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CCS on Waste to Energy

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This report describes work decommissioned by WOOD Plc (Italy) and LEAP Scarl (Laboratorio Energia e Ambiente Piacenza) on behalf of IEAGHG. The principal researchers were:

- Giulio Bortoluzzi, LEAP Scarl
- Antonio Conversano, LEAP Scarl
- Rano Fisher, Wood Plc
- Manuel Gatti, LEAP Scarl
- Lucia Manna, Wood Plc
- Fabio Poretti, LEAP Scarl
- Vincenzo Tota, Wood Plc
- Federico Vigano, LEAP Scarl
- Massimo Zanasso, Wood Plc

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The IEAGHG manager for this report was: Monica Garcia Ortega

The expert reviewers for this report were:

- Niels Berghout (IEA)
- Earl Goetheer (TNO)
- Robin Quartier (VBSA)
- Ruby Ray (WOOD Plc, UK)

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Further information or copies of the report can be obtained by contacting IEAGHG at:

IEAGHG, Pure Offices, Cheltenham Office Park
Hatherley Lane, Cheltenham,
GLOS., GL51 6SH, UK

Tel: +44 (0)1242 802911
E-mail: mail@ieaghg.org Internet: www.ieaghg.org

CCS ON WASTE TO ENERGY

It is estimated that, by 2050, 3.75 billion tons[1] of waste will be produced annually and 11.1% of it will be incinerated (The World Bank). Globally, it is estimated that 1.76 billion tons[1] of CO_2 were generated from solid waste treatment and disposal in 2016, representing 5% of the total global CO_2 emissions (The World Bank). In waste-to-energy (WtE) facilities, the waste incineration of 1 ton of municipal solid waste (MSW) is associated with the release of about 0.7-1.7 tons[1] of CO_2. (Zero Waste Europe, 2019). The CO_2 content in the flue gas emitted from WtE facilities is approximately 6-12%, depending on the feedstock and treatment process (Zehenhoven R. and Kilpinen P). IEAGHG identified the need to explore the implementation of CCUS (Carbon Capture & Utilization/Storage) as a CO_2 emissions mitigation pathway in the WtE sector under different regional scenarios.

This report is divided into 5 sections: overview of WtE frameworks and WtE with CCS projects; review of regulations for WtE plants; overview of strategies to cut down CO_2 emissions from WtE plants; review of challenges on the integration of CO_2 capture systems on WtE plants; and assessment of the market potential of the WtE-CCU/CCS integration.

Key messages

- Approximately, there are 2,100 WtE facilities in 42 countries. They have a treatment capacity of around 360 million tons of waste per year. Asia and Europe lead the WtE sector.
- Globally, the WtE feedstock typically reflects the income level of the region. The higher the income the lower the percentage of organic matter.
- WtE plants are too small to generate large economies of scale. The specific costs of the adopted technologies are rather high, leading to very capital-intensive facilities. Consequently, the continuity of operation and revenue from both selling electricity and waste treatment fee are key considerations.
- Key factors with a significant influence on the integration of the CO_2 capture system with the WtE plant are: the location; the type of CO_2 capture system; the feedstock; the incineration technology; and the installation scenario (i.e. greenfield or retrofit).
- Amine-based chemical absorption is the preferred capture technology on current WtE facilities. This option, for partial and full CO_2 capture, has been considered for the seven projects identified in this study, based in The Netherlands, Norway, and Japan.
- The first concern with the use of an amine-based chemical absorption system is the flue gas composition, as amines can be easily degraded in the presence of impurities. For the integration of this CO_2 capture system in WtE facilities the flue gas requires pre-treatment. The chemical handling, spatial integration, and energy supply to cover the energy requirement for the CO_2 capture system are also important factors to consider.

[1] The original reference provided the values in tonnes. The following conversion has been used: 1 ton=0.907185 tonne

- Decisions on the integration of a CO_2 capture system with a WtE facility, or a district heating scheme (if existing), and with the transport, and storage or use of the CO_2, will depend on the specific location or region amongst other techno-economic aspects.
- In this study, ten regions were selected for the analysis of the market potential of CCUS in the WtE sector: South Africa, USA, India, Japan, Germany, Italy, The Netherlands, UK, Norway, and Australia (see Table 6).
- A review of the regulatory frameworks in these countries was carried out to highlight and compare different schemes. European Emission Level Values (ELVs) at the WtE stack were identified as more stringent compared to the USA (California) and Japan, while Australia and South Africa are similar. Indian thresholds are slightly higher compared to the EU countries.
- These ten regions were analysed under eight proposed criteria (opportunity for CCS/CCU; possible integration with district heating; local CO_2 emission factors for power and heat generation; CCUS regulation and carbon pricing mechanisms for WtE; diffusion of WtE; social acceptance of WtE and CCUS; WtE regulation: NOx and SOx emission limits; and average WtE plant size). Under these criteria, the USA, The Netherlands, and Germany showed the highest relative market potential, while Japan, Norway, and UK also have relatively good capability. India presented the lowest relative potential due to the lack of environmental policies related to CO_2 capture in WtE facilities.

Scope of Work

A team composed by Wood Italy and LEAP was commissioned by IEAGHG to provide a comprehensive analysis of the WtE sector and the role and potential of CCUS systems in its decarbonisation.

The main objectives of this study are: to review the distribution of WtE plants worldwide; identify trends and challenges in reducing CO_2 emissions in these facilities; deliver a literature review of regulations and current projects and initiatives; and estimate the relative potential of the integration of CCUS systems in WtE plants in different regions.

The countries selected for this study are South Africa, the USA, India, Japan, Germany, Italy, The Netherlands, Norway, UK, and Australia.

Findings of this study

The average generation per capita of municipal solid waste (MSW) at global level is 0.74 kg per day, and it is projected to increase up to 2.6 billion tons in 2030 and 3.4 billion tons in 2050. Asia and Europe lead this sector by means of the number of facilities in operation[2], with 1,500 and 490 plants respectively.

WtE plants could play an important role in the energy and CO_2 markets. Greenhouse gas (GHG) emissions can be reduced and become a driver to maximize the energy production efficiency of a WtE facility.

The main challenges of operating a WtE plant are linked to their size. WtE plants serve specific collection areas. Consequently, their size is based on the amount of treated waste and its energy content. The plant capacities are one-two orders of magnitude smaller than conventional fossil power stations. Consequently, WtE plants are too small to follow large economies of scale, as the specific costs of the adopted technologies are rather high, leading to very capital-intensive facilities. WtE plants therefore need significant annual revenues from the fee for the treatment of waste and the sale of electrical/thermal energy generated. Based on these criteria, the continuity of operation and reliability are key considerations.

Potential tools to increase the energy efficiency, contributing to reduce CO_2 emissions as well, are:

- Reduction of the combustion air excess
- Use of the flue gas recirculation
- Increase of the steam cycle parameters (e.g. temperature and pressure)
- Increase of the biogenic fraction of municipal waste.

As seen in Table 1, the highest increase on gross electric efficiency is obtained by increasing the steam cycle parameters.

[2] Data from 2018

Table 1 Comparison between operational factors to improve the gross electric efficiency of a Waste-to-Energy plant

	Primary Air/fuel ratio (kg/kg)	Steam T, °C	Steam P, bar	Boiler Efficiency	Gross Electrical Efficiency	ΔkWh/t waste	$\Delta tCO_2/kWh$
Benchmark	1.9	400	40	86.5	26.4	/	/
Reduced Air Excess	1.39	400	40	87.7	26.6	5.55	0.126
External Superheating	1.9	520	90	87	29.7	91.6	0.007
High Steam Parameters	1.9	500	90	86.5	30.2	105.5	0.006
Steam Reheating	1.9	420	90	86.5	29.9	97.2	0.007

For the selected countries in this study, South Africa, USA, India, Japan, Germany, Italy, The Netherlands, UK, Norway, and Australia, the CO_2 emission factors (ton CO_2/ton waste) have been evaluated, based on the data available for all, or only part, of the WtE plants in operation. Once the average emission factors have been determined, they have been applied to the total amount of treated waste (most recent available datum) to estimate the total $CO_{2,eq}$ emissions at country level[3] (Table 2).

In WtE plants, CO_2 is emitted as a component in the fluegas and can be divided into biogenic and greenhouse gas emissions. Direct fossil CO_2 emissions from the stack of WtE plants contributes to the current fossil CO_2 emissions. However, WtE plants also generate energy (electricity and/or heat) which otherwise would be produced in alternative ways which would emit larger CO_2 emissions. Consequently, CO_2 emissions are avoided (shown as negative values)[4]. This is significant in countries with high emissions from conventional electricity/heat production or with low waste recovery options. Additionally, implementing a CO_2 capture system offers a further reduction of CO_2 emissions (Table 2).

[3] All the reported results depend on the hypothesis introduced in the methodology
[4] The quantification of these will depend on the region and its energy market

Table 2 Summary of CO_2 emission factors from WtE plants (ton CO_2, eq / ton waste) for the selected countries

Country	Current fossil $CO_{2,eq}$ emissions					Additional Contribution from Potential Capture from WtE
	WtE Stack*	**Energy prod. (electricity & heat)**	**Landfill**	**Bottom Ash**	**TOTAL**	
The Netherlands	0.521	-0.304	-0.585	-0.060	**-0.427**	**-1.018**
Norway	0.497	-0.478	-0.600	-0.060	**-0.641**	**-1.001**
Italy	0.555	-0.292	-0.565	-0.060	**-0.363**	**-1.041**
Germany	0.521	-0.299	-0.585	-0.060	**-0.424**	**-1.017**
United Kingdom	0.509	-0.125	-0.593	-0.060	**-0.268**	**-1.009**
USA	0.524	-0.340	-0.584	-0.060	**-0.460**	**-1.019**
Japan	0.497	-0.399	-0.600	-0.060	**-0.562**	**-1.001**
India	0.663	-0.252	-1.600	-0.020	**-1.209**	**-1.117**
Australia	NA	NA	NA	NA	**NA**	**NA**
South Africa	NA	NA	NA	NA	**NA**	**NA**

* including RDF production

An overview of the regulatory frameworks relevant to WtE and CCS in the selected countries was carried out. This assessment covers: (i) air emission threshold limits at chimney stack; (ii) waste water discharge threshold limits; (iii) potential feedstock constraints; (iv) potential opportunities/constraints related to the energy (electrical/thermal); (v) prescriptions for the management of the waste produced; (vi) relevant laws; and (vii) potential/expected evolution of relevant laws.

The European Emission Level Values (ELVs) at the WtE stack were identified as more stringent compared to these in the USA (California) and Japan, while in Australia and South Africa these are similar. Indian thresholds are slightly higher compared to the EU countries.

The EU ETS was identified as a significant CO_2 reduction scheme in Europe, although waste incineration plants processing MSW are excluded. Specific incentives in Germany, The Netherlands, and Norway support the implementation of CCS in WtE incinerators. UK is implementing different green funding through schemes, while Australia is working on a new ETS. South Africa is working on tax-free allowances and public sector funding solutions for WtE. The Californian cap and trade rules include 400 businesses that represent 85% of the state's GHG emissions, while the Indian Ministry of New and Renewable Energy (MNRE) is working towards financial incentives applicable to WtE. The Japanese JVETS (Voluntary Emission Trading Scheme) is focused on the J-Credit Scheme and the JCM (Joint Crediting Mechanism) on developing and exporting low carbon technologies, products and services outside Japan.

Seven ongoing WtE projects were identified in The Netherlands, Norway and Japan. Further information is included in Table 3.

