gross efficiencies, corrected to net efficiency with annual average heat load
[10] Annual average efficiency based on optimised AEB / Martin GmBH net electrical efficiency and ISWA CE report 2015 high efficiency CHP plant gross efficiencies, corrected to net efficiency with annual average heat load
[11] CEMBUREAU
[12] ISWA CE report 2015, AD plant net efficiency
[13] UK Department of Energy and Climate Change, Advanced AD net efficiency
[14] ISWA CE report 2015, net efficiency with annual average heat load
[15] ISWA CE report 2015, net efficiency of biomethane production at 100% annual load
[16] Typical net power / heat only efficiency of a gasification system as an emerging technique
[17] High efficiency claimed by optimised emerging techniques such as *Two Stage Combustion with Plasma* with energy recovery through an internal combustion engine
[18] Typical net efficiency of an emerging technique producing a fuel product

Waste incineration plants (electrical power): From Task 1, Table 1.47 (repeated below), it can be seen that WI plants recovered 110PJ of electrical power in 2013. From Task 2 and Table 3.63, it is assumed that net electrical efficiency is currently 22% in power-only mode and 16% in CHP mode. Taking into account that approximately 31% of the fleet of WI power plants in the EU-28 operate in power-only mode and 69% operate in CHP mode[132], the overall electrical efficiency is estimated at 17.7%; this equates to 110PJ of the energy currently recovered as electrical power.

Where proven improvement techniques are applied to the baseline waste quantities, (where the fleet of EU-28 WI plants could operate at a net electrical efficiency of 33% in power-only mode using improvement techniques such as radiant superheaters) electrical power output could increase from current levels of 110PJ to 181PJ. In CHP mode, a net annual average electrical efficiency of 27% could be achieved. Again, taking into account that approximately 31% of the fleet of WI power plants in the EU-28 operate in power-only mode and 69% operate in CHP mode, the overall net electrical efficiency is estimated to increase to around 29%.

Copy of Table 1.47: Estimation of the waste-derived energy recovery in the EU-28 for the five pathways studied (n.a. = no data available)

	Com-bustion plants	WI plants		CL plants	AD plants			Other WtE plants
		Heat recovery (PJ)	Electricity recovery (PJ)	Thermal energy conversion (PJ)	Heat recovery (PJ)	Electricity recovery (PJ)	Biomethane production (PJ)	
2006		180	81	127				
2007		165	89	141				
2008		183	92	149				
2009		177	97	154				
2010	n.a.	199	105	165		n.a. (not available)		
2011		228	106	184				
2012		265	106	177				
2013		275	110	176				
2014		n.a.	n.a.	n.a.	33	70	12	n.a.

[132] CEWEP Report III Annex A, 2012.

Waste incineration plants (heat export): From Task 1, Table 1.47 it can be seen that WI plants exported 275PJ of heat in 2013.

From Task 2 and Table 3.63, it is assumed that the net heat recovery efficiency is currently 72% in heat-only mode and 51% in CHP mode. Taking into account that approximately 20% of the fleet of WI heat plants in the EU-28 operate in heat-only mode[133] and 80% operate in CHP mode, the overall heat recovery efficiency is estimated at 55%; this equates to 275PJ of the energy currently recovered as heat.

Where proven improvement techniques are applied to the baseline waste quantities (where WI plants could operate at a net annual average heat efficiency of 69% using improvement techniques such as flue-gas condensation), the heat energy output could increase to from 275PJ to 340PJ.

Cement and lime production, thermal energy conversion: From Task 1, Table 1.47 it can be seen that CL plants converted 176PJ of thermal energy from waste in 2013. From Task 2 and Table 3.63, it is assumed that net annual average energy conversion efficiency is currently 75%.

Where proven improvement techniques are applied to the baseline waste quantities (where CL plants could operate at a net annual average energy efficiency of 80% by incremental improvements in design), the thermal energy conversion could increase to 188PJ.

Anaerobic digestion plants: From Task 1, Table 1.47 it can be seen that AD plants recovered a total of 115PJ of energy in 2014, split between power, heat and biomethane. From Task 2 and Table 3.63, it is assumed that the net annual average energy conversion efficiency is currently 18% in power-only mode and 36% in CHP mode.

Where proven improvement techniques from Task 2 are applied to AD (such as gas-to-grid (GtG) which has a net annual average energy efficiency of 41%), it is estimated that energy recovery could increase to 163PJ. This increase is calculated as follows:

- It is assumed that AD plants recovering both heat and power are working at a relatively high efficiency (36%) and will therefore continue to produce both heat and power. The power element of these AD CHP plants is calculated at 32PJ.
- With a total of 70PJ of electrical power recovered, power-only AD plants are estimated to recover 38PJ.
- Where these power-only AD plants convert to GtG, efficiency increases from 18% to 41%, increasing energy recovery from 38PJ to around 86PJ. Carrying over the output from current AD CHP heat and power plants and current GtG plants gives a total energy recovery of 163PJ.

This calculation assumes that current levels of organic waste treatment continue. There may be the potential to capture higher levels of organic waste for AD.

Combustion and other WtE plants: From Task 1, Table 1.47 it can be seen that no reliable estimates of current energy recovery from waste in ‘Combustion’ and ‘Other’ WtE plants across the EU-28 have been able to be established in this study. Therefore no reliable estimation of increased energy recovery can be made at this time.

[133] CEWEP Report III Annex A, 2012.

5.2.1 Calculation summary

Taking the energy contributions from each of the three WtE pathways for which data were available, the overall technical potential for the improvement of energy recovery from WtE is summarised below in Table 3.64 for the application of proven techniques.

It can be seen below that the application of proven improvement techniques can increase energy recovery by a further 173PJ which equates to 26%.

Table 3.64: Summary of WtE technical potential

Scenario	Energy recovered - Average (PJ)	Improvement potential (PJ)	Energy recovered - Optimised (PJ)
WI power	110	71	181
WI heat	275	65	340
CL plants	176	12	188
AD electricity	70	-38	32
AD heat	33	0	33
AD fuel	12	86	98
Total	**676**	**173**	**872**

6 Annexes

6.1 Annex 1- List of conversion factors

6.1.1 Lower calorific values of wastes

	Unit	Low Heating Value			Sources
		Average	Min.	Max.	
Biogas	MJ/Nm^3	25.6	25.6	25.6	1
Biodiesel	MJ/kg	36.6	36.6	36.6	1
Sorting residues	MJ/kg	15.0	13.0	18.0	1
Household and similar wastes	MJ/kg	9	8.0	10.0	2
Mixed and undifferentiated materials	MJ/kg	13.0	8.0	18.0	2
Waste oil (mineral and synthetic)	MJ/kg	30.6	27.0	34.2	1
Waste tyres, waste rubber	MJ/kg	29.4	27.2	31.5	1
Waste solvents	MJ/kg	27.5	23.0	32.0	1
Wood waste	MJ/kg	13.4	7.3	19.5	1
Plastic waste	MJ/kg	35.7	19.2	44.3	1, 10
Paper waste	MJ/kg	16.7	9.4	23.9	1
Textile waste	MJ/kg	17.4	13.0	21.8	1
Discarded equipment	MJ/kg	15.0$^{(1)}$	15.0	15.0	3
Waste containing PCB	MJ/kg	15.0	15.0	15.0	4
Combustion wastes	MJ/kg	15.0	15.0	15.0	4
Chemical wastes	MJ/kg	24.9	8.5	41.2	7
Animal and mixed food waste	MJ/kg	17.0	12.0	25.0	1
Animal faeces, urine and manure	MJ/kg	6.0	2.0	10.0	5, 8
Vegetal wastes	MJ/kg	16.0	14.0	18.0	9
Dried municipal sewage sludge	MJ/kg	9.7	3.7	15.7	1, 6

(1) Assuming discarded vehicles refers to car shredded waste.