Table 3 Summary of WtE + CCUS projects

Country	Plant	Total Waste Processed [t/y]	Total CO_2 Produced [t/y]	CO_2 capture plant type	CO_2 capture plant status	Total CO_2 Captured [t/y]	CO_2 %mol conc. in flue gases	Removal Target[5]	CCU/CCS Technology
Netherlands	HVC-Alkmaar Project 1	682,412	673,882	Amine technology	Ongoing	4,000	N.A.	N.A.	Liquefied CO_2 for greenhouse horticulture
	HVC-Alkmaar Project 2	“	“	Amine technology	Feasibility study	75,000	N.A.	60%	Liquefied CO_2 for greenhouse horticulture
Netherlands	AEB Amsterdam	1,284,164	1,268,112	Amine technology (MEA based)	Feasibility study	450,000	N.A.	90%	Feasibility study
Netherlands	AVR-Duiven	360,635	400,000 (reported)	Amine technology (MEA based)	Plant Start-up	50,000-60,000	10%	90%	Liquefied CO_2 for greenhouse horticulture
Netherlands	AVR Rozenburg	N.A.	1,153,319	N.A.	N.A.	800,000	N.A.	N.A.	FEED Study ongoing based on the operator's experience in Duiven
Netherlands	Twence-Hengelo	608,000	600,000 (estimated)	Amine Absorption by Aker solutions	Full-scale project under engineering study	100,000	10-11%	N.A.	Liquefied CO_2 for greenhouse OR for the production of formic acid OR to be mineralized into construction materials
Norway	Fortum-Klemetsrud	375,000-400,000 (reported)	430,000-460,000 (reported)	Shell Cansolv engineered and built by Technip (reported)	Concept study completed. Pilot tests ongoing since Feb 2019. FEED ongoing	414,000	10-12%	90%	CO_2 to be delivered by truck to the Oslo harbor where it is liquefied and sent by ship to long term storage in the North Sea (logistics under study)
Japan	Saga City-Japan	74,010	54,000 (220 t/day reported)	Chemical absorption based on specific amine solvent	Full-scale plant in operation since 2016	2,500 (10 t/day reported)	8-18%	80-90%	Gaseous CO_2 stored in a 100 m^3 buffer and delivered via pipeline to nearby algae cultivation

[5] Removal target refers to the removal of the CO_2 content of the stream to be treated.

As seen in Table 3, the amine-based chemical absorption is the preferred CO_2 capture system in WtE facilities with CCUS systems. Based on the information used in this study, only amine-based chemical absorption was analysed in detail. For this reason, the interaction between the WtE plant and the amine-based chemical absorption system, and the requirements of both sections to run with the minimum disruption were examined.

The first concern towards the use of an amine-based chemical absorption system is the flue gas composition. Amines can be easily degraded in the presence of oxygen, SO_x, and NO_x. Consequently, the flue gas requires pre-treatment to keep these components under control, together with a low HCl content.

Additionally, the chemical handling, spatial integration, and energy supply to cover the energy requirement for the CO_2 capture system are important factors to consider. Stops in operation must be adequate to integrate the operations of the WtE and CO_2 capture plant with minimum disruption.

For a further look at the integration of a CO_2 capture system in a WtE plant, and the consequent operational challenges, a comprehensive technical review of three theoretical cases was carried out. It should be noted that CO_2 compression is not included in the analysis.

Table 4 Description of the study cases in this work

Case 1: CFB WtE plant	**Case 2: Grate boiler WtE plant**	**Case 3: Grate boiler WtE plant, integrated with a District heating (DH) network[6]**
Power output of 20MWe, with net electrical efficiency of 25.4% (non cogenerative)	Power output of 20MWe, with net electrical efficiency of 24.4% (non cogenerative)	Power output of 20MWe, with net electrical efficiency of 24.4% (non cogenerative)
Fluegas: 180,000 Nm^3/h	Fluegas: 180,000 Nm^3/h	Fluegas: 180,000 Nm^3/h
CO_2 content: 12% (v/v) (150 °C) (50 t CO_2/h)	CO_2 content: 8.2% (v/v) (150 °C) (35.3 t CO_2/h)	CO_2 content: 8.2% (v/v) (150 °C) (35.3 t CO_2/h)
Steam cycle: 115 t/h, 60 barg, 430 °C	Steam cycle: 101.5 t/h, 61 barg, 420 °C	Steam cycle: 101.5 t/h, 61 barg, 420 °C
CO_2 capture system: 90% CO_2 removal, steam requirement of 70 t/h, heat duty of regeneration of 3GJ/tCO_2	CO_2 capture system: 90% CO_2 removal, steam requirement of 51 t/h, heat duty of regeneration of 3GJ/tCO_2	CO_2 capture system: 90% CO_2 removal, steam requirement of 51 t/h, heat duty of regeneration of 3GJ/tCO_2 Recovery of additional energy with a heat pump. Integrated with district heating (12.3 MWth available from a Direct Contact Cooler, with a loss of 2.7MWe due to the heat pump power consumption)

6 Central/district heating is common in some regions (e.g. some European locations). However, other regions do not have the required infrastructure and the use of central/district heating is not as widespread.

Cases 1 and 2 (Table 4) showed the importance of the energy requirements for the CO_2 capture system, where finding heat recovery sources in the WtE facility becomes crucial. Heat recovery from the flue gas could be a potential option for energy integration. Case 3 (Table 4) includes the integration of a WtE plant with a district heating network and additional energy recovery through a heat pump. The objective was to analyse the competition between investing the energy from the WtE plant on the CO_2 capture system or using it in the district heating scheme. The results showed that on a district heating scheme, it is possible to recover enough energy from the WtE to cover the needs of the CO_2 capture system. The implementation was modelled through the integration of a heat pump, with some energy penalty associated.

The relative market potential was analysed in this study taking into account key criteria that have a significant influence on the integration of the CCUS in an existing WtE, with dependence of the location. The following list covers the identified criteria:

- Opportunity for CCS/CCU
- Possible integration with district heating
- Local CO_2 emission factors for power and heat generation
- CCUS regulation and carbon pricing mechanisms for WtE
- Diffusion of WtE
- Social acceptance of WtE and CCUS
- WtE regulation: NO_x and SO_x emission limits
- Average WtE plant size

Each region was analysed under these criteria and was given a relative score, as described in Table 5. Each criteria is evaluated with a score from 1 to 10, 1 being the least favourable scenario and 10 the most favourable scenario with regards to the market potential of CCS projects in WtE plants. An overview of the relative scores is included in Table 6

Table 5 Overview of lowest and highest scores for the criteria included in this study

Criteria	**Relative less favourable (score 1)**	**Relative most favourable (score 10)**
Opportunity for CCU/ CCS	CO_2 cannot be stored/ used	There is a market to storage/ use the CO_2
Integration with DH	Low integration	High integration
CO_2 emissions factor	Low CO_2 emissions factor of the electricity grid	High CO_2 emissions factor of the electricity grid
CCUS regulation: carbon pricing for WtE[7]	There is not a carbon pricing regulation	There is a carbon pricing regulation which includes negative emissions
WtE diffusion	Low diffusion	High diffusion
WtE and CCS social acceptance	Low acceptance	High acceptance
WtE regulations: NO_x and SO_x emission limits	High emissions (not favourable for the amine-based chemical absorption system)	Low emissions
Plant size	Low capacity	High capacity (favourable due to the economies of scale)

DH: District heating

[7] Note that the "CCUS Regulation: Carbon pricing for WtE" criterion in this report describes all Carbon Tax and Cap and Trade emissions (also known as ETS, Emission Trading Systems) programs relative to GHGs. Four main options are considered for this criterion. The total absence of an Emission Trading System is valuated with lowest mark (1-3), while the highest value (9-10) is assigned to an ETS program that includes both the Waste-to-Energy sectors and incentives for Negative Emission Technologies (NET). In the middle, there are the Cap and Trade systems that cover the WtE but not the NETs (7- 8), and the programs which do not include either of them (4-6).

Table 6 Relative evaluation of each location under the criteria proposed in this study

Criteria	weight %	Italy	The NL	UK	Norway	South Africa	Germany	Australia	Japan	India	USA
Opportunity for CCU/CCS	20%	6	9	8	8	6	8	7	7.5	6	9
Integration with DH	10%	7	8	5	10	1	9	3	4	2	6
CO2 emissions factor	10%	7	8	6	5	10	8	9	8	9	8
CCUS Regulation: Carbon pricing for WtE	20%	6	6	6	6	9	6	6	9	1	9
WtE diffusion	15%	6	6	7	4	1	8	3	10	5	8
WtE and CCUS social acceptance	10%	3.5	8	5.5	10	1	4.5	8.5	2	1	3
WtE Regulation: NOx/SOx Emission limits	10%	7	8	7	7	7	8	7	6	1	9
Plant Size	5%	4	10	5	2	3	6	5	1	7	9

The overall potential estimated for each country is shown in Table 7. It is calculated as a weighted sum of all the scores for each considered criterion. The shade of the colour denotes the relative favorability, from red (less favorable) to green (more favourable), going through intermediate favorable scores (yellow and orange).

Table 7 Relative WtE-CCUS market potential

Italy	The NL	UK	Norway	South Africa	Germany	Australia	Japan	India	USA
5.95	7.60	6.45	6.70	5.20	7.25	6.05	6.85	3.80	7.85

As seen in Table 7, the countries with the highest potential for the integration of CCUS in WtE facilities are the USA, The Netherlands, and Germany. Relatively good potential was also identified in Japan, Norway, and UK. India showed the lowest potential, mainly due to the lack of environmental policies regulating CO_2 capture and the low WtE diffusion, compared to other locations.

Comments from the reviewers

A review was undertaken by four recognised international experts from the industrial sector and academia. The draft was generally well received, with reviewers remarking on the significant contribution of this report to the future CO_2 capture context.

The comments from the reviewers can be divided into the following three sections.

- The CO_2 capture system: some reviewers commented on the amines considered, heat of absorption assumed, amine emissions and degradation. The contractor and IEAGHG manager agreed on differences reported in the literature. However, further discussions on these issues are out of the project's scope. In this study, a transparent description of the CO_2 capture system is included. Differences with other studies are expected. Based on these differences, the reader can identify and extrapolate to some extend the results included in this document. The contractor, however, reviewed the TRL of the CO_2 capture technologies initially reported, and took into consideration the comments from the reviewers.

- The flue gas from the WtE facility and the integration of the CO_2 capture system with the facility. One reviewer discussed the potential impurities to be found in the flue gas from the WtE facility, and the variability, depending on the waste composition. In addition, another reviewer provided further insights on European policies linked to regulations on emissions and landfilling. This information was taken into account in the final version of this study.

- Additional comments were received on the score given to two criteria: opportunity for CCU/CCS; and WtE and CCUS social acceptance. The reviewer considered that both scores should be lower for Australia. On the one hand, the reviewer considered that there is a lower opportunity for CCU/CCS for several regions, compared with the scores given in this report as currently there is only limited deployment. On the other hand the reviewer considered that, although Norway was assessed with the highest social acceptance, and a score of 10 was given, the surveys showed that 54% of the population supported CCU/CCS. Similarly, the rest of the countries show a high score, while the acceptance is limited. The reviewer considered that these high scores might lead to a misinterpretation, as the reader might understand that a score of 10 means that 100% of the population supports CCU/CCS. Based on these comments, the contractor changed the opportunity for CCU/CCS in Australia from 8 to 7 and included a further description on the assessment of the different regions under the given relative criteria. Moreover, additional information on the limitations of this methodology based on peer-reviewed publications, and other sources of information, was provided in the final report.

The high/medium/low potential in different regions is expressed as relative numerical values without units. This relative concept is only for comparative purposes, which is explained in the text. The relative market potential ranking should therefore be applied with discretion. The methodology is designed to show transparency despite its limitations.

Conclusions

This study has provided the first overview of the WtE sector and the relative potential of CCS/CCU to reduce CO_2 emissions in these facilities in different regions.

The results show the differences on regulations and feedstock from one region to another. Additionally, common challenges on the integration of the CCS/CCU system include the need to add a pre-cleaning step prior to the chemical absorption process. Moreover, the integration should take into account the energy and special integration with the original facility.

To assess the market potential, a set of relative criteria was proposed in this study. This includes the following factors: (a) opportunity for CCS/CCU; (b) possible integration with district heating; (c) local CO_2 emission factors for power and heat generation; (d) CCUS regulation and carbon pricing mechanisms for WtE; (e) diffusion of WtE; (f) social acceptance of WtE and CCUS; (g) WtE regulation: NO_x and SO_x emission limits; and (h) average WtE plant size. Each factor has a contribution of 10-20%.