Sources:
1 – UBA, 2013 ""Waste derived fuels: Characterisation and suitability for end-of-waste"
2 – Carl Wilen, "Review of waste processing technology for SRF" for IEA Bioenergy Agreement - Task 36, March 2004
3 – Anne Dekeukelaere, "Co-processing waste in the cement industry: A solution to natural resource preservation and total emission reduction", Cementis Consulting, 2011
4 – Default value based on average of LHV of wastes sent for incineration considered in this study
5 – Brændstofvurderinger på husdyrgødninger, Force Technology, 2010 (http://www2.mst.dk/udgiv/publikationer/2010/978-87-92668-89-9/pdf/978-87-92668-90-5.pdf)
6 – Pyromex waste-to-energy , "Energy Information and Data", Rotkreuz, Switzerland (http://www.sludgefacts.org/Ref87_2.pdf)
7 – Janusz Bujak, "Experimental Study of the Lower Heating Value of Medical Waste", Polish Journal of Environmental Studies, Vol. 19, No. 6 (2010), 1151-1158
8 - Biofuel.org.uk (http://biofuel.org.uk/solid-biofuels.html)
9 - GREET, "The Greenhouse Gases, regulated emissions, and energy use in transportation model", released August 26, 2010
10 - Columbia University, "Energy and economic value of municipal solid waste, including non-recycled plastics, currently landfilled in the 50 states", 2014

6.1.2 Conversion factors for units

Prefix	Symbol	Conversion factor
Kilo	K	10^{3}
Mega	M	10^{6}
Giga	G	10^{9}
Tera	T	10^{12}
Peta	P	10^{15}

6.2 Annex 2 - Detailed list of waste treatment methods according to the Waste Statistics Regulation

Recovery operations pursuant to Annex II of the Waste Framework Directive

Code	Types of recovery operations
R1	Use principally as a fuel or other means to recover energy
R2	Solvent reclamation/regeneration
R3	Recycling/reclamation of organic substances which are not used as solvents (including composting and other biological transformation processes)
R4	Recycling/reclamation of metals and metal compounds
R5	Recycling/reclamation of other inorganic materials
R6	Regeneration of acids or bases
R7	Recovery of components used for pollution abatement
R8	Recovery of components from catalysts
R9	Oil re-refining or other reuses of oil
R10	Land treatment resulting in benefit to agriculture or ecological improvement
R11	Use of wastes obtained from any of the operations numbered R1 to R10

Disposal operations pursuant to Annex I of the Waste Framework Directive

Code	Types of disposal operations
D1	Deposit into or onto land (e.g. landfill)
D2	Land treatment (e.g. biodegradation of liquid or sludgy discards in soils)
D3	Deep injection (e.g. injection of pumpable discards into wells, salt domes or naturally occurring repositories)
D4	Surface impoundment (e.g. placement of liquid or sludgy discards into pits, ponds or lagoons)
D5	Specially engineered landfill (e.g. placement into lined discrete cells which are capped and isolated from one another and the environment)
D6	Release into a water body except seas/oceans
D7	Release into seas/oceans including sea-bed insertion
D10	Incineration on land
D12	Permanent storage (e.g. emplacement of containers in a mine)

6.3 Annex 3 - Mass balance between waste generation and treatment

6.3.1 Mass balance for household and similar wastes

Difference (%) = (Treatment-Generation)/Generation

	2010			2012		
	Generation	Treatment	Difference	Generation	Treatment	Difference
Total EU-28	**178,896**	**153,150**	-14%	**169,655**	**137,343**	-19%
United Kingdom	28,956	20,791	-28%	28,261	17,019	-40%
France	22,179	21,281	-4%	22,371	21,949	-2%
Germany	21,376	20,895	-2%	20,955	16,764	-20%
Spain	21,120	13,359	-37%	19,584	10,299	-47%
Italy	21,378	22,092	3%	18,043	16,939	-6%
Poland	8,638	8,080	-6%	8,774	9,578	9%
Netherlands	7,432	5,616	-24%	7,185	5,865	-18%
Romania	4,464	4,309	-3%	5,343	4,690	-12%
Portugal	6,024	5,817	-3%	4,661	4,564	-2%
Greece	4,771	4,771	0%	4,305	4,342	1%
Bulgaria	3,107	3,043	-2%	3,110	3,073	-1%
Czech Republic	3,309	3,519	6%	3,100	3,176	2%
Hungary	3,195	3,104	-3%	2,897	2,954	2%
Belgium	2,570	1,856	-28%	2,837	2,141	-25%
Ireland	3,265	1,103	-66%	2,737	1,021	-63%
Denmark	2,806	2,566	-9%	2,733	2,528	-7%
Austria	3,664	1,225	-67%	2,624	1,138	-57%
Sweden	2,511	2,367	-6%	2,587	2,326	-10%
Finland	2,031	1,668	-18%	1,594	2,007	26%
Croatia	1,337	1,218	-9%	1,396	1,352	-3%
Slovakia	1,458	1,446	-1%	1,382	1,362	-1%
Lithuania	1,065	1,064	0%	1,016	792	-22%
Latvia	563	586	4%	727	526	-28%
Slovenia	777	560	-28%	560	314	-44%
Estonia	305	277	-9%	294	137	-53%
Luxembourg	210	154	-27%	208	166	-20%
Malta	218	210	-4%	206	153	-25%
Cyprus	173	173	0%	166	166	0%

6.3.2 Mass balance for mixed and undifferentiated materials

Difference (%) = (Treatment-Generation)/Generation

	2010			2012		
	Generation	Treatment	Difference	Generation	Treatment	Difference
Total EU-28	**52,372**	**34,948**	**-33%**	**46,941**	**33,123**	**-29%**
France	12,258	8,532	-30%	9,869	4,990	-49%
United Kingdom	7,117	1,251	-82%	7,408	1,761	-76%
Germany	6,861	5,398	-21%	6,996	5,160	-26%
Italy	6,429	5,059	-21%	5,859	4,408	-25%
Poland	2,056	1,622	-21%	3,631	2,629	-28%

	2010			2012		
	Generation	Treatment	Difference	Generation	Treatment	Difference
Belgium	4,641	2,024	-56%	3,061	3,779	23%
Spain	2,068	2,530	22%	2,021	2,236	11%
Denmark	961	890	-7%	1,039	981	-6%
Finland	1,884	1,951	4%	993	980	-1%
Greece	998	258	-74%	989	244	-75%
Netherlands	894	791	-11%	905	865	-4%
Sweden	1,093	1,913	75%	835	2,928	251%
Ireland	466	120	-74%	741	155	-79%
Portugal	369	253	-31%	387	255	-34%
Hungary	392	158	-60%	380	329	-13%
Czech Republic	288	325	13%	348	232	-33%
Latvia	13	54	315%	307	266	-13%
Romania	2,610	1,153	-56%	288	447	55%
Bulgaria	87	20	-77%	167	33	-80%
Austria	86	49	-44%	140	110	-21%
Slovenia	86	54	-38%	134	50	-63%
Slovakia	130	109	-17%	130	105	-20%
Estonia	53	19	-63%	81	10	-87%
Cyprus	89	89	0%	78	78	0%
Croatia	258	246	-5%	59	58	-1%
Lithuania	82	78	-5%	51	37	-29%
Luxembourg	92	1	-99%	33	1	-96%
Malta	11	1	-91%	11	1	-94%

6.3.3 Mass balance for sorting residues

Difference (%) = (Treatment-Generation)/Generation

	2010			2012		
	Generation	Treatment	Difference	Generation	Treatment	Difference
Total EU-28	**54,877**	**53,860**	**-2%**	**65,417**	**62,994**	**-4%**
Germany	13,972	12,584	-10%	16,396	15,171	-7%
Italy	9,971	5,976	-40%	13,536	11,421	-16%
Spain	6,080	6,219	2%	7,505	7,628	2%
United Kingdom	4,181	11,966	186%	5,944	10,599	78%
France	6,193	4,478	-28%	5,857	4,278	-27%
Poland	4,664	3,903	-16%	5,651	4,813	-15%
Belgium	1,538	1,844	20%	1,700	809	-52%
Sweden	1,278	855	-33%	1,656	1,000	-40%
Austria	1,395	999	-28%	1,611	1,535	-5%
Netherlands	2,336	1,821	-22%	1,412	2,073	47%
Romania	602	666	11%	695	741	7%
Denmark	490	283	-42%	510	280	-45%
Ireland	501	548	9%	491	440	-10%
Portugal	166	133	-20%	357	272	-24%
Czech Republic	295	269	-9%	352	329	-6%
Bulgaria	56	32	-43%	323	99	-69%
Finland	683	706	3%	293	351	20%
Greece	155	155	0%	253	250	-2%
Hungary	148	248	68%	228	315	38%
Lithuania	36	23	-36%	219	148	-33%

	2010			2012		
	Generation	Treatment	Difference	Generation	Treatment	Difference
Estonia	35	29	-18%	144	74	-48%
Slovenia	17	56	236%	81	61	-25%
Slovakia	24	19	-19%	78	71	-8%
Malta	8	9	9%	50	60	22%
Luxembourg	41	34	-16%	34	41	23%
Croatia	8	1	-83%	29	5	-82%
Latvia	4	0	-97%	11	127	1,062%
Cyprus	2	2	0%	3	3	0%

6.4 Annex 4 - Calculation of improvement technique ratings

The calculation of average annual net efficiency for CHP installations is shown below.

Reduced efficiency	Net CHP energy efficiency	Net **annual average** energy efficiency
Electrical – <22% net eff. in power only (20% of time) Electrical – <16% net eff. in CHP mode (80% of time)		< 17%
Heat – <64% net eff. in CHP mode (80% of time)		< 51%
Overall	<80%	< 68%

No change in efficiency	Net CHP energy efficiency	Net **annual average** energy efficiency
Electrical – approx. 25% eff. in power only (20% of time) Electrical – approx. 18% eff. in CHP mode (80% of time)		Approx. 19%
Heat – approx. 65% eff. at 80% load factor		Approx. 51%
Overall	Approx. 83%	Approx. 71%

Increased efficiency	Net CHP energy efficiency	Net **annual average** energy efficiency
Electrical – >29% eff. in power only (20% of time) Electrical – >22% eff. in CHP mode (80% of time)		> 23%
Heat – >66% eff. at 80% load factor		> 53%
Overall	> 88%	> 76%

6.5 Annex 5 - Subscoring for technique applicability

Technique	Location	Waste stream	Retrofit		Applicability
Combustion plants					
Mixing of waste with a primary fuel prior to combustion	g	r	g		a
Gasification of waste for gas injection with a primary fuel	g	a	a		a
Special grate for co-incineration of waste	a	a	r		a
Waste and biomass co-firing	a	a	g		a
WI plants					
Waste pretreatment	g	g	g		g
Advanced combustion control	g	g	g		g
Advanced moving grate	g	g	r		a
Environmentally optimised combustion process	g	g	r		a
Effective boiler cleaning	g	g	g		g
Reduced energy consumption through flue-gas recirculation	a	g	r		a
High steam parameters for boilers and superheaters	g	g	r		a
Flue-gas condensation and component cooling	r	g	a		a
Heat pumps	r	g	a		a
District cooling (100% load)	r	g	g		a
4th generation heat networks	r	g	g		a
Co-generation using waste feedstocks	a	r	g		a
High steam parameters (emerging)	g	g	r		a
Use of the mass and energy balance method to measure waste biogenic content	g	g	g		g
Heat and power decoupling	r	g	r		r
Use of ilmenite as a bed material in a circulating fluidised bed (CFB) reactor	a	g	a		a
Organic Rankine Cycle turbine for low-grade heat utilisation	g	g	g		g
CL plants					
Conversion of waste heat to power in cement kiln applications	g	g	g		g
Use of waste-derived syngas as fuel for cement kiln burners	g	g	r		a
Hydrogen extracted from waste syngas as fuel for cement kiln burners	g	g	r		a

Technique	Location	Waste stream	Retrofit		Applicability
Anaerobic digestion (AD) plants					
Micro anaerobic digestion (AD)	g	r	g		a
Sewage sludge advanced AD - THP	a	r	a		a
Sewage sludge advanced AD - ITHP	a	r	a		a
High-rate dry AD	g	r	a		a
AD with biogas injection to grid (GtG)	g	r	g		a
AD with liquefaction of biogas to liquefied biomethane (LBM)	g	r	g		a
AD with compression of biogas to compressed biomethane (CBM)	g	r	g		a
Sewage sludge advanced AD with advanced energy recovery (gasification)	a	r	a		a
Sewage sludge advanced AD with advanced energy recovery (pyrolysis)	a	r	a		a
Enzymatic conversion of waste to biogas	g	g	r		a
Fermentation of packaged food waste	g	r	r		r
Bio-thermic digestion	g	r	r		r
Other WtE plants					
Biodiesel from hydrogenation of oils and fats	g	r	r		r
Bubbling fluidised bed gasifier	g	g	r		a
Two-stage combustion	g	g	r		a
Two-stage combustion with plasma	g	g	r		a
High-efficiency CFB gasification	g	g	r		a
Plasma gasification	g	g	r		a
Direct melting systems	g	g	r		a
High-temperature gasification	g	g	r		a
Combined pyrolysis and gasification	g	g	r		a
Slow pyrolysis	g	r	r		r
Flash pyrolysis	g	r	r		r
Pyrolysis of waste tyres	a	r	r		r
Pyrolysis of paper sludge	a	r	r		r
Direct liquefaction	g	r	r		r
Waste plastics to diesel	g	r	r		r
Gas turbines	g	g	r		a
Bioethanol from organic sources	g	r	r		r
Bioethanol from MSW	g	g	r		a
Gasification with syngas methanation and conversion to biomethane	a	g	r		a

Note: Emerging techniques are noted in red italics.

6.6 Annex 6 – Eurostat EU-28 calculation data for the construction of the two energy recovery scenarios

Waste treated per capita (kg/capita) by Member State for each waste stream (2012 Data)

Member State	Population	Waste treated per capita (kg/capita)											
		Wood waste	Plastic waste	Paper waste	Textile waste	Waste tyres	Waste solvents	Chemical waste	Mixed and undifferentiated materials	Sorting residues	Animal and vegetal waste	Dried municipal sewage sludge	House-hold and similar waste
Total (EU-28)	502,159,333	105	25	77	5	5	4	20	66	125	169	17	274
Austria	8,408,121	114	42	239	6	7	4	14	13	183	228	32	135
Belgium	11,094,850	145	21	118	6	6	5	21	341	73	328	10	193
Bulgaria	7,327,224	21	10	28	0	3	0	5	5	13	101	5	419
Croatia	4,275,984	17	5	43	0	:	0	1	14	1	27	:	316
Cyprus	862,011	14	86	158	32	6	0	0	91	3	258	3	192
Czech Republic	10,505,445	5	21	33	7	5	1	7	22	31	27	24	302
Denmark	5,580,516	32	18	127	0	6	4	18	176	50	136	156	453
Estonia	1,325,217	534	2	5	1	8	0	1,143	8	56	49	57	104
Finland	5,401,267	2,083	10	105	2	9	4	35	181	65	341	10	372
France	63,375,971	94	31	78	2	5	6	22	79	68	115	4	346
Germany	80,327,900	135	26	55	3	5	9	30	64	189	171	41	209
Greece	11,086,406	10	7	20	0	3	0	2	22	23	41	13	392
Hungary	9,931,925	14	12	73	1	4	3	11	33	32	62	75	297
Ireland	4,582,707	35	16	0	0	5	5	2	34	96	63	29	223
Italy	59,394,207	65	26	73	3	6	3	10	74	192	97	1	285
Latvia	2,044,813	9	17	13	1	5	0	1	130	62	38	:	257
Lithuania	3,003,641	48	10	22	2	4	0	11	12	49	87	6	264
Luxembourg	524,853	28	34	:	:	:	1	3	2	79	164	8	316
Malta	417,546	2	0	0	:	0	:	2	2	145	35	23	367