South Africa, the USA, India, Japan, Germany, Italy, The Netherlands, Norway, and Australia were analysed under the proposed criteria. The USA, The Netherlands, and Germany showed the highest relative potential, while Japan, Norway, and UK have also relative good capability. India presented the relative lowest relative potential due to the lack of environmental policies related to CO_2 capture in WtE facilities.

Recommendations

It is recommended that IEAGHG should continue to maintain a watching brief on the WtE sector, especially on new CCS/CCU projects in these facilities, as part of the decarbonising portfolio for the industrial sector.

This study has provided the first overview of the WtE sector and has assessed the relative potential of the integration of CCS/CCU technologies as a decarbonisation strategy in WtE facilities in different regions. Based on the results of this study the following areas for further work are recommended:

- A complete economic analysis of amine-based chemical absorption on WtE facilities, including detailed modelling, calculations, and sensitivity analysis.

- A further techno-economic analysis to assess the potential of other CO_2 capture systems on WtE facilities, together with a sensitivity analysis to clarify under which circumstances other technologies would be more beneficial than chemical absorption.

- A further regional economic and financial analysis is recommended. Asia has been identified as one of the regions with a significant potential to produce energy-from-waste. Additionally, other regions might have different economic and financial profiles.

- A detailed analysis of the potential of the WtE sector to contribute, with negative emissions, to deeper global CO_2 emissions reductions by 2030 and 2050.

- Further investigation on load hours and its impact on plant performance. The availability of feedstock has a significant impact on the techno-economic performance of the plant, and it is also linked to the market dynamics and government policies. A further study on how designers and operators can take these factors into account is recommended.

- Further investigation linked to CO_2 transport and storage is also recommended. A well-designed cluster infrastructure could drastically reduce the cost of the entire WtE+CCS facility, as the liquefaction and storage sections would be common to other facilities in the cluster.

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1. Introduction

1.1 Study background and objectives

Waste management is a very scattered and complex system made up by different plants and facilities that treat / recover / dispose different types of waste (e.g. "municipal" or "special"), based on the policies adopted in each country and the available technologies.
According to the recent modification (Directive (EU) 2018/851 - EU, 2018) of the European Waste Framework Directive (WFD, 2008/98/EC), Municipal Solid Waste (MSW) is defined as:

- mixed waste and separately collected waste from households, including paper and cardboard, glass, metals, plastics, bio-waste, wood, textiles, packaging, waste electrical and electronic equipment, waste batteries and accumulators, and bulky waste, including mattresses and furniture;
- mixed waste and separately collected waste from other sources, where such waste is similar in nature and composition to waste from households.

On the other hand, the updated WFD defines as "special" all the wastes that cannot be classified as MSW, like the waste generated by large offices and commercial activities, as well as industries, agriculture, Construction & Demolition (C&D), mines, etc.
The overall production of "special" waste in industrialized countries is significantly higher than that of MSW: for example, in the European Union, MSW is estimated to represent 7 - 10 % of the total waste generated (EU, 2018).

While the management of MSW is the result of public planning, the management of special waste is typically dispersed and depends, for a large extent, on the initiatives of waste producers and private waste management companies. As a result, plants for MSW recovery are relatively large plants equipped with energy recovery facilities, whereas special waste is often incinerated in medium-small plants that feature energy recovery only in very limited cases[1].
Hence, the investigation presented in the next chapters focuses on MSW and plants devoted to its treatment.

Focusing on MSW, on behalf of IEA GHG, in the present study Wood has addressed all the opportunities and challenges related to the application of Carbon Capture Utilisation/Storage (CCU/CCS) to the Waste to Energy (WtE) sector. The main objective is to carry out an initial overview of this integration CCS/CCU opportunity before IEAGHG considers proceeding to more detailed evaluations.

[1] For example, in Italy in 2017 the 40 operating WtE plants for MSW have treated 6.1 Mt of mixed waste, mainly MSW, whereas additional 1.5 Mt of special waste was incinerated in more than 150 other smaller facilities.

The main activities of the study have been the following:

- Review the current status and diffusion of the WtE business and the plants distribution worldwide, focusing on ten selected countries, analyse trends and tools adopted by WtE plants in reducing CO_2 emissions and identify the main challenges in this kind of plants, focusing particularly on reliability.
- Carry out a literature research to provide an overview of the regulations applicable to the WtE and CCS sectors in ten selected countries (same as mentioned above).
- Collect information regarding ongoing projects/initiatives aiming at integrating Carbon Capture with WtE facilities, identify potential challenges and opportunities of this integration in the design (theoretical review) and the operation of the plants.
- Finally estimate the potential of the CCU/CCS/WtE integration based on the various aspects analysed throughout the course of the study, focusing on the ten selected counties.

For the execution of the requested study activities, Wood has engaged LEAP scarl to provide their capabilities and skills especially as far as Waste-to-Energy plants and their design issues and operational challenges are concerned.

As already mentioned, some of the analysis tasks of the present study have been focused on a restricted group of countries that have been selected depending on several parameters, like:

- the geographical zone and the urbanization level;
- the branching of the electricity/heat network;
- the presence of large scale WtE plants;
- the type of waste incinerated and the type of energy recovery;
- the potential for CCS/CCU applied to WtE plants;
- the availability of potential destinations for the captured CO_2.

As a result, 10 significant countries have been selected to represent the possible trends worldwide in terms of energy recovery from waste and CCS/CCU potential. The selected countries, from the five continents, are:

- Africa: South Africa;
- America: USA;
- Asia: India, Japan;
- Europe: Germany, Italy, The Netherlands, Norway, UK;
- Oceania: Australia.

Despite the only WtE plant operating in Africa is located in Ethiopia, South Africa has been selected because of the higher level of urbanization and the more effective electricity grid.

Among the countries of the American continent, the USA are the reference nation in terms of installed WtE plants and the country with the greater potential for enhancements also regarding CCS/CCU. These are the main reasons why the USA have been chosen, together with the fact that as a country it is very active in terms of CCS/CCU projects in other sectors and its decisions could generate significant impacts worldwide.
Japan and India are two opposite cases in Asia, with the former representing a pioneer country in waste incineration and CO_2 capture from WtE, while the latter can be considered an arising country for WtE diffusion on large scale.
Regarding Europe, several countries have been selected because there are significant differences between North-Western countries like The Netherlands and Norway, where most of the WtE plants produce both heat and electricity, and South Europe countries like Italy, where often the energy output of WtE is only electricity.
Australia has been chosen as a focus country for Oceania because there are several ongoing projects of WtE facilities and, as a growing country, potential applications in the future.

1.2 Structure of the report

An overview of the study report structure is provided as follows:

- Section A – Executive Summary: Summary of the study basis, methodology and key findings.
- Section B – Update of WtE plants with and without CCS/CCU systems:
  - General overview of the framework of WtE plants worldwide with particular focus on a restricted group of countries that have been selected to represent the possible trends worldwide in terms of energy recovery from waste and CCS/CCU potential;
  - Description of the current status of projects involving the integration of WtE plants with CO_2 Capture and Utilisation/Storage (CCU/CCS) facilities, based on both a literature research and customized inquiries have been sent (via private e-mails) to relevant plant operators.
- Section C – Review global and local regulations for WtE plants: Analysis of the regulations related to WtE/CCS with focus on the ten selected countries. Thematic issues are air emission, waste water discharges, potential feedstock, incentives, solid residues, relevant laws and potential changes to the current regulatory standards are investigated.
- Section D – Review of strategies of WtE plants on cutting down CO_2 emissions: Comprehensive analysis focused on multiple sub-tasks:
  - Review trends and tools adopted in WTE plants (without Carbon capture) in reducing CO_2 emission;

- Review contribution of WTE plants to the local energy production and CO_2 emission and analyze the lifecycle CO_2 savings associated with WtE plants (even without Carbon Capture)
- Theoretical review of the carbon capture options for WtE plants and the issues related to energy integration of the capture system within the WtE plant.
- Elaboration of a list of potential use and destination of the captured CO_2, including an overview of the options in the national context of the ten selected countries

- Section E – Review of challenges on WtE plants operation with and without carbon capture: Presentation of the outcome of two study tasks focused on WtE plants operational issues, especially in relation to continuity of operation, and operating challenges linked to adding a CCS/CCU system to the WtE plant (addressing both risks and opportunities)

- Section F – Assessment of market potential of WtE-CCU/CCS integration: Conclusive section reporting the elaboration of a tool to evaluate potentiality of WtE-CCU/CCS integration at a country level, based on criteria depending on the geographical location, and its application to the ten countries selected for this study. The elaborated tool is anyhow intended as universal, i.e. it could be potentially applied to any country worldwide.

1.3 List of acronyms and abbreviations

The following table summarizes all the acronyms and abbreviations that have been used in the report, for easier reference.

Acronyms	Definition
AC	Activate Carbon
AV	Average Value
APC	Air Pollution Control
BAT	Best Available Technology
BFW	Boiler Feed Water
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture Storage
CCU	Carbon Capture Utilization
CEMS	Continuous Emission Monitoring System

Acronyms	Definition
CFB	Circulating Fluidized Bed
CHP	Combined Heat and Power
COP	Coefficient of Performance
DCC	Direct Contact Cooler
DCS	Distributed Control System
DH	District Heating
ELV	Emission Level Values
EOR	Enhanced Oil Recovery
ESP	Electrostatic Precipitator
ETS	Emission Trading System
FEED	Front End Engineering Design
FF	Fabric Filter
FGR	Flue Gas Recirculation
FGT	Flue Gas Treatment
GGH	Gas-Gas Heater
GHGs	Green Houses Gases
GWP	Global Warming Potential
ID	Induced Draft
IRL	Integration Readiness Level
LCA	Life Cycle Assessment
LHV	Lower Heating Value
MD	Median Value
MSW	Municipal Solid Waste
MW_E	Electric megawatts
MW_{LHV}	Megawatts of combustion power (LHV basis)
MW_T	Thermal megawatts
NA	Not Available
NET	Negative Emission Technology

Acronyms	Definition
NGCC	Natural Gas Combined Cycle
OEE	Overall Equipment Effectiveness
PCC	Post-Combustion Capture
PSA	Pressure Swing Adsorption
RDF	Refuse Derived Fuel
SRF	Solid Recovered Fuel
SCR	Selective Catalytic Reduction
SNCR	Selective Non-Catalytic Reactor
TOC	Total Organic Carbon
TRL	Technological Readiness Level
TSA	Temperature Swing Adsorption
WtE	Waste to Energy

2. Current status of WtE plants (without CO_2 capture)

2.1 Overview of plants worldwide with selected country focus

Even limiting the analysis to only WtE plant, several missing data had to be retrieved and the focus on some selected countries is done by presenting data from sources referring to different years. The investigation on WtE plants and their characteristics started from the reports from the International Solid Waste Association (ISWA, 2013) and the Confederation of European Waste-to-Energy Plants (CEWEP, 2012), where quite comprehensive data on European countries were retrieved. Nevertheless, many data on heat and electricity production were not updated or even missing, due to reluctance of plant owners/managers to disseminate data or to discrepancies among the different countries in accounting and processing such data. Where available, specific country reports were considered (e.g. Japan, UK, Italy) or even reports/datasheets from plant owners in case of poor or controversial data.

2.1.1 Overview of the framework of WtE plants worldwide

The first objective of the study has been to carry out a general overview of the framework of WtE plants worldwide.

The production of Municipal Solid Waste is strictly related to the economic development, the industrialization level and the local climate (World Bank, 2018). Countries with higher GDP tend to produce greater amounts of waste as levels of consumerism are higher. Even the level of urbanization plays a key role, since urban population generates twice the amount of waste produced by its rural counterpart.

Municipal Solid Waste generated worldwide is estimated to be approximately 2.02 billion tons (year 2016): the lowest productions are recorded for the Middle East and North Africa Region (129 million tons), while the highest values are noted in the East Asia and Pacific Region (468 million tons). Values for the different regions are shown in Figure 1.

The average generation per capita settles on 0.74 kg of waste per day, with the lowest values recorded for the Sub-Saharan Region (0.46 kg/capita/day) and the highest values noted in the North American Region (2.21 kg/capita/day). Values for the different regions are shown in Figure 2.