Member State	Population	Waste treated per capita (kg/capita)											
		Wood waste	Plastic waste	Paper waste	Textile waste	Waste tyres	Waste solvents	Chemical waste	Mixed and undifferentiated materials	Sorting residues	Animal and vegetal waste	Dried munici-pal sewage sludge	House-hold and similar waste
Netherlands	16,730,348	121	31	134	3	4	5	56	52	124	864	20	351
Poland	38,063,792	149	15	40	1	5	0	14	69	126	86	1	252
Portugal	10,542,398	70	8	42	2	6	0	12	24	26	13	19	433
Romania	20,095,996	151	21	48	0	2	0	4	22	37	839	6	233
Slovakia	5,404,322	61	13	17	1	4	0	12	19	13	140	9	252
Slovenia	2,055,496	118	19	186	0	5	4	13	24	30	114	66	153
Spain	46,818,219	27	24	105	2	5	4	18	48	163	50	2	220
Sweden	9,482,855	133	21	159	0	8	1	37	309	105	169	5	245
United Kingdom	63,495,303	33	41	104	21	4	0	5	28	167	110	17	268

: No data on waste treatment available

Wood waste treatment methods for 2012

Share of the country in total	Cumulated share	GEO/WST_OPER	Total waste treatment (kt)	Landfill / disposal (D1-D7, D12) (kt)	Incineration / disposal (D10) (kt)	Incineration / energy recovery (R1) (kt)	Recovery other than energy recovery (kt)	Landfill / disposal (D1-D7, D12) (%)	Incineration / disposal (D10) (%)	Incineration / energy recovery (R1) (%)	Recovery other than energy recovery (%)
0%	0%	Luxembourg	15	0	0	0	15	0%	0%	0%	100%
0%	0%	Ireland	160	0	0	18	142	0%	0%	11%	88%
20%	21%	Germany	10,836	0	5	8,260	2,571	0%	0%	76%	24%
11%	32%	Poland	5,678	0	2	2,286	3,390	0%	0%	40%	60%
21%	53%	Finland	11,252	2	44	8,426	2,780	0%	0%	75%	25%
1%	54%	Estonia	707	0	0	289	419	0%	0%	41%	59%
3%	57%	Belgium	1,613	1	786	136	691	0%	49%	8%	43%
7%	64%	Italy	3,854	2	13	776	3,064	0%	0%	20%	80%
6%	70%	Romania	3,033	1	0	1,039	1,993	0%	0%	34%	66%
0%	71%	Slovenia	242	0	0	202	40	0%	0%	83%	16%
4%	75%	Netherlands	2,032	3	11	1,043	975	0%	1%	51%	48%
2%	76%	Austria	957	3	0	446	508	0%	0%	47%	53%
0%	77%	Lithuania	143	0	0	85	58	0%	0%	59%	41%
2%	79%	Sweden	1,258	6	3	1,191	58	1%	0%	95%	5%
1%	80%	Portugal	743	5	1	585	152	1%	0%	79%	20%
0%	81%	Hungary	135	1	0	29	104	1%	0%	22%	77%
4%	85%	United Kingdom	2,109	25	0	347	1,736	1%	0%	16%	82%
1%	85%	Slovakia	332	4	5	56	266	1%	2%	17%	80%
0%	85%	Croatia	74	1	0	21	51	2%	0%	29%	70%
2%	88%	Spain	1,247	26	0	3	1,218	2%	0%	0%	98%
0%	88%	Denmark	177	5	0	30	142	3%	0%	17%	80%
11%	99%	France	5,964	274	93	1,614	3,983	5%	2%	27%	67%
0%	100%	Bulgaria	155	26	0	79	50	17%	0%	51%	32%
0%	100%	Czech Republic	49	10	1	26	12	20%	3%	52%	25%
0%	100%	Latvia	18	4	0	6	8	23%	3%	30%	44%
0%	100%	Greece	116	80	0	11	26	69%	0%	9%	22%

Share of the country in total	Cumulated share	GEO/WST_OPER	Total waste treatment (kt)	Landfill / disposal (D1-D7, D12) (kt)	Incineration / disposal (D10) (kt)	Incineration / energy recovery (R1) (kt)	Recovery other than energy recovery (kt)	Landfill / disposal (D1-D7, D12) (%)	Incineration / disposal (D10) (%)	Incineration / energy recovery (R1) (%)	Recovery other than energy recovery (%)
0%	100%	Cyprus	12	11	0	0	1	90%	0%	0%	10%
0%	100%	Malta	1	1	0	0	0	96%	4%	0%	0%

Plastic waste treatment methods for 2012

Share of the country in total	Cumulated share	GEO/WST_OPER	Total waste treatment (kt)	Landfill / disposal (D1-D7, D12) (kt)	Incineration / disposal (D10) (kt)	Incineration / energy recovery (R1) (kt)	Recovery other than energy recovery (kt)	Landfill / disposal (D1-D7, D12) (%)	Incineration / disposal (D10) (%)	Incineration / energy recovery (R1) (%)	Recovery other than energy recovery (%)
3%	3%	Austria	352	0	0	40	312	0%	0%	11%	89%
0%	3%	Luxembourg	18	0	0	6	12	0%	0%	34%	66%
2%	4%	Sweden	202	0	0	105	97	0%	0%	52%	48%
17%	21%	Germany	2,113	2	31	436	1,644	0%	1%	21%	78%
3%	24%	Romania	428	2	1	19	407	1%	0%	4%	95%
1%	25%	Ireland	74	1	0	0	73	1%	0%	0%	99%
0%	25%	Latvia	35	0	0	0	35	1%	0%	0%	99%
4%	29%	Netherlands	511	7	3	87	414	1%	1%	17%	81%
5%	34%	Poland	583	10	0	9	564	2%	0%	2%	97%
12%	46%	Italy	1,523	44	32	44	1,403	3%	2%	3%	92%
0%	46%	Finland	52	2	10	32	8	4%	19%	61%	16%
21%	67%	United Kingdom	2,619	122	0	0	2,497	5%	0%	0%	95%
2%	69%	Belgium	230	13	3	17	196	6%	2%	7%	85%
1%	69%	Denmark	100	6	0	4	89	6%	0%	4%	89%
0%	70%	Croatia	22	2	0	0	20	7%	0%	0%	93%
9%	79%	Spain	1,143	81	0	0	1,062	7%	0%	0%	93%
0%	79%	Estonia	3	0	0	0	3	10%	0%	0%	90%
1%	79%	Hungary	114	13	3	8	91	11%	2%	7%	80%
1%	80%	Bulgaria	73	8	0	3	61	11%	0%	5%	84%
1%	81%	Portugal	84	10	0	3	71	11%	0%	4%	84%
0%	81%	Slovenia	39	5	2	0	32	13%	4%	0%	83%
0%	81%	Lithuania	31	5	0	0	26	15%	0%	0%	84%
1%	82%	Slovakia	69	11	0	1	57	16%	0%	1%	83%
2%	84%	Czech Republic	225	46	0	28	151	20%	0%	13%	67%
15%	99%	France	1,934	931	0	776	227	48%	0%	40%	12%

Share of the country in total	Cumulated share	GEO/WST_OPER	Total waste treatment (kt)	Landfill / disposal (D1-D7, D12) (kt)	Incineration / disposal (D10) (kt)	Incineration / energy recovery (R1) (kt)	Recovery other than energy recovery (kt)	Landfill / disposal (D1-D7, D12) (%)	Incineration / disposal (D10) (%)	Incineration / energy recovery (R1) (%)	Recovery other than energy recovery (%)
1%	99%	Greece	83	53	0	1	29	64%	0%	1%	36%
1%	100%	Cyprus	74	66	0	0	8	89%	0%	0%	11%
0%	100%	Malta	0	0	0	0	0	100%	0%	0%	0%