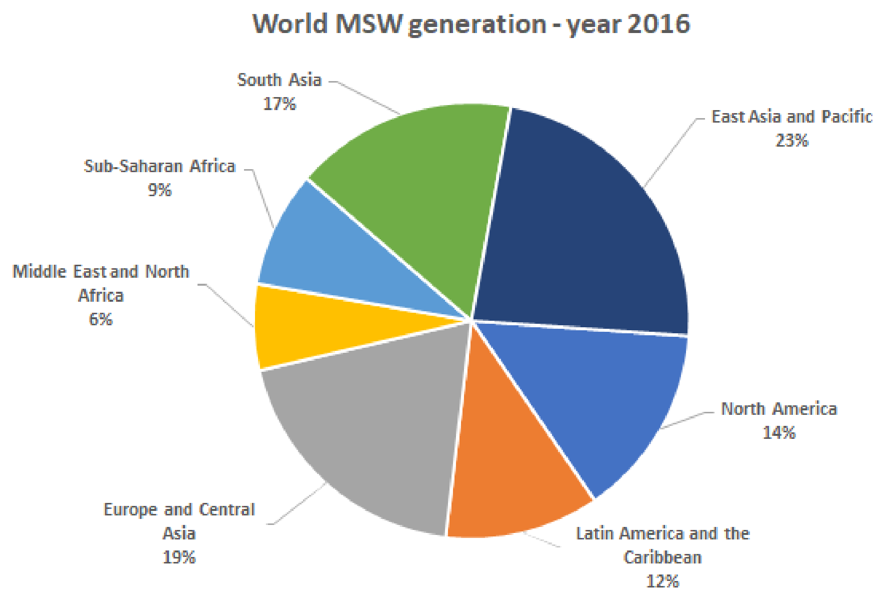

Figure 1: Municipal Solid Waste production worldwide (year 2016, data from World Bank, 2019)

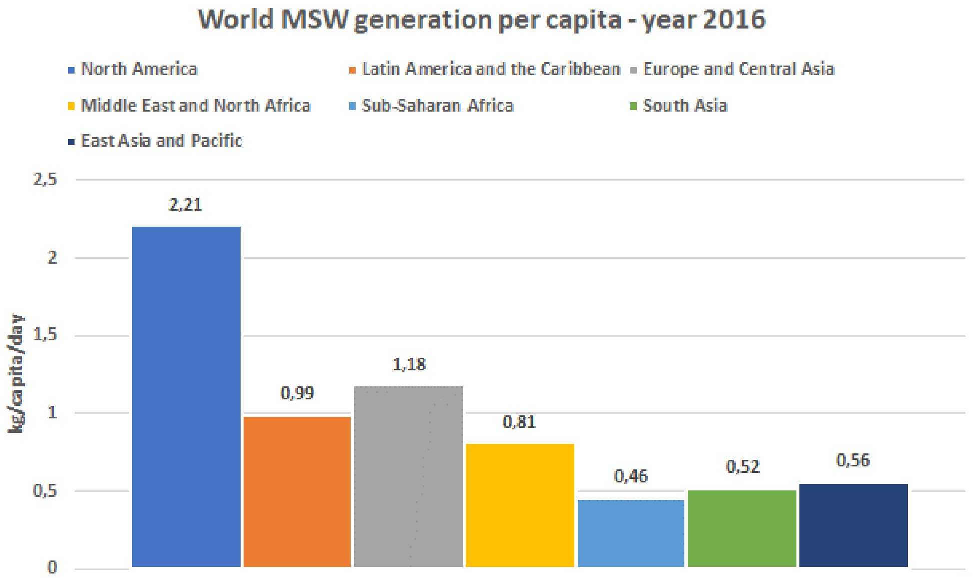

Figure 2: Municipal Solid Waste production per capita worldwide (year 2016, data from World Bank, 2019)

Projections on MSW generation worldwide, linked to the evolution of the Gross Domestic Product per capita throughout the years, lead to an increase to 2.59 billion tons by 2030 and to approximately 3.4 billion tons by 2050 (Figure 3).

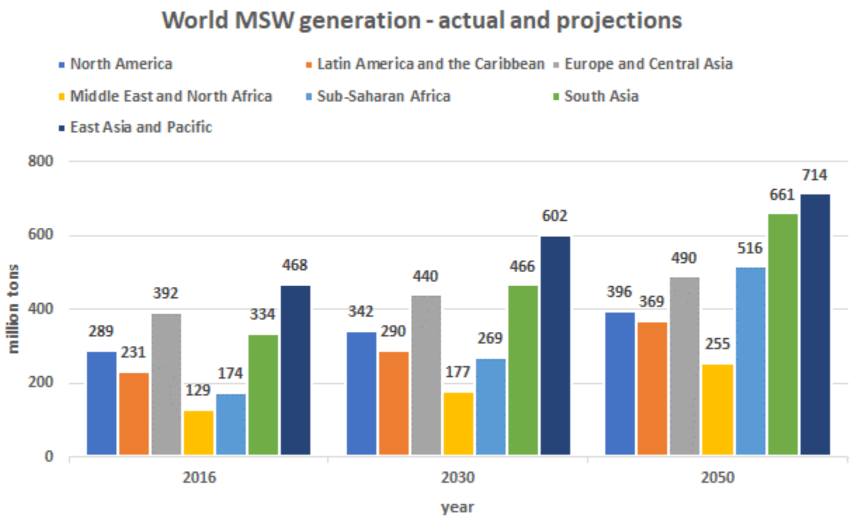

Figure 3: Municipal Solid Waste production worldwide - actual and projections (data from World Bank, 2019)

Figure 4 shows the average composition of MSW worldwide (data from World Bank, 2018): the main contributions are given by food and green (44%), paper and cardboard (17%) and other/plastics (14% and 12%).

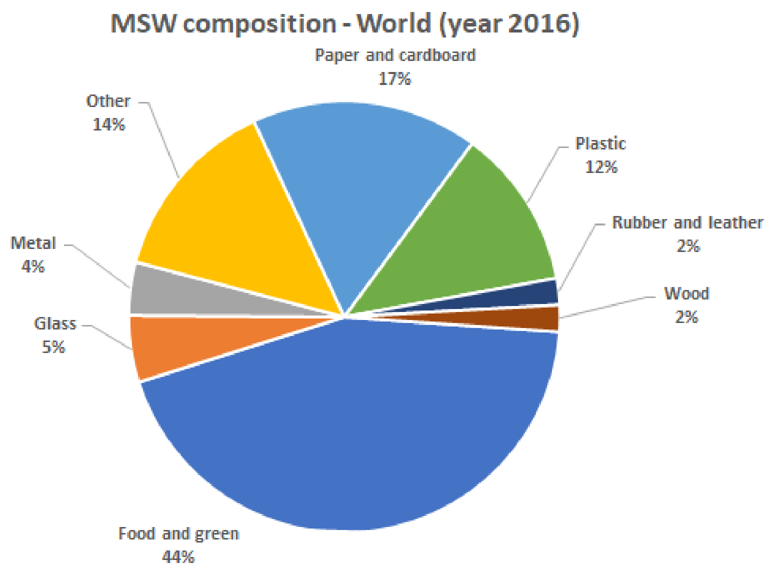

Figure 4: Municipal Solid Waste composition worldwide (year 2016, data from World Bank, 2019)

Typically, the higher the income level of the Region, the lower the percentage of organic matter. Moreover, the high rate of food and green is related to food loss and waste (1.3 billion tons per year according to the Food and Agriculture Organization of the United Nations).

The diffusion of WtE plants in the world encompass the presence of around 2,100 facilities in 42 countries. They have a treatment capacity of around 360 million tons of waste per year. Asia and Europe lead the way with respectively more than 1,500 and 490 plants in operation in 2018 (Table 1).

Table 1- Number of WtE plants worldwide (source Geosyntec and Deltaway Energy, 2018)

Region	Number of plants
Africa	1
America	92
Asia	1,503
Europe	492
Oceania	1
TOT.	**2,090**

2.1.2 *Focus on the selected countries*

For each selected country, an analysis of waste generation and treatment has been carried out, focusing on Municipal Solid Waste, followed by an examination of the WtE framework (number of plants, amount of waste treated, installed capacity, electricity/heat production).

South Africa

According to Department of Environmental Affairs (DEA) of the Republic of South Africa, South Africa generated approximately 108 million tons of waste in 2011, of which 49 million tons was general waste, 1 million tons was hazardous waste and the remaining 58 million tons was unclassified waste. Considering data for 2012, the overall general waste composition is made up by non-recyclable municipal waste (35%), followed by construction and demolition waste (20%), metals (13%), organic waste (13%), paper (8%), plastic (6%), glass (4%) and tires (1%).

Waste management services rely heavily on landfills for the disposal of waste. In 2011, 90% of all South Africa's waste was disposed into landfill sites, whereas the remaining 10% was recycled. No conventional WtE plants for MSW treatment are active in South Africa by now. In 2012, there were, however, 11 licensed treatment facilities for waste from public and private health care institutions, providing an annual treatment capacity of approximately 56,400 t/y. Based on the waste treatment capacity, 35% of such facilities were incineration plants.
In 2019 the first energy recovery plant in South Africa has been installed in the neighborhood of the city of Cape Town (Afrox/New Horizons Energy complex is made up by two treatment section, one Mechanical Biological Treatment (MBT) and one Anaerobic Digestion (AD) coupled with an upgrading section for the biogas-to-biomethane conversion).

The WtE potential of the country is related to the implementation of the waste management hierarchy (art. 4 of WFD), which leads, as first step for a sustainable waste management treatment, to avoid dump sites. The National Waste Management Strategy document, issued in 2011, is based on the principles of providing a methodology for the classification of waste, implementing baseline regulatory standards for managing waste at each stage of the waste management hierarchy, identifying categories of waste that require special waste management measures due to the risks to human health and the environment.

United States of America

According to the US Environmental Protection Agency, the MSW generation in the country reached 262.4 million tons in 2015 and a specific production of 2.03 kg per capita per day.
However, it is fundamental to underline that the methodology adopted by the USA EPA for the evaluation of the MSW generation cannot be easily comparable with other countries. Europe (Eurostat) applies a "site-specific" methodology, which is a direct approach that relies on the

measurement of MSW collected at waste treatment facilities. The USA EPA instead applies a materials flow methodology (indirect approach) where MSW amounts are not measured directly but they are calculated based on industry production data. The calculation hence for MSW generation in the USA is quite complex and it could contain estimations and missing gaps. Moreover, the US EPA and Eurostat define MSW treatment categories differently, so the full comparison of MSW statistics could become very critical.

The main contribution to the composition of US MSW is given by paper and cardboard (26%), followed by organic waste (15%) and plastics (13%). Given the shares of the different fractions, the LHV is expected to be around 10 MJ/kg.

Regarding MSW management, data from US EPA (2015) show that, due to the large amount of free land, landfill disposal is still the most used method for waste management (53%) at the expense of material and energy recovery.

According to the 2016 Directory of Waste-to-Energy facilities, 77 WtE plants were operating in the country, located in only 22 out of the 50 States, with Florida and New York leading the way with 11 and 10 facilities respectively. The total amount of waste treated is approximately 27.8 million tons per year, for an average plant capacity of 357,200 t/y.

60 WtE plants, out of 77, are grate-based plants and they are fed with MSW or MSW+industrial waste or sewage sludges. The other 13 plants out of 77, such as the ones in Hartford, West Palm Beach, Ames, Orrington, West Wareham, Detroit, Red Wing, Portsmouth Virginia, LaCrosse, Mankato, Honolulu, are fed instead with Refuse Derived Fuel (RDF). The 4 WtE plans left are considered modular, meaning that they can be moved from site to site. Modular systems burn unprocessed, mixed MSW but they differ from mass burn facilities in that they are much smaller and portable.

The typical output of US WtE plants is electricity only to the grid (59 plants), with the combined production of heat and power limited to 15 facilities and the heat-only production (i.e. steam export) limited to 3 plants.

The total amount of electricity production reached 20,850 GWh/y in 2016, with an installed gross electric capacity higher than 2,500 MW_E and with an installed thermal capacity of CHP plants higher than 2,700 MW_T.