Paper waste treatment methods for 2012

Share of the country in total	Cumulated share	GEO/WST_OPER	Total waste treatment (kt)	Landfill / disposal (D1-D7, D12) (kt)	Incineration / disposal (D10) (kt)	Incineration / energy recovery (R1) (kt)	Recovery other than energy recovery (kt)	Landfill / disposal (D1-D7, D12) (%)	Incineration / disposal (D10) (%)	Incineration / energy recovery (R1) (%)	Recovery other than energy recovery (%)
0%	0%	Ireland	2	0	0	0	2	0%	0%	0%	100%
1%	1%	Slovenia	382	0	0	0	382	0%	0%	0%	100%
0%	1%	Latvia	26	0	0	0	26	0%	0%	0%	100%
4%	5%	Sweden	1,503	0	0	6	1,497	0%	0%	0%	100%
5%	10%	Austria	2,006	0	0	11	1,995	0%	0%	1%	99%
11%	21%	Germany	4,423	0	4	38	4,381	0%	0%	1%	99%
13%	34%	France	4,913	0	0	204	4,709	0%	0%	4%	96%
0%	34%	Luxembourg	0	0	0	0	0	0%	0%	0%	0%
0%	34%	Malta	0	0	0	0	0	0%	100%	0%	0%
4%	38%	Poland	1,507	0	0	3	1,505	0%	0%	0%	100%
1%	40%	Finland	569	0	13	34	522	0%	2%	6%	92%
6%	45%	Netherlands	2,242	0	0	0	2,242	0%	0%	0%	100%
2%	47%	Denmark	711	0	0	4	707	0%	0%	1%	99%
11%	58%	Italy	4,308	1	2	0	4,305	0%	0%	0%	100%
3%	62%	Belgium	1,312	0	0	0	1,311	0%	0%	0%	100%
0%	62%	Croatia	183	0	0	0	183	0%	0%	0%	100%
17%	79%	United Kingdom	6,578	5	0	0	6,573	0%	0%	0%	100%
2%	81%	Romania	955	1	0	10	944	0%	0%	1%	99%
0%	82%	Estonia	7	0	0	0	7	0%	0%	0%	100%
1%	83%	Portugal	444	1	0	0	443	0%	0%	0%	100%
0%	83%	Lithuania	65	0	0	0	65	0%	0%	0%	100%
13%	96%	Spain	4,934	14	0	0	4,920	0%	0%	0%	100%
2%	97%	Hungary	725	5	0	1	719	1%	0%	0%	99%
1%	98%	Greece	225	2	0	0	223	1%	0%	0%	99%
1%	99%	Czech Republic	349	5	0	9	334	1%	0%	3%	96%

Share of the country in total	Cumulated share	GEO/WST_OPER	Total waste treatment (kt)	Landfill / disposal (D1-D7, D12) (kt)	Incineration / disposal (D10) (kt)	Incineration / energy recovery (R1) (kt)	Recovery other than energy recovery (kt)	Landfill / disposal (D1-D7, D12) (%)	Incineration / disposal (D10) (%)	Incineration / energy recovery (R1) (%)	Recovery other than energy recovery (%)
0%	99%	Slovakia	93	2	0	0	91	2%	0%	0%	97%
1%	100%	Bulgaria	202	64	0	0	138	32%	0%	0%	68%
0%	100%	Cyprus	136	83	0	0	53	61%	0%	0%	39%

Textile waste treatment methods for 2012

Share of the country in total	Cumulated share	GEO/WST_OPER	Total waste treatment (kt)	Landfill / disposal (D1-D7, D12) (kt)	Incineration / disposal (D10) (kt)	Incineration / energy recovery (R1) (kt)	Recovery other than energy recovery (kt)	Landfill / disposal (D1-D7, D12) (%)	Incineration / disposal (D10) (%)	Incineration / energy recovery (R1) (%)	Recovery other than energy recovery (%)
5%	5%	France	126	0	0	0	126	0%	0%	0%	100%
0%	5%	Ireland	0	0	0	0	0	0%	0%	13%	87%
2%	7%	Austria	47	0	0	23	24	0%	0%	48%	52%
0%	7%	Luxembourg	0	0	0	0	0	0%	0%	0%	0%
0%	7%	Malta	0	0	0	0	0	0%	0%	0%	0%
0%	7%	Sweden	0	0	0	0	0	0%	0%	0%	0%
11%	18%	Germany	264	0	5	41	217	0%	2%	16%	82%
56%	75%	United Kingdom	1,331	6	10	0	1,315	0%	1%	0%	99%
3%	77%	Belgium	68	1	0	0	66	2%	0%	0%	98%
0%	78%	Finland	8	0	0	0	8	4%	0%	0%	96%
8%	86%	Italy	198	11	2	0	185	6%	1%	0%	94%
2%	89%	Netherlands	57	3	0	20	34	6%	0%	35%	59%
0%	89%	Latvia	1	0	0	1	0	7%	0%	93%	0%
0%	89%	Denmark	3	1	0	0	2	19%	0%	6%	75%
0%	89%	Greece	2	0	0	0	1	22%	0%	0%	78%
1%	90%	Poland	35	8	0	2	25	22%	0%	6%	72%
0%	90%	Slovenia	1	0	0	0	1	28%	0%	0%	72%
0%	91%	Romania	7	2	1	2	2	34%	8%	32%	27%
3%	94%	Czech Republic	73	28	0	21	25	38%	0%	28%	34%
0%	94%	Bulgaria	2	1	0	0	1	42%	0%	7%	51%
0%	94%	Hungary	8	4	0	2	2	46%	1%	28%	24%
3%	97%	Spain	77	35	0	2	39	46%	0%	3%	51%
0%	98%	Slovakia	6	4	0	1	1	67%	1%	15%	17%
0%	98%	Lithuania	7	5	0	0	2	68%	0%	1%	31%

Share of the country in total	Cumulated share	GEO/WST_OPER	Total waste treatment (kt)	Landfill / disposal (D1-D7, D12) (kt)	Incineration / disposal (D10) (kt)	Incineration / energy recovery (R1) (kt)	Recovery other than energy recovery (kt)	Landfill / disposal (D1-D7, D12) (%)	Incineration / disposal (D10) (%)	Incineration / energy recovery (R1) (%)	Recovery other than energy recovery (%)
0%	98%	Croatia	2	1	0	0	0	73%	0%	0%	27%
1%	99%	Portugal	20	15	0	1	5	73%	0%	3%	24%
0%	99%	Estonia	1	1	0	0	0	98%	0%	0%	2%
1%	100%	Cyprus	28	27	0	0	0	99%	0%	0%	1%

Waste tyres and waste rubber treatment methods for 2012

Share of the country in total	Cumulated share	GEO/WST_OPER	Total waste treatment (kt)	Landfill / disposal (D1-D7, D12) (kt)	Incineration / disposal (D10) (kt)	Incineration / energy recovery (R1) (kt)	Recovery other than energy recovery (kt)	Landfill / disposal (D1-D7, D12) (%)	Incineration / disposal (D10) (%)	Incineration / energy recovery (R1) (%)	Recovery other than energy recovery (%)
1%	1%	Denmark	36	0		0	36	0%	0%	0%	100%
2%	3%	Finland	46	0		3	43	0%	0%	7%	93%
3%	6%	Netherlands	62	0		11	51	0%	0%	18%	82%
3%	9%	Belgium	66	0		12	54	0%	0%	18%	82%
1%	9%	Slovakia	23	0		6	17	0%	0%	26%	74%
1%	11%	Hungary	36	0		10	26	0%	0%	28%	72%
3%	14%	Portugal	64	0		24	40	0%	0%	38%	63%
0%	14%	Slovenia	10	0		5	5	0%	0%	50%	50%
9%	23%	Spain	219	0		116	103	0%	0%	53%	47%
8%	30%	Poland	185	0		100	85	0%	0%	54%	46%
13%	43%	France	323	0		175	148	0%	0%	54%	46%
17%	61%	Germany	424	0		234	190	0%	0%	55%	45%
2%	63%	Romania	46	0		26	20	0%	0%	57%	43%
2%	65%	Austria	60	0		36	24	0%	0%	60%	40%
3%	68%	Sweden	76	0		48	28	0%	0%	63%	37%
0%	68%	Croatia						0%	0%	0%	0%
0%	68%	Luxembourg						0%	0%	0%	0%
0%	68%	Malta	0	0		0	0	0%	0%	0%	0%
11%	79%	United Kingdom	282	12		127	143	4%	0%	45%	51%
1%	81%	Greece	36	2		21	13	6%	0%	58%	36%
13%	94%	Italy	330	20		191	119	6%	0%	58%	36%
0%	95%	Estonia	11	1		0	10	9%	0%	0%	91%
0%	95%	Latvia	11	1		5	5	9%	0%	45%	45%
1%	96%	Ireland	24	3		10	11	13%	0%	42%	46%
2%	98%	Czech Republic	54	12		27	15	22%	0%	50%	28%
1%	99%	Lithuania	13	3		4	6	23%	0%	31%	46%