The MSW landfill disposal ratio in the US is still today quite significant (53%), with 28 out of the 50 states still without WtE plants. Henceforth there is a huge potential for energy from waste enhancement. The proper application of the waste management hierarchy that requires waste diversion from landfills is possible only in the presence of an adequate WtE capacity.

India

Altough there are no precise and reliable estimates of MSW generation in India, this can be assumed in a wide range between 50 and 70 million tons per year, with respect especially to the cumulative production in the Indian urban areas and comparing some alternative estimations made by different subjects through the years.

Concerning the average Indian MSW composition, some data have been retrieved from the Central Pollution Control Board (CPCB): the main contribution is given by compostable matter (42%), followed by inert (40%) and paper (6%). Given the shares of the different fractions, CPCB estimated an average LHV value around 7.3 MJ/kg.

Based on the information available for the year 2012 by the CPCB, municipal authorities have set up so far only 279 compost plants, 172 bio-methanation plants, 29 RDF production plants (such as Mechanical-Biological Treatment - MBT - plants) and 8 Waste-to-Energy plants that mainly burn RDF. However, it is also reported that many of the overall facilities above are not even working. In any case, the current most severe issue is that these facilities allow to treat only the 19% of the total production of MSW, while the remaining 81% is disposed indiscriminately at dump yards in an unhygienic manner by the municipal authorities leading to problems of health and environmental degradation.

This is why, according as well to the final Draft Background paper "*A 21st Century Vision on Waste to Energy in India*" (May 2018), India currently suffers an alarming landfill urgency.

As said, only 8 WtE plants are operating in the country and the total installed capacity is equal to 94.1 MW_E.

According to the Task Force on Waste to Energy of the Planning Commissioning of the Government of India, in a foreseeable future of 5-7 years the non-recovered waste has a potential of generating 440 MW_E of power from 32,890 ton/day of combustible wastes including Refuse Derived Fuel (RDF), 1.3 million cubic meters of biogas per day or 72 MW_E of power capacity from biogas and 5.4 million metric tons of compost annually to support agriculture. The potential for new WtE installations is hence significantly important and in a longer projection (2050) it has been estimated that the number of energy recovery facilities can increase up to 2,780 MW_E in terms of electric capacity.

Finally, according to the final Draft Background paper *"A 21st Century Vision on Waste to Energy in India"* (May 2018), around 50 WtE projects have been left incomplete through the years, held up at different stages or stranded for a variety of reasons (legal complications, lack of financial support from banks, non-availability of land, etc.). A quick completion of these 50 WtE projects, which have already been initiated, could help many cities and towns to tackle effectively the waste issue (the full list of these plants is available in the cited report).

Japan

Based on the data from the Japanese Ministry of the Environment, the national production of MSW hit 44 million tons in 2014.
A composition of the Municipal Solid Waste generated in the municipality of Kyoto have been retrieved from literature (Source: Asia Biomass Energy Cooperation Promotion Office) and, given the shares of the different fractions, the LHV is expected to be around 10 MJ/kg. The main contribution is given by organic waste (36%), followed by paper and cardboard (30%) and plastics (11%).
Due to the lack of free land for waste disposal and the obligations to treat waste locally, the primary objectives of waste incineration in Japan has always been the volume reduction and the ease of the disposal process. Japan has historically been a pioneer of waste incineration, resulting in many small-scale disposal-only plants for the use of individual municipalities.

As a consequence of the peculiar history of Japan, incineration (including WtE) rate is the highest in the world, being around 80%.
However, although the modernization of installations has improved energy recovery from MSW incineration and modern Waste-to-Energy plants are now incentivized to recover energy on a larger scale, Japan is still very far from European's records.
As a matter of fact, 64-67% of Japanese incineration facilities have a heat recovery system, which has been a percentage almost constant in the last ten years. More specifically, in 2013, there were in the country 778 plants recovering residual heat, but only 328 of them (28.0%) were equipped with power generation facilities.
In 2015, a slight increase through the years has been registered with approximately 350 facilities equipped with power generation as well.

With respect to the same year, 1,141 waste incineration plants were operating in the country, evenly located across the Japanese territory. The total amount of waste treated is approximately 181,899 t/day, for an average plant capacity of 159.4 t/day. Of the 1'141 facilities in operation, 89% are incineration plants, and 9% (103 plants) are gasification plants.

As a matter of fact, Japan has been one of the few countries in the world that historically has developed a significant number of gasification facilities for waste treatment, mainly due to the potential benefits that may justify their adoption related to material recovery and operation/emission control such as recovery of metals in non-oxidized form, collection of ashes in inert-vitrified form and lower generation of some pollutants. With a focus on the Japanese slagging gasification technologies, the 6 leading companies, that in 2013 as reference year, have licensed, developed and constructed gasification plants in Japan are Nippon Steel (as largest supplier), Kobelco-Eco, JFE, Hitachi Zosen, Ebara, Mitsui Engineering & Shipbuilding. One of the main gasification-based technologies adopted in Japan is the Direct Melting System

(DMS) offered by the Nippon Steel and implemented for example in the Shin-Moji WtE plant, one of the largest waste gasification and ash melting plants in the world.

However, combustion remains the most predominant way of WtE and among the different technologies installed in combustion-type waste incineration plants, grate combustors lead the way (71% in number) followed by fluidized bed reactors (17% in number).

In 2009, the Japanese Ministry of the Environment made a subsidy system and a guidebook to promote the construction of incinerators for Municipal Solid Waste with high power generation efficiency. In the guidebook, various existing technological options and combinations were recommended to achieve more than 20% of power generation efficiency in MSW plants with a capacity of 500 ton/day. As a result, the power generation efficiency raised from 15.8% (weighted mean for years 2003-2007) to 20.2% in newly constructed facilities.
Although the modernization of installations has improved energy recovery from MSW incineration, Japan is still very far from European's records, mainly because of the small size of the facilities in Japan. In addition, most of the heat cannot be used because of the lack of district heating infrastructure. In fact, central/district heating is not widespread as it is in Europe.

Germany

According to the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), the MSW generation in the country reached 52 million tons in 2015.
Some data on MSW composition have been retrieved for the Hamburg district: the main contribution is given by organic waste (33%), followed by paper and cardboard (16,5%). Typical values for LHV of the residual waste range from 8.5 to 10 MJ/kg, while water and ash content are respectively 30% and 28%.

Based on year 2017 data from CEWEP, among the European countries, Germany is the one with the highest rate of recycling and composting (68%) and the one with the lowest rate for landfill disposal (1%), the WtE covering a share of the 31%. This brings to a good balance between material and energy recovery from waste.
According to ISWA and CEWEP, globally 81 WtE plants are operating in Germany, evenly distributed all over the country and with a major concentration in North Rhine–Westphalia. The total amount of waste treated is approximately 22.6 million tons per year, for an average plant capacity of 305,000 t/y.
Most of the plant are fed with a mixture of MSW and commercial waste or sludge, and are grate-based, whereas a few plants uses only RDF in fluidized bed combustors.
The nominal LHV of the processed waste ranges from 8.5 to 12 MJ/kg for grate-based incinerators, from 14 to 18 MJ/kg for fluidized bed reactors.
The typical output of German WtE plants is the combination of electricity to the grid and heat for district heating.

The total amount of electricity production reached 5,768 GWh/y, with an installed electricity production capacity of 1,925 MW_E (2016).
Data on heat production are available for 40 plants, with a total amount of 11,800 GWh/y (2013).

As Germany imports some waste from UK, Norway and Ireland to full load its WtE plants, the ratio of landfill disposal is very limited (1%) and the thermal treatment rate is relevant (31%) no significant developments in the number of installed WtE plants or in the amount of waste treatment capacity are foreseen.

The Netherlands

Based on the data from Statistics Netherlands (CBS), the national production of municipal solid waste hit 9 million tons in 2016.
A MSW composition has been retrieved from literature (World Bank, 2012) and, given the shares of the different fractions, the LHV is expected to be around 10 MJ/kg. The main contribution is given by organic waste (36%), followed by paper and cardboard (28%) and plastics (14%).

Like in Germany, the waste management system in The Netherlands is based on a good balance between material (54%) and energy recovery (44%), with a small residual rate of landfill disposal (1%), based on year 2017 data from CEWEP.
Globally 13 WtE plants are operating in the country. The plants are evenly distributed, with the biggest facilities located in the most urbanized Western part of the Netherlands.
The total amount of waste treated is approximately 7 million tons per year, for an average plant capacity of 540,000 t/y.
Most of the plants are fed with a mixture of MSW and industrial waste, and are grate-based, whereas only 2 plants (Beuningen, Midden-Drenthe) use RDF in fluidized bed combustors.
The nominal LHV of the treated waste ranges from 8.4 to 13 MJ/kg for grate-based plants, while it is approximately 14 MJ/kg for fluidized bed combustors.
The typical output of Dutch WtE plants is the combination of electricity to the grid and heat for district heating.
The total amount of electricity production reached 1,997 GWh/y in 2016, whereas data on heat production are available for 5 plants, with a total amount of 962 GWh/y (2013).

Through the years The Netherlands has achieved a significant thermal treatment rate. Moreover, like Germany, they import some waste from the UK to full load their WtE plant fleet. For this reason, together with the very limited amount of landfill disposal, no significant developments in the WtE sector are foreseen in The Netherlands, in terms of number of plants and waste treatment capacity.

Norway

According to Statistics Norway, the MSW generation in the country reached 2.42 million tons in 2017.

Looking at the MSW composition that have been retrieved from literature (European Environmental Agency), the main contribution is given by paper and cardboard (27%), followed by wood (17%) and food/garden waste (15% each). Given the shares of the different fractions, the LHV is expected to be around 10 MJ/kg, whereas an estimation of the biogenic fraction of the residual waste is about 52% on energy basis (Avfall Norge, 2010).

Based on year 2017 data from CEWEP, Norway is one of the European countries (together with Finland, Sweden and Denmark) with the highest rate of thermal treatment (53%), which overcomes the recycling (including composting) rate (39%) mainly because WtE plants are massively exploited to supply heat for the district heating networks. Nevertheless, the overall result is a correct balance between material and energy recovery, ensuring almost zero use of landfilling.
Globally 17 WtE plants are operating in the country, most of them located in the major urban centers of the southern part of the country. The total amount of waste treated is approximately 1.53 million tons per year, for an average capacity of 85,000 t/y.
Most of the plants are fed with a mixture of MSW and industrial or commercial waste, and they are grate-based, whereas only 1 plant (in Oslo) uses RDF in a fluidized bed combustor.
The nominal LHV of the treated waste ranges from 10.5 to 12 MJ/kg for grate-based plants, whereas it is around 13 MJ/kg for the fluidized bed combustor.
The typical output of Norwegian WtE plants is heat for district heating, with the production of electricity limited to half of the facilities.
The total amount of electricity production reached 430 GWh/y in 2015 as a result of the average plant capacity of 61 MW_E, whereas the total heat production reached 3,800 GWh/y in 2015.
Although Norway has an unexploited capacity for WtE, it exports waste to Sweden due to lower gate fees and significantly higher revenues from energy sales than the ones achieved by Norwegian WtE plants.
No significant developments in the number of installed WtE plants or waste treatment capacity are foreseen. The major cities in Norway (Oslo, Bergen, Trondheim and Stavanger) have already a well-developed infrastructure for district heating. The remaining district heating market is limited and only for small-scale applications. This makes difficult to build new WtE plants that can ensure the full utilization of the recovered energy.

Italy

Based on the data from “Catasto Nazionale Rifiuti” managed by the “Istituto Superiore di Protezione e Ricerca Ambientale (ISPRA)”, the national production of MSW hit 29.6 million tons in 2017, Some data on MSW composition have been retrieved from ISPRA: the main contribution is given by organic waste (36%), followed by paper and cardboard (23%) and plastics (13%). Given the shares of the different fractions, the LHV is expected to be around 10 MJ/kg.

Based on year 2017 data from CEWEP, among the selected European countries, Italy is yet the one with the highest rate of landfill disposal (23%) and the lowest rate of thermal treatment (19%). The recycling rate is growing year by year, being very close to the standards set by the European Union (50% by 2020).
In total, 39 WtE plants are operating in the country: 26 of them are located in the northern part of Italy, while only 7 and 6 can be found in the center and southern regions respectively.
The total amount of treated waste is about 6.1 million tons per year, for an average plant capacity of 153,000 t/y. According to ISPRA, in 2017 the 26 plants in northern Italy treated 4'469'251 ton. More specifically these plants are concentrated in the regions of Lombardia (13 plants) and Emilia Romagna (8 plants) and in 2017 these two regions have treated 3,4 ml tons of MSW, covering about half of the whole national WtE treatment.
The central and southern part of Italy are currently the ones suffering a relevant WtE deficit together with the fact that there aren’t new plants scheduled to enter into operation in the near future.
In general, most of the plants are fed with a mixture of unsorted MSW and pretreated waste from MBT (Mechanical Biological Treatment), and they are grate-based, whereas 7 plants uses only RDF in fluidized bed combustors.
The nominal LHV of the processed waste ranges from 9.2 to 11.5 MJ/kg for grate-based plants, whereas it is around 14.5 MJ/kg for fluidized bed reactors.
The typical output of Italian WtE plants is the electricity to the grid, with the combined production of heat and power limited to a quarter of the facilities, especially in northern Italy.
The total amount of electricity production reached 1,750 GWh/y in 2017 as the result of an average plant capacity of 22 MW_E. The total heat production reached 1,150 GWh/y in 2017.
Unlike other more virtuous EU countries (like Sweden, Denmark, Netherlands or Germany), still today the MSW landfill disposal ratio in Italy is quite significant (23%).
The distribution of WtE plants is very fragmented, with some regions in the north with overcapacity and some regions in the south with no facilities at all, causing alarming problems of public sanitation.

Significant improvements in energy recovery from waste are theoretically possible, both in South Italy (installation of WtE plants dedicated to electricity production) and in North Italy (integration with district heating networks). However, the public opposition and the social unacceptance of WtE technologies are still very high. In 2016, the Italian Government estimated a need for additional WtE capacity for 1.8 million t/y, based on a number of very optimistic assumptions. Such an estimate clashes with the current use of landfilling of almost 7 Mt/y.

United Kingdom

Based on the data from the UK Department for Environment Food & Rural Affairs (DEFRA), the MSW generation in the country hit 27 million tons in 2016.
Some data on MSW composition have been retrieved from literature (Zero Waste Scotland): the main contribution is given by food waste (23%), followed by paper and cardboard (20%) and garden waste (17%). Typical values for LHV of the unsorted waste range from 8.9 MJ/kg for household waste to 11 MJ/kg for commercial & industrial waste.

Like the Italian case, according to year 2017 data from CEWEP, in the United Kingdom a significant amount of MSW is disposed into landfills (17%), with a recycling rate of 44% that stood below the EU28 average (46%), while the thermal treatment (37%) is higher than the European average value (29%).
In total, 42 WtE plants are operating in the country: most of them are located in England, especially in the central and southern part, while no plants can be found in Wales.
The total amount of waste treated is approximately 10.9 million tons per year, for an average plant capacity of 260,000 t/y.
Most of the plants are fed only with MSW or MSW+commercial waste. They are grate-based plants and there is no fluidized bed-based plant using RDF. The nominal LHV of the treated waste ranges from 8.5 to 10.5 MJ/kg.
The typical output of UK WtE plants is electricity to the grid, with the combined production of heat and power limited to 6 facilities.
The total amount of electricity production reached 7,146 GWh/y in 2017, with a net export of 6,187 GWh/y and an installed capacity higher than 920 MW_E. The total heat production reached 865 GWh/y in 2017.

UK exports over two million tons of RDF for energy recovery mainly to The Netherlands, Norway, Denmark and Germany. The absence of RDF recovery facilities combined with a rising landfill tax and high gate fees at the relatively few operating facilities were justifiable economic drivers for the UK to export RDF. However, this is not for sure the most desired or straightforward waste management solution to pursue. Strategically, in a national waste management perspective, the UK still has a significant gap to be filled potentially with WtE technologies. Scarlat et al. estimated the need of approximately 20 new plants able to treat more than 5.6 million tons per year of waste (for an average plant capacity of 225,000 t/y).

Australia

According to data processed by Blue Environment Pty Ltd for the Department of the Environment and Energy of the Australian Government, the MSW generation in the country reached 13.8 million tons in 2017.

Looking at the MSW composition that have been retrieved from literature (Blue Environment Pty Ltd), the main contribution is given by food (39%), inert waste like metals or glass (21%) and garden/green waste (19%). No data on the calorific value nor on the biogenic fraction of the waste have been found but, given the shares of the different fractions, the LHV could be between 8 and 9 MJ/kg.

Based on year 2016-2017 data from Blue Environment Pty Ltd, the material recovery share is 46%, including recycling and composting, whilst in terms of energy recovery no incineration/WtE plants are currently operating in Australia and the landfill disposal represents the most adopted option for waste management (54% overall). However, this figure includes some landfills with biogas collection and energy recovery based on internal combustion engines. Such landfills receive around 9% of the overall waste generation.
There are several WtE plants in Australia under development/planning in the near future, for an overall treatment capacity of approx. 2 million tons per year.

As the energy recovery is only guaranteed by the waste disposed to landfills equipped with biogas recovery systems, which in any case represents an absolutely minority share of the total waste landfilled, there is considerable interest within government and industry in expanding energy recovery from waste. All the possible alternatives have been taken into account and analyzed (traditional mass-burn incineration, gasification and pyrolysis, anaerobic digestion, mechanical-biological treatment).
Therefore, several proposals for large-scale Waste-to-Energy facilities treating MSW are at various stages of development, mainly in the States of West Australia, Queensland and Victoria, while the State of New South Wales recently declined another large-scale proposal.
Based on typical household waste composition in Australia, about half energy recovered would be biogenic and half fossil: combustion of this type of waste would result in greenhouse gas emissions at about half rate of bituminous coal per unit of power generated (estimated by Blue Environment Pty Ltd, 2018).

2.2 Trends and tools to reduce CO_2 emissions in WtE plants

WtE plants can play a significant role in both the energy and the CO_2 markets. By recovering the energy content of waste, they can contribute in fulfilling the energy needs of society, mainly with the production of electricity and/or heat, and in replacing fossil fuels use (with associated CO_2 emissions) for the same duty. Moreover, a significant share of the energy content of Municipal Solid Waste (MSW) is biogenic and, therefore, carbon neutral.

The reduction of GHG emissions in the atmosphere can be therefore an important driver to maximize the energy production efficiency of a WtE facility.

2.2.1 *Identification of the tools*

The tools that could be used to increase the energy efficiency of a Waste-to-Energy, contributing to reduce CO_2 emissions as well, have been identified and analysed in the following. They are:

- Reduction of the combustion air excess;
- Use of the flue gas recirculation;
- increase of the steam cycle parameters (e.g. temperature and pressure);
- increase of the biogenic fraction of municipal waste.

There is a trade-off in setting the combustion air excess: on one hand a minimum air excess is necessary to ensure complete combustion with minimization of unburnt fuel in flue gas, with consequent CO emissions increase, on the other hand the plant efficiency is favoured by low air excess to minimize the thermal loss at the stack and reduce the parasitic load of the plant associated with air and flue gas blowers.
Combustion air excess also strongly influences the generation of thermal NOx in the combustion. Lower oxygen level has both benefits and drawbacks on the NOx formation in a Waste-to-energy process. In fact, the benefits of lower oxygen levels are related to the potential for reducing thermal NOx formation, which, at the same combustion temperature, is promoted by the amount of fresh nitrogen supplied to the combustion with the combustion air. However, it has to be remarked that the reduction of air excess itself would also lead to higher combustion temperature, which would be in favor of thermal NOx generation. Hence, the reduction of the combustion air excess could be effective only when it is combined to other techniques helping in controlling the combustion temperature, namely the Flue Gas Recirculation (FGR) described later.

The Flue Gas Recirculation (FGR), used to control the combustion temperature to reduce thermal NOx generation, reduces the thermal losses by sensible heat at the boiler exit because the recycled Flue Gas partially substitute the secondary air injection necessary to improve the mixing and the homogeneity of flue gas [1]. The possible reduction in the amount of secondary air is in the range of 10-15% [2].

Figure 5 is a general process diagram of an incinerator with flue gas recirculation.

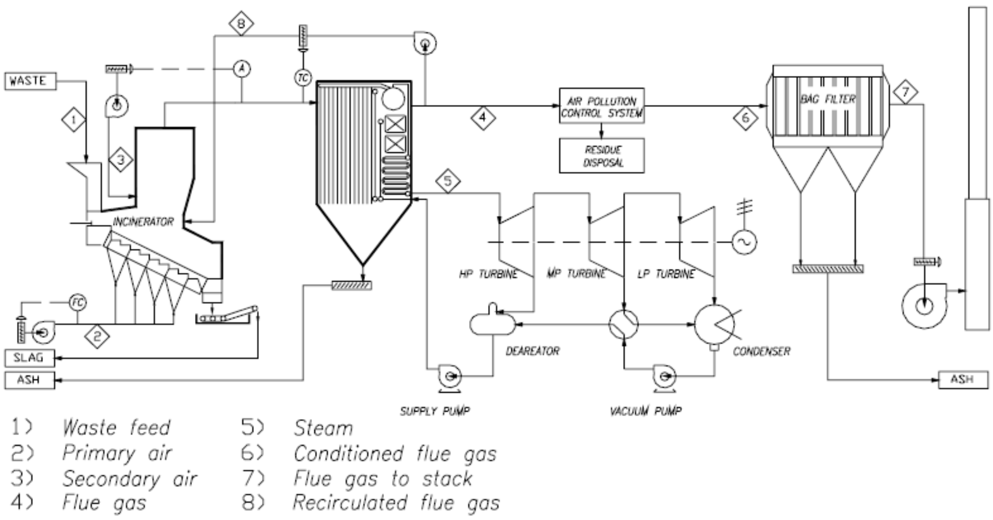

Figure 5 - Incineration plant with flue gas recirculation **[2]**

In general, the FGR extraction point can be downstream the Flue Gas Treatment to limit the corrosion in the duct but causing some thermal losses. Otherwise, the flue gas is recirculated upstream the treatment train and the corrosion risk can be overcome by the elimination of joints and avoiding the condensation of flue gas by temperature control [2].

Regarding the steam cycle parameters, the heat surfaces of a boiler in a Waste-to-Energy facility are exposed to temperature higher than 850°C. At this condition, the walls are subjected to a strong corrosion caused by meta chlorides in the ashes and the HCl present in the flue gas [3]. The steam cycle conditions at 40 bar and 400°C are typically an economic compromise between power generation and corrosion rate [4] [5] [1] with the flue gas temperature at boiler outlet of about 190°C [6]. As shown in Figure 6, the Waste-to-Energy plants in Europe have average steam cycle operating conditions in accordance with those above mentioned.

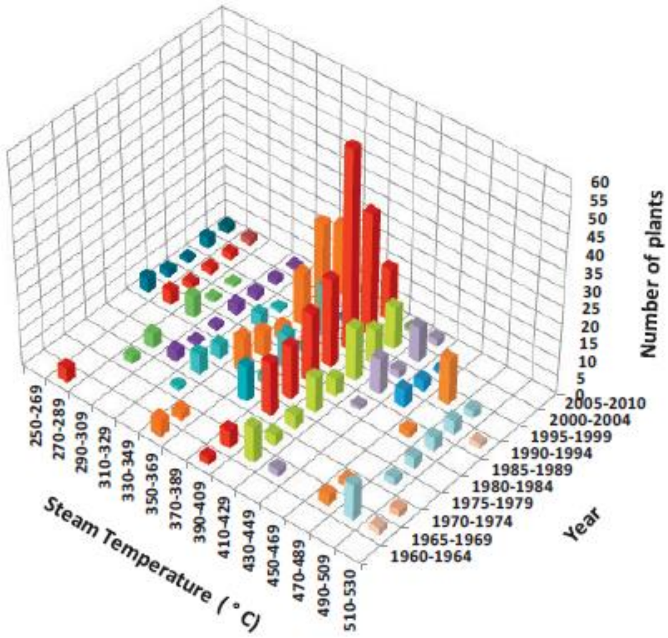

Figure 6- Steam cycle parameters in WtE plants in Europe in the last 50 years **[5]**

In the last ten years, the number of plants with higher steam temperature and pressure have increased to improve the energy recovery. One of the most effective method to allow efficiency improvement and sustain increased corrosion rates is to protect the coils in the boiler from corrosion by using Inconel® 625 as cladding, while the boiler walls are protected with SiC plates.