Share of the country in total	Cumulated share	GEO/WST_OPER	Total waste treatment (kt)	Landfill / disposal (D1-D7, D12) (kt)	Incineration / disposal (D10) (kt)	Incineration / energy recovery (R1) (kt)	Recovery other than energy recovery (kt)	Landfill / disposal (D1-D7, D12) (%)	Incineration / disposal (D10) (%)	Incineration / energy recovery (R1) (%)	Recovery other than energy recovery (%)
1%	100%	Bulgaria	22	8		4	10	36%	0%	18%	45%
0%	100%	Cyprus	5	5		0	0	100%	0%	0%	0%

Waste solvents treatment methods for 2012

Share of the country in total	Cumulated share	GEO/WST_OPER	Total waste treatment (kt)	Landfill / disposal (D1-D7, D12) (kt)	Incineration / disposal (D10) (kt)	Incineration / energy recovery (R1) (kt)	Recovery other than energy recovery (kt)	Landfill / disposal (D1-D7, D12) (%)	Incineration / disposal (D10) (%)	Incineration / energy recovery (R1) (%)	Recovery other than energy recovery (%)
0%	0%	Croatia	0	0	0	0	0	0%	0%	0%	100%
0%	0%	Greece	0	0	0	0	0	0%	0%	0%	100%
0%	0%	Latvia	0	0	0	0	0	0%	0%	0%	100%
0%	0%	Portugal	4	0	0	0	4	0%	0%	0%	100%
10%	11%	Italy	183	0	43	0	140	0%	23%	0%	77%
0%	11%	Estonia	0	0	0	0	0	0%	1%	52%	47%
3%	14%	Belgium	55	0	38	0	17	0%	69%	0%	31%
40%	53%	Germany	709	0	215	306	188	0%	30%	43%	27%
0%	54%	Sweden	7	0	5	1	1	0%	72%	20%	8%
0%	54%	Czech Republic	8	0	5	2	1	0%	73%	20%	7%
0%	55%	Slovenia	8	0	7	1	1	0%	82%	11%	7%
1%	56%	Finland	22	0	21	0	1	0%	95%	0%	5%
1%	57%	Ireland	21	0	13	8	0	0%	60%	37%	2%
2%	59%	Austria	32	0	0	32	0	0%	0%	100%	0%
0%	59%	Lithuania	0	0	0	0	0	0%	100%	0%	0%
0%	59%	Luxembourg	0	0	0	0	0	0%	2%	98%	0%
0%	59%	Malta	0	0	0	0	0	0%	0%	0%	0%
5%	64%	Netherlands	91	0	13	34	44	0%	14%	37%	48%
2%	66%	Hungary	32	0	18	0	13	0%	57%	0%	43%
0%	66%	Poland	5	0	1	0	3	0%	32%	2%	67%
22%	88%	France	395	1	102	164	127	0%	26%	42%	32%
0%	88%	Cyprus	0	0	0	0	0	2%	4%	0%	94%
0%	88%	Romania	1	0	0	0	1	3%	8%	1%	87%
11%	99%	Spain	190	6	0	30	154	3%	0%	16%	81%
0%	99%	Slovakia	1	0	0	0	1	17%	14%	1%	68%
0%	99%	United Kingdom	0	0	0	0	0	20%	0%	0%	80%

Share of the country in total	Cumulated share	GEO/WST_OPER	Total waste treatment (kt)	Landfill / disposal (D1-D7, D12) (kt)	Incineration / disposal (D10) (kt)	Incineration / energy recovery (R1) (kt)	Recovery other than energy recovery (kt)	Landfill / disposal (D1-D7, D12) (%)	Incineration / disposal (D10) (%)	Incineration / energy recovery (R1) (%)	Recovery other than energy recovery (%)
1%	100%	Denmark	22	6	0	14	1	28%	0%	66%	6%
0%	100%	Bulgaria	0	0	0	0	0	49%	0%	0%	51%

Chemical waste treatment methods for 2012

Share of the country in total	Cumulated share	GEO/WST_OPER	Total waste treatment (kt)	Landfill / disposal (D1-D7, D12) (kt)	Incineration / disposal (D10) (kt)	Incineration / energy recovery (R1) (kt)	Recovery other than energy recovery (kt)	Landfill / disposal (D1-D7, D12) (%)	Incineration / disposal (D10) (%)	Incineration / energy recovery (R1) (%)	Recovery other than energy recovery (%)
0%	0%	Luxembourg	2	0	0	0	2	0%	0%	0%	100%
24%	24%	Germany	2,409	36	448	601	1,324	1%	19%	25%	55%
9%	33%	Netherlands	937	16	510	82	330	2%	54%	9%	35%
0%	33%	Slovenia	27	0	3	11	13	2%	11%	40%	47%
6%	39%	Italy	575	20	159	73	323	3%	28%	13%	56%
0%	39%	Greece	25	1	0	2	23	4%	0%	7%	89%
0%	39%	Latvia	2	0	0	0	2	4%	0%	0%	96%
14%	53%	France	1,366	74	626	409	257	5%	46%	30%	19%
0%	53%	Ireland	8	0	0	5	1	6%	6%	69%	19%
5%	58%	Poland	532	37	46	2	447	7%	9%	0%	84%
3%	61%	United Kingdom	334	32	131	0	171	9%	39%	0%	51%
1%	63%	Austria	119	12	0	79	2	10%	0%	66%	1%
1%	64%	Hungary	106	12	41	26	26	12%	39%	25%	25%
1%	64%	Romania	73	9	8	10	46	12%	11%	14%	63%
2%	67%	Belgium	235	31	111	1	93	13%	47%	0%	40%
1%	68%	Denmark	100	21	0	66	13	21%	0%	66%	13%
9%	76%	Spain	861	185	0	65	611	21%	0%	8%	71%
15%	91%	Estonia	1,515	383	0	3	1,129	25%	0%	0%	75%
1%	92%	Czech Republic	76	20	31	11	14	26%	41%	15%	18%
0%	92%	Lithuania	33	9	0	0	24	26%	1%	0%	72%
0%	92%	Croatia	4	1	0	2	1	30%	0%	38%	31%
2%	94%	Finland	192	73	55	2	61	38%	29%	1%	32%
3%	98%	Sweden	354	137	24	49	144	39%	7%	14%	41%
1%	99%	Portugal	122	79	14	1	27	65%	12%	1%	23%
1%	100%	Slovakia	63	43	4	1	15	68%	6%	1%	24%
0%	100%	Cyprus	0	0	0	0	0	72%	1%	4%	23%

Share of the country in total	Cumulated share	GEO/WST_OPER	Total waste treatment (kt)	Landfill / disposal (D1-D7, D12) (kt)	Incineration / disposal (D10) (kt)	Incineration / energy recovery (R1) (kt)	Recovery other than energy recovery (kt)	Landfill / disposal (D1-D7, D12) (%)	Incineration / disposal (D10) (%)	Incineration / energy recovery (R1) (%)	Recovery other than energy recovery (%)
0%	100%	Malta	1	1	0	0	0	75%	25%	0%	0%
0%	100%	Bulgaria	38	33	0	0	4	88%	1%	0%	11%

Mixed and undifferentiated materials treatment methods for 2012

Share of the country in total	Cumulated share	GEO/WST_OPER	Total waste treatment (kt)	Landfill / disposal (D1-D7, D12) (kt)	Incineration / disposal (D10) (kt)	Incineration / energy recovery (R1) (kt)	Recovery other than energy recovery (kt)	Landfill / disposal (D1-D7, D12) (%)	Incineration / disposal (D10) (%)	Incineration / energy recovery (R1) (%)	Recovery other than energy recovery (%)
0%	0%	Luxembourg	1	0	0	0	1	0%	31%	0%	69%
0%	0%	Austria	110	0	0	103	1	0%	0%	94%	1%
11%	12%	Belgium	3,779	119	617	2,882	160	3%	16%	76%	4%
1%	12%	Greece	244	12	0	1	231	5%	0%	1%	94%
3%	15%	Denmark	981	73	0	356	552	7%	0%	36%	56%
8%	23%	Poland	2,629	208	8	91	2,321	8%	0%	3%	88%
16%	39%	Germany	5,160	439	319	1,925	2,477	8%	6%	37%	48%
9%	48%	Sweden	2,928	300	3	2,354	272	10%	0%	80%	9%
0%	48%	Slovenia	50	6	0	7	37	11%	0%	14%	75%
13%	61%	Italy	4,408	587	202	679	2,940	13%	5%	15%	67%
1%	62%	Hungary	329	48	2	208	71	15%	1%	63%	22%
3%	65%	Netherlands	865	144	33	117	571	17%	4%	14%	66%
1%	66%	Romania	447	76	1	69	300	17%	0%	15%	67%
1%	67%	Latvia	266	46	0	2	218	17%	0%	1%	82%
5%	72%	United Kingdom	1,761	387	131	65	1,178	22%	7%	4%	67%
1%	73%	Portugal	255	56	1	13	186	22%	0%	5%	73%
3%	76%	Finland	980	267	61	436	217	27%	6%	44%	22%
0%	76%	Lithuania	37	15	0	3	19	41%	0%	8%	51%
1%	77%	Czech Republic	232	118	2	14	98	51%	1%	6%	42%
0%	77%	Bulgaria	33	18	0	9	6	54%	0%	26%	20%
0%	77%	Estonia	10	6	0	0	4	62%	0%	1%	37%
0%	77%	Croatia	58	37	0	0	21	64%	0%	0%	36%
0%	77%	Slovakia	105	68	2	2	33	65%	2%	2%	32%
0%	78%	Ireland	155	103	0	29	23	67%	0%	19%	15%
15%	93%	France	4,990	4,080	231	304	376	82%	5%	6%	8%
7%	100%	Spain	2,236	1,911	0	194	131	85%	0%	9%	6%

Share of the country in total	Cumulated share	GEO/WST_OPER	Total waste treatment (kt)	Landfill / disposal (D1-D7, D12) (kt)	Incineration / disposal (D10) (kt)	Incineration / energy recovery (R1) (kt)	Recovery other than energy recovery (kt)	Landfill / disposal (D1-D7, D12) (%)	Incineration / disposal (D10) (%)	Incineration / energy recovery (R1) (%)	Recovery other than energy recovery (%)
0%	100%	Cyprus	78	74	0	0	4	95%	0%	0%	5%
0%	100%	Malta	1	1	0	0	0	99%	1%	0%	0%

Sorting residues treatment methods for 2012

Share of the country in total	Cumulated share	GEO/WST_OPER	Total waste treatment (kt)	Landfill / disposal (D1-D7, D12) (kt)	Incineration / disposal (D10) (kt)	Incineration / energy recovery (R1) (kt)	Recovery other than energy recovery (kt)	Landfill / disposal (D1-D7, D12) (%)	Incineration / disposal (D10) (%)	Incineration / energy recovery (R1) (%)	Recovery other than energy recovery (%)
0%	0%	Latvia	127	0	0	127	0	0%	0%	100%	0%
3%	3%	Netherlands	2,073	75	13	1,337	649	4%	1%	64%	31%
24%	28%	Germany	15,171	949	1,952	9,606	2,663	6%	13%	63%	18%
0%	28%	Denmark	280	25	0	133	122	9%	0%	47%	44%
2%	30%	Austria	1,535	163	0	1,151	222	11%	0%	75%	14%
1%	31%	Czech Republic	329	40	2	114	174	12%	1%	35%	53%
0%	31%	Portugal	272	65	0	148	59	24%	0%	54%	22%
0%	32%	Estonia	74	18	0	52	4	24%	0%	70%	5%
0%	32%	Hungary	315	78	1	117	119	25%	0%	37%	38%
2%	34%	Sweden	1,000	256	0	442	302	26%	0%	44%	30%
1%	35%	Belgium	809	229	509	50	21	28%	63%	6%	3%
0%	35%	Slovenia	61	19	20	17	4	31%	33%	29%	7%
1%	36%	Ireland	440	169	0	178	94	38%	0%	40%	21%
0%	36%	Luxembourg	41	18	11	12	0	45%	27%	29%	0%
0%	36%	Croatia	5	2	0	2	1	46%	0%	32%	22%
0%	36%	Bulgaria	99	46	0	52	0	47%	0%	53%	0%
1%	36%	Finland	351	171	15	41	125	49%	4%	12%	36%
0%	37%	Slovakia	71	41	0	30	0	57%	0%	42%	0%
8%	44%	Poland	4,813	2,776	85	958	995	58%	2%	20%	21%
1%	45%	Romania	741	490	0	248	2	66%	0%	34%	0%
18%	64%	Italy	11,421	7,638	2,479	573	731	67%	22%	5%	6%
12%	76%	Spain	7,628	5,739	0	956	933	75%	0%	13%	12%
7%	82%	France	4,278	3,505	148	394	231	82%	3%	9%	5%
0%	83%	Malta	60	50	0	0	10	83%	0%	0%	17%
0%	83%	Greece	250	222	0	0	28	89%	0%	0%	11%
17%	100%	United Kingdom	10,599	9,670	6	302	621	91%	0%	3%	6%

Share of the country in total	Cumulated share	GEO/WST_OPER	Total waste treatment (kt)	Landfill / disposal (D1-D7, D12) (kt)	Incineration / disposal (D10) (kt)	Incineration / energy recovery (R1) (kt)	Recovery other than energy recovery (kt)	Landfill / disposal (D1-D7, D12) (%)	Incineration / disposal (D10) (%)	Incineration / energy recovery (R1) (%)	Recovery other than energy recovery (%)
0%	100%	Lithuania	148	148	0	0	0	100%	0%	0%	0%
0%	100%	Cyprus	3	3	0	0	0	100%	0%	0%	0%

Animal and vegetal waste treatment methods for 2012

Share of the country in total	Cumulated share	GEO/WST_OPER	Total waste treatment (kt)	Landfill / disposal (D1-D7, D12) (kt)	Incineration / disposal (D10) (kt)	Incineration / energy recovery (R1) (kt)	Recovery other than energy recovery (kt)	Landfill / disposal (D1-D7, D12) (%)	Incineration / disposal (D10) (%)	Incineration / energy recovery (R1) (%)	Recovery other than energy recovery (%)
0%	0%	Luxembourg	86	0	0	0	86	0%	0%	0%	100%
2%	2%	Austria	1,914	0	0	14	1,899	0%	0%	1%	99%
4%	7%	Belgium	3,637	0	43	16	3,579	0%	1%	0%	98%
16%	23%	Germany	13,729	3	32	1,403	12,292	0%	0%	10%	90%
2%	25%	Sweden	1,599	1	0	26	1,572	0%	0%	2%	98%
0%	25%	Slovenia	234	0	0	6	228	0%	0%	3%	97%
4%	29%	Poland	3,268	6	46	42	3,174	0%	1%	1%	97%
7%	36%	Italy	5,743	11	15	187	5,530	0%	0%	3%	96%
17%	53%	Netherlands	14,458	42	484	352	13,580	0%	3%	2%	94%
0%	53%	Ireland	288	3	0	29	256	1%	0%	10%	89%
1%	54%	Denmark	759	11	0	63	686	1%	0%	8%	90%
0%	54%	Latvia	78	1	0	3	73	2%	0%	4%	94%
0%	54%	Estonia	65	1	0	0	63	2%	0%	1%	97%
0%	54%	Lithuania	261	8	0	9	243	3%	0%	3%	93%
2%	57%	Finland	1,841	60	152	61	1,568	3%	8%	3%	85%
8%	65%	United Kingdom	7,008	233	312	589	5,874	3%	4%	8%	84%
3%	68%	Spain	2,363	80	0	100	2,183	3%	0%	4%	92%
1%	68%	Hungary	620	23	1	167	428	4%	0%	27%	69%
0%	69%	Czech Republic	282	15	2	53	212	5%	1%	19%	75%
9%	77%	France	7,296	586	15	325	6,371	8%	0%	4%	87%
1%	78%	Slovakia	757	105	28	5	618	14%	4%	1%	82%
0%	78%	Portugal	133	19	11	15	88	14%	8%	11%	66%
0%	78%	Croatia	114	17	0	2	95	15%	0%	2%	83%
1%	79%	Greece	452	73	18	57	304	16%	4%	13%	67%
0%	79%	Cyprus	222	52	7	2	162	23%	3%	1%	73%
20%	99%	Romania	16,855	5,214	40	100	11,501	31%	0%	1%	68%