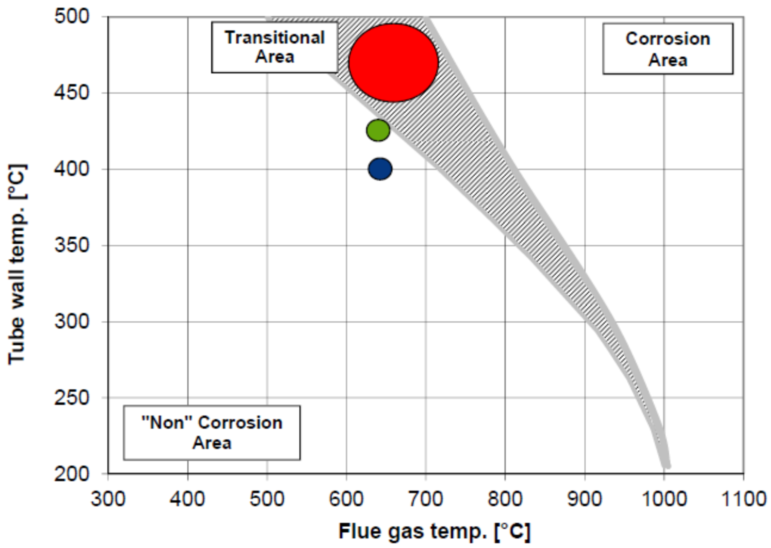

Figure 7- Corrosion diagram for a conventional boiler in an incinerator **[7]**. Blue circle: steam T= 400°C and P=40 bar; green circle steam T= 430°C and 70bar; red circle steam T and P much higher.

Figure 7 defines the range of operative conditions in which the heaters tube walls are or not in corrosion area for different flue gas temperatures.

Considering that the tube walls are exposed to an average flue gas temperature of 650-800 °C, three points are indicated. The blue point refers to steam generated at 400°C and 40 bar as a conventional benchmark boiler, the green point is steam at 430°C and 70 bar. The red zone covers the plants where both the steam pressure and temperature are much higher than conventional conditions.

Another possibility to effectively enhance steam temperature and pressure considering corrosion risk constrains is related to the use of CFB boilers instead of grate boilers. In fact, some CFB technologies (e.g. Sumitomo-Foster Wheeler, as adopted in Lomellina plant in Italy) has a final superheater in the fluidized bed itself, which is subject to erosion but at lower corrosion rates than those associated to the heat recovery at the same temperature and from the flue gas. In practical terms, a +20°C superheating temperature increase is achievable with no incremental corrosion risk as the temperature profile of the heat recovery from the flue gas in unchanged.

Pressure and temperature around 500°C and 90 bars can also be reached by placing a final superheating stage in the boiler [6]. The superheaters meet the flue gas in the boiler zone at temperature above 800°C. For a longer lifetime, the final superheaters are protected with SiC monolithic concrete, because the Inconel® 625 cladding requires a greater effort in maintenance. There are several WtE examples in Europe that have applied this method and they have demonstrated that the SiC protection have guaranteed 10 years of lifetime [6].

A different method is to adopt an intermediate reheating of the steam coming out of the high-pressure turbine. Its main advantage is the high electric power produced. An operating WtE plant with the steam reheater is the AEB facility in Amsterdam. The steam released from the drum has a pressure of 130 bar and reheats the steam from the HP stage of the turbine until 440°C. The furnace walls are protected with Inconel cladding.

Another method is to achieve higher steam temperatures through external superheating of steam, from 400°C to 520°C, firing oil or gas. This variant is implemented in the Heringen WtE plant in Germany. The external superheaters consist in bottom fired natural gas with natural draft. The external superheater has the same corrosion risk of the boiler in the standard case (excess air of 60%, steam produced at 40bar and 400°C), because the superheater is not exposed to the flue gas from waste combustion. It improves the power production, but it is not the best action to take for the improvement of the WtE efficiency when this is aimed at reducing the carbon footprint. In fact, the increase of efficiency is achieved with fossil fuels combustion, and additional GHG emissions are produced [6].

2.2.2 Description of the impacts and examples

The different measures previously described are compared in terms of boiler efficiency and gross electrical efficiency. According to literature assumptions, it was considered an average Low Heat Value (LHV) for the waste of 10.4 MJ/Kg and an average biogenic fraction of 40% [4] [1], where the biogenic fraction is the percentage of waste of biological origin.

The comparison between the different methods is shown in Table 2 in terms of theoretically achievable final electrical efficiency and boiler efficiency compared with a defined benchmark by changing the air excess and the steam parameters. In the last column, it is reported the effect of each tool on CO_2 emissions, expressed as delta tons of CO_2 per kWh produced. The ratio is estimated by calculating the increment of kWh/tons of waste burned produced in WtE by applying the discussed tools and considering that, for 1 ton of MSW burned, 0.7 ton of CO_2 are produced [1]. The quantity $\Delta tCO_2/kWh$ is calculated for each case compared with the benchmark.

Table 2- Comparison between tools to improve the Waste-to-Energy plant **[6]**

	Primary Air/fuel ratio (kg/kg)	Steam T, °C	Steam P, bar	Boiler Efficiency	Gross Electrical Efficiency	ΔkWh/t waste	$\Delta tCO_2/kWh$
Benchmark	1.9	400	40	86.5	26.4	/	/
Reduced Air Excess	1.39	400	40	87.7	26.6	5.55	0.126

	Primary Air/fuel ratio (kg/kg)	Steam T, °C	Steam P, bar	Boiler Efficiency	Gross Electrical Efficiency	ΔkWh/t waste	$\Delta tCO_2/kWh$
External Superheating	1.9	520	90	87	29.7	91.6	0.007
High Steam Parameters	1.9	500	90	86.5	30.2	105.5	0.006
Steam Reheating	1.9	420	90	86.5	29.9	97.2	0.007

The largest gross electrical efficiency improvement is given by acting on steam cycle conditions, which results on an increase of gross electrical efficiency of 3.8% compared with the benchmark case [6] [1] . The recently-built WtE facilities, in fact, operate with higher temperature whose benefits are combined with lower air excess, achievable thanks to flue gas recirculation.

Table 3 lists the examples of Waste-to-Energy plants worldwide in which the improvements described above were implemented taken from public information available in the literature. The reported results underline the effects of those tools on CO_2 emissions. The emission offset was calculated considering that the emission factor of a Combined Cycle Gas Turbine (CCGT) is 0.38 tCO_2/MWh, as average of the values given in the literature [8] [9] [10] [11] [12]

Table 3- Waste-to-Energy plants with integration of improvement tools *Data are referred to a single treatment line (data from **[8] [9] [10] [12] [13]**)

	Brescia (IT)	AEB (NL)	Mainz (GE)	RIVERSIKE (UK)	RENO-NORD (DK)	OSLO (NW)
Type of furnace	grate	grate	grate	grate	grate	grate
Waste treated, t/h	100	100	33*	32*	20*	20
LHV, MJ/kg	6.3-13.8	10	9.8	7-13	12	12
Primary air to fuel ratio, kg/kg	-	1.4	-	-	1.5	-

	Brescia (IT)	AEB (NL)	Mainz (GE)	RIVERSIKE (UK)	RENO-NORD (DK)	OSLO (NW)
Steam produced, t/h	-	44	100	54	81	77.2
Steam cycle, bar/°C	60/450	130/440	42/550	72/427	50/425	41.5/402
Steam Re-heating	No	Yes	No	No	No	No
Biogenic Waste, %	27	53	-	54	-	50-60
CO_2 avoided for electricity, tCO_2/MJ	0.02	0.33	-	0.54	0.23	0.08
CO_2 avoided for heating, tCO_2/MJ	0.30	0.03	0.12		0.59	0.71
Electricity produced, GWh	60	888	-	462	18 (MW)	53
Heat produced, GWh	796	70	48 (MW)	-	47 (MW)	449
Electric Efficiency, %	27	30	25.8	27	27	-

The avoided CO_2 emissions is evaluated with respect to the base case, where the energy (electricity and heat) is produced by natural gas fired plants.

2.3 Analysis of lifecycle CO_2 savings associated with WtE

2.3.1 Methodology

As stated by the European Waste Framework Directive (WFD, Dir. 98/2008/EC), the evaluation of the environmental sustainability of waste management in general, and of various treatment options, must be based on its Life Cycle Assessment (LCA). This technique, which is defined by the international set of norms ISO 14040, quantifies the environmental impacts associated with the production/treatment of a reference unit of product/material/etc. by considering not only the direct emissions associated with such an activity, but also the indirect emissions, as well as the emissions avoided/substituted.

In the case of WtE, a simple representation of this approach is depicted in Figure 8.

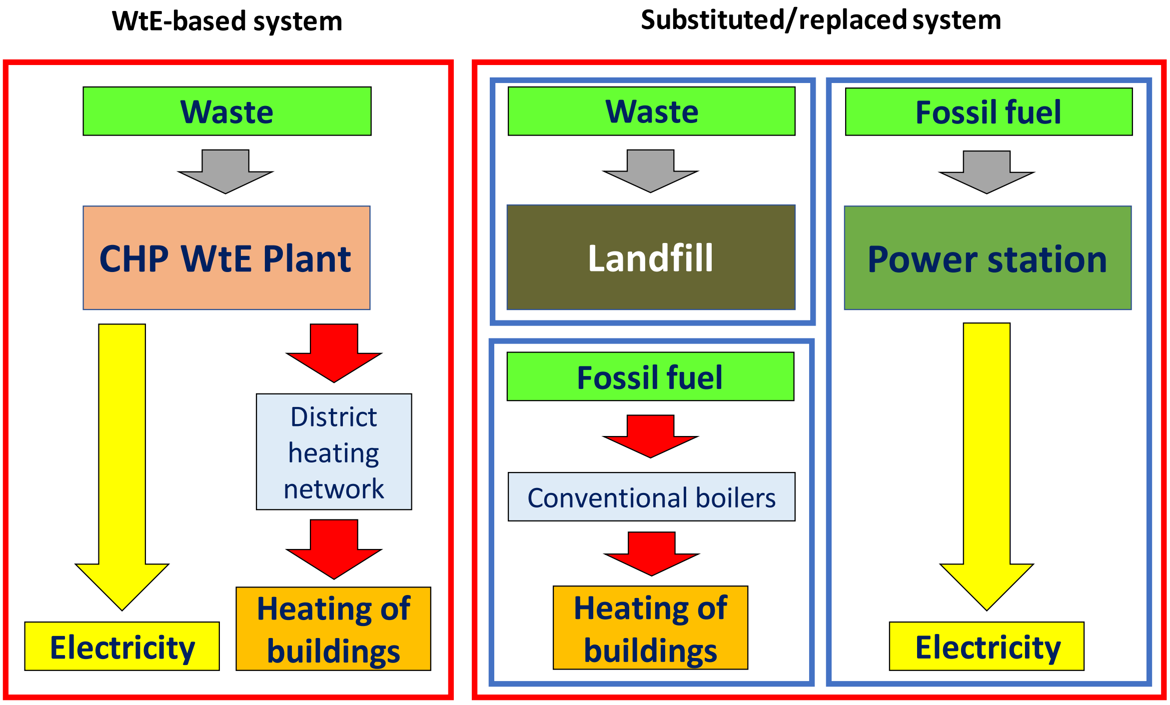

Figure 8: Simple representation of the systems to be considered when applying LCA to a CHP WtE plant.