Share of the country in total	Cumulated share	GEO/WST_OPER	Total waste treatment (kt)	Landfill / disposal (D1-D7, D12) (kt)	Incineration / disposal (D10) (kt)	Incineration / energy recovery (R1) (kt)	Recovery other than energy recovery (kt)	Landfill / disposal (D1-D7, D12) (%)	Incineration / disposal (D10) (%)	Incineration / energy recovery (R1) (%)	Recovery other than energy recovery (%)
0%	99%	Malta	14	9	5	0	0	61%	37%	0%	2%
1%	100%	Bulgaria	738	712	0	11	15	97%	0%	1%	2%

Dried municipal sewage sludge treatment methods for 2012

Share of the country in total	Cumulated share	GEO/WST_OPER	Total waste treatment (kt)	Landfill / disposal (D1-D7, D12) (kt)	Incineration / disposal (D10) (kt)	Incineration / energy recovery (R1) (kt)	Recovery other than energy recovery (kt)	Landfill / disposal (D1-D7, D12) (%)	Incineration / disposal (D10) (%)	Incineration / energy recovery (R1) (%)	Recovery other than energy recovery (%)
0%	0%	Cyprus	3	0	0	0	3	0%	0%	0%	100%
1%	1%	Italy	72	0	0	0	72	0%	0%	0%	100%
0%	1%	Lithuania	18	0	0	0	18	0%	0%	0%	100%
10%	11%	Denmark	869	0	34	0	836	0%	4%	0%	96%
0%	11%	Luxembourg	4	0	1	0	4	0%	16%	0%	84%
1%	13%	Belgium	107	0	89	0	19	0%	83%	0%	17%
0%	13%	Croatia	0	0	0	0	0	0%	0%	0%	0%
0%	13%	Latvia	0	0	0	0	0	0%	0%	0%	0%
1%	13%	Poland	57	0	57	0	0	0%	100%	0%	0%
13%	26%	United Kingdom	1,078	5	229	0	844	0%	21%	0%	78%
1%	27%	Spain	103	1	100	0	2	1%	97%	0%	2%
0%	27%	Malta	10	0	0	0	10	2%	0%	0%	98%
1%	28%	Estonia	75	1	0	0	74	2%	0%	0%	98%
4%	32%	Netherlands	331	10	321	0	0	3%	97%	0%	0%
3%	35%	Austria	266	14	139	0	114	5%	52%	0%	43%
2%	37%	Slovenia	135	7	13	0	115	5%	10%	0%	85%
9%	46%	Hungary	748	40	24	0	684	5%	3%	0%	91%
3%	49%	Czech Republic	247	13	8	0	226	5%	3%	0%	91%
2%	50%	Greece	149	10	39	0	100	6%	26%	0%	67%
1%	52%	Romania	113	11	0	0	102	10%	0%	0%	90%
39%	91%	Germany	3,314	384	1,009	0	1,922	12%	30%	0%	58%
1%	92%	Finland	53	6	32	0	15	12%	59%	0%	29%
3%	95%	France	262	40	207	0	14	15%	79%	0%	5%
1%	95%	Sweden	47	8	1	0	38	16%	3%	0%	80%
0%	96%	Bulgaria	33	7	0	0	27	20%	0%	0%	80%
2%	97%	Ireland	132	26	0	0	105	20%	0%	0%	80%

Share of the country in total	Cumulated share	GEO/WST_OPER	Total waste treatment (kt)	Landfill / disposal (D1-D7, D12) (kt)	Incineration / disposal (D10) (kt)	Incineration / energy recovery (R1) (kt)	Recovery other than energy recovery (kt)	Landfill / disposal (D1-D7, D12) (%)	Incineration / disposal (D10) (%)	Incineration / energy recovery (R1) (%)	Recovery other than energy recovery (%)
2%	99%	Portugal	195	47	0	0	148	24%	0%	0%	76%
1%	100%	Slovakia	50	43	3	0	4	86%	6%	0%	7%

Household and similar waste treatment methods for 2012

Share of the country in total	Cumulated share	GEO/WST_OPER	Total waste treatment (kt)	Landfill / disposal (D1-D7, D12) (kt)	Incineration / disposal (D10) (kt)	Incineration / energy recovery (R1) (kt)	Recovery other than energy recovery (kt)	Landfill / disposal (D1-D7, D12) (%)	Incineration / disposal (D10) (%)	Incineration / energy recovery (R1) (%)	Recovery other than energy recovery (%)
12%	12%	Germany	16,764	30	6,905	7,474	2,356	0%	41%	45%	14%
2%	14%	Sweden	2,326	27	0	2,296	4	1,2%	0%	99%	0%
1%	15%	Austria	1,138	18	0	1,069	51	2%	0%	94%	5%
4%	19%	Netherlands	5,865	125	25	5,705	10	2%	0%	97%	0%
2%	21%	Belgium	2,141	47	569	1,479	45	2%	27%	69%	2%
2%	22%	Denmark	2,528	91	0	2,232	205	4%	0%	88%	8%
0%	23%	Luxembourg	166	22	122	0	22	14%	73%	0%	13%
12%	35%	Italy	16,939	6,200	2,595	33	8,111	37%	15%	0%	48%
16%	51%	France	21,949	9,223	5,058	6,728	940	42%	23%	31%	4%
1%	52%	Finland	2,007	887	2	902	216	44%	0%	45%	11%
3%	56%	Portugal	4,564	2,713	42	923	887	59%	1%	20%	19%
12%	68%	United Kingdom	17,019	10,562	5,190	0	1,267	62%	30%	0%	7%
7%	75%	Poland	9,578	7,158	51	17	2,352	75%	1%	0%	25%
0%	75%	Cyprus	166	130	0	0	36	78%	0%	0%	22%
2%	77%	Czech Republic	3,176	2,558	0	586	32	81%	0%	18%	1%
7%	85%	Spain	10,299	8,796	7	1,496	0	85%	0%	15%	0%
2%	87%	Hungary	2,954	2,533	0	366	55	86%	0%	12%	2%
1%	88%	Ireland	1,021	883	0	134	4	86%	0%	13%	0%
1%	89%	Slovakia	1,362	1,188	4	163	7	87%	0%	12%	1%
0%	89%	Estonia	137	127	0	0	10	93%	0%	0%	7%
3%	92%	Romania	4,690	4,557	0	6	126	97%	0%	0%	3%
0%	93%	Slovenia	314	311	0	0	3	99%	0%	0%	1%
1%	94%	Croatia	1,352	1,347	0	0	6	100%	0%	0%	0%
0%	94%	Latvia	526	526	0	0	0	100%	0%	0%	0%
2%	96%	Bulgaria	3,073	3,073	0	0	0	100%	0%	0%	0%
3%	99%	Greece	4,342	4,342	0	0	0	100%	0%	0%	0%

Share of the country in total	Cumulated share	GEO/WST_OPER	Total waste treatment (kt)	Landfill / disposal (D1-D7, D12) (kt)	Incineration / disposal (D10) (kt)	Incineration / energy recovery (R1) (kt)	Recovery other than energy recovery (kt)	Landfill / disposal (D1-D7, D12) (%)	Incineration / disposal (D10) (%)	Incineration / energy recovery (R1) (%)	Recovery other than energy recovery (%)
1%	100%	Lithuania	792	792	0	0	0	100%	0%	0%	0%
0%	100%	Malta	153	153	0	0	0	100%	0%	0%	0%

LF-NA-28230-EN-N

JRC Mission

As the science and knowledge service of the European Commission, the Joint Research Centre's mission is to support EU policies with independent evidence throughout the whole policy cycle.

EU Science Hub
ec.europa.eu/jrc

@EU_ScienceHub

EU Science Hub - Joint Research Centre

Joint Research Centre

EU Science Hub

Publications Office

doi:10.2791/870953

ISBN 978-92-79-63778-0