WtE plants emit directly into the atmosphere mainly the CO_2 contained in the flue gas. Part of it is fossil and, hence, must be considered as a greenhouse gas emission, and part is biogenic, i.e. carbon neutral. Other emissions (indirect) are those associated with the handling / treatment / possible recovery or disposal of solid residues, as well as those associated with the construction materials used to build the plant, those associated with the energy consumed to build the plants and imported by the plant from the grid, those associated with the production of reactants for flue gas cleaning, etc.

However, WtE plants produce useful forms of energy, typically electricity and/or heat that would be produced in alternative ways. These replaced/substituted productions are associated to CO_2 emissions that are avoided thanks to the WtE plant.

Similarly, the management/treatment of the waste would be carried out in an alternative way without the WtE plant. In the example depicted in Figure 8, WtE replaces landfilling and avoids the associated emissions.

The net CO_2 emission of a WtE plant is the algebraic sum of all the direct/indirect and avoided contributions. The direct (fossil) emissions increase the overall emission figure, whereas avoided emissions reduce such value. When the result is positive, the WtE plant emits more fossil CO_2 than the alternative systems. When, instead, the result is negative, the WtE plant is less CO_2-intensive than the alternative systems.

The LCA is an evaluation approach that requires significant amount of detailed data. However, for WtE plants the result is typically determined by the main following contributions:

- Direct emissions associated with the discharge of flue gas into the atmosphere, mainly related to the oxidation of the carbon content of the incinerated waste; in addition, some CO_2 emissions are due to the combustion of fossil fuels in auxiliary burners (typically, during startup and shut-down phases, as well as seldomly to contribute to combustion control). Part of the emissions from the oxidation of the carbon content of the waste are biogenic (i.e. carbon neutral) and part fossil. As a rule of thumb, MSW with LHV of 10 MJ/kg has a biogenic energy content roughly equal to 51%, whereas RDF with LHV of 13 MJ/kg features roughly 44% [14] biogenic energy content[2]. Moreover, RDF is associated to some indirect emissions due to its production from MSW through a complex Mechanical Biological Treatment (MBT), which features energy consumptions, production of residues, recovery of materials. Only fossil emissions are considered for WtE plants without CCU/CCS, since biogenic emissions are carbon neutral. However, when CCU/CCS is applied, also the biogenic CO_2 production is relevant, since it can be captured too leading to negative direct emissions (i.e. the system indirectly captures CO_2 from the environment).
- Avoided emissions associated with the production of useful effects; WtE plants use waste to produce electricity and/or heat that otherwise would be generated, from country to country, with a different energy mix. This energy mix depends on the mix of generation technologies and the amounts of fossil fuels consumed. Consequently, there are three key parameters that determine the relevance of this emission contribution (that is always negative, i.e. "avoided"):
    - the energy efficiency of WtE plants, which defines the amount of electricity/heat produced per unit of treated waste;
    - the fuel mix for electricity/heat production in the country;
    - the average efficiency for the conventional production of electricity/heat from mix in the considered country.

[2] This is due to the upstream Mechanical Biological Treatment (MBT) needed to produce RDF, where part of the biogenic material is consumed and/or removed with the aim of increasing the LHV (by reducing moisture and ash contents).

The adopted methodology uses countries data on both the production of useful effects from WtE (electricity and/or heat) and the carbon intensity of the power generation sector.

- Avoided emissions associated with the alternative management/treatment of the waste. The waste being used as feedstock by WtE plants would otherwise have been disposed to landfill. In the large volume of waste inside a landfill, anaerobic digestion processes take place over time, with the production of a biogas rich in CH_4, CO_2 and other gases. This biogas features a high greenhouse potential if released in the environment, since the GWP_{100} of biogenic CH_4 is 27 times that of fossil CO_2. The decomposition of the biogenic share of the waste and the concomitant production of biogas develop through time at a diminishing rate, taking many years to be completed. A formula to assess the methane production of a landfill site is given by the First Order Decay (FOD) method (Tier 2) [16]. Modern landfills in developed countries generally collect the produced biogas and burn it in a flare (rough CH_4 oxidation to biogenic CO_2) or, even better, in a gas engine (CH_4 converted to biogenic CO_2 with the benefit of the production of electricity with an average efficiency of 30-35%). On the other hand, the dump sites still existing in developing countries have no biogas collection so all produced CH_4 is emitted into the atmosphere with no treatment or energy recovery. Consequently, the overall fossil CO_2 equivalent emission deriving from the landfilling of waste is the sum of the following contributions:
  - direct emissions of fossil $CO_{2,eq}$ due to the methane contained in the non-collected biogas and released directly into the atmosphere as a greenhouse gas;
  - avoided fossil $CO_{2,eq}$ emissions related to the electricity produced by the biogas-powered engines, which replaces the production of the same amount of electricity by the single country generation system.
- Potential avoided emissions associated with the possible recovery of solid residues. Bottom ash typically undergoes metal separation (ferrous and non-ferrous, mainly aluminum), then the inert fraction can be used as road background (added to the mixture of sand, bitumen and water for the creation of the foundation layer), as landfill recovery (replacing gravel, sand or clay), as raw material to be used for the preparation of raw flour fed to cement kilns, as raw material in the concrete or ceramic production. The inert fraction can also be subjected to vitrification processes (high temperatures treatment up to 1,500 °C) followed by rapid phases of quenching in water, to obtain amorphous materials, with properties similar to glass. The recovery of scrap metals (typically aluminum and iron) for secondary metal production avoids the use of a significant amount of raw materials (depending on the quality loss of which they are subjected by oxidation and corrosion). In a state-of-the-art recovery system, relevant recovery efficiencies can be achieved, starting from 43% for heavy non-ferrous scraps and reaching 85% for ferrous and stainless-steel scraps [17]. Assuming a complete

substitution scenario (i.e. 1 t of secondary material replaces 1 t of primary material) the avoided $CO_{2,eq}$ emissions can range from 0.1 ton $CO_{2,eq}$ / ton of collected bottom ash for a baseline case with only ferrous scrap recovery (85%) and landfill disposal of the mineral fraction, to 0.4 ton $CO_{2,eq}$ / ton of collected bottom ash for the case of enhanced recovery of scraps and mineral fraction sent to road construction.

2.3.2 *Assessment of CO_2 emissions from WtE plants in the selected countries*

Following the methodology previously described, an assessment of the CO_2 emission factors for each of the main contributions and the calculation of the total amount of the fossil CO_2 equivalent emissions associated to WtE operations have been carried out for the countries selected for a focused analysis during the course of the study (see para. 1). Furthermore, the potential for capturing CO_2 from the flue gas of WtE plants (including both fossil and biogenic CO_2) has been reported.
For each country, some CO_2 emission factors (ton CO_2/ton waste) have been evaluated, based on the data available for all, or only part, of the WtE plants in operation. Data on waste treatment capacity or electricity/heat productions were often missing or not consistent (different sources): only the most significant plants have been considered to carry out the calculation. Once the average emission factors have been determined, they have been applied to the total amount of treated waste (most recent available datum) to estimate the total $CO_{2,eq}$ emissions at country level. All the reported results depend on the hypothesis introduced in the methodology.

In this analysis, only the direct fossil CO_2 emissions from the stack of WtE plants give a positive contribution, whereas all the other terms are negative (avoided emissions). The total result itself is negative, leading to the conclusion that WtE plants, where in operation, already play a beneficial role for CO_2 emission savings, especially in the countries where waste recovery options are minimal and the average emissions for the conventional production of electricity/heat from the fuel mix are significant.

Table 4 reports a summary of the $CO_{2,eq}$ emission factors associated to WtE in the selected countries (Australia and South Africa are not considered because no WtE plant burning MSW/RDF is currently in operation).

Table 4 - Summary of CO_2 emission factors from WtE plants (ton $CO_{2,eq}$ / ton waste) for the selected countries

Country	Current fossil $CO_{2,eq}$ emissions					Additional Contribution from Potential Capture from WtE
	WtE Stack*	Energy prod. (electricity & heat)	Landfill	Bottom Ash	TOTAL	
The Netherlands	0.521	-0.304	-0.585	-0.060	**-0.427**	**-1.018**
Norway	0.497	-0.478	-0.600	-0.060	**-0.641**	**-1.001**
Italy	0.555	-0.292	-0.565	-0.060	**-0.363**	**-1.041**
Germany	0.521	-0.299	-0.585	-0.060	**-0.424**	**-1.017**
United Kingdom	0.509	-0.125	-0.593	-0.060	**-0.268**	**-1.009**
USA	0.524	-0.340	-0.584	-0.060	**-0.460**	**-1.019**
Japan	0.497	-0.399	-0.600	-0.060	**-0.562**	**-1.001**
India	0.663	-0.252	-1.600	-0.020	**-1.209**	**-1.117**
Australia	NA	NA	NA	NA	**NA**	**NA**
South Africa	NA	NA	NA	NA	**NA**	**NA**

** includes RDF production*

The total fossil-equivalent CO_2 emission factors show that WtE is always associated to significant CO_2 emission savings in all the considered countries, even without considering CO_2 capture. This latter option (CO_2 capture) offers the potential for a significant enhancement of the CO_2 emission saving figures, entailing the possible doubling or even more increasing of the results for such a performance indicator.

2.4 Operating challenges of WtE plant

Modern WtE plants are mostly based on the same technologies of fossil fuel-fired power stations. However, since they are targeted to serve certain collection areas, their size, in terms of thermal input, is determined by the amount of treated waste and the corresponding energy content. As a matter of fact, this leads to plant capacities that are one-two orders of magnitude smaller than conventional fossil power stations. Therefore, WtE plants are too small to generate large economies of scale, the specific costs of the adopted technologies are rather high, leading to very capital-intensive facilities. To ensure their economic sustainability, WtE plants need relevant annual revenues, which come from both the fee for the treatment of waste and the sale of electrical/thermal energy. Hence, the continuity of operation and, therefore, reliability, are of crucial relevance for WtE plants. Moreover, failures imply maintenance interventions, which are typically very expensive on these facilities, due to both some peculiarities of the adopted technological options (like the refractory lining of the combustion chamber and part of the boiler) and the high costs of the spare parts (are linked to the aforementioned high costs of the technologies).

Reliability is relevant also for the possible integration of WtE plants with CCS systems. For example, unplanned stops with complete interruption (or even significant reduction) of flue gas flow can compromise the working regime of absorption columns and require repeating start-up sequences.

2.4.1 Potential failures occurring in WtE plants

Although the significantly smaller size, the complexity of a modern WtE facility is greater than that of power plants. To ensure the proper working of a WtE plant, many systems must interact: feeding system, combustion system, steam generator, steam cycle, Air Pollution Control (APC) system, solid residues handling, etc.

Reliability is a crucial aspect for all the WtE plants treating unsorted waste, since they normally receive waste from the urban collection. Prolonged full stop of the plant may require the activation of other waste treatment options, like waste export to other WtE plants, landfills, etc., which are very expensive and add to the costs of interrupting operation. To increase plant availability, a maintenance program is adopted and continuously improved throughout the whole life of the plant. During scheduled stops, both ordinary and preventive maintenance are carried out, as well as upgrading interventions can be put in place. Ordinary maintenance is devoted to the replacement of worn out parts, whereas preventive maintenance is aimed at improving the continuity of operation by reducing accidental stops through periodic inspections of the most critical components (pumps, valves, dampers, combustion grates, pressure parts, bridge cranes and buckets, transformers and electrical substations). Upgrading interventions can be carried out both to improve the performances of the plant and to comply with updates of the applicable normative.

In the following paragraphs, some sections of WtE plants are analysed and their potential failures are discussed.

Waste feeding system

The waste stored in the bunker is fed to the combustor(s) of grate-based WtE plants through loading hoppers, by means of bridge cranes. In fluidized bed-based WtE plants, the Refuse Derived Fuel (RDF), obtained from a pre-treatment of the MSW, is typically transported through conveyor belts and fed by means of screw-type plug feeders. Both bridge cranes and conveyor belts are normally redundant. Loading hoppers and plug feeders are, instead, critical components. The blocking of loading hoppers in grate-based plants occurs often, but it is an event that can be managed in a limited time, without significantly affecting the operation of the combustion line. The blocking of a plug feeder in a fluidized bed combustor can lead to the shutdown of the line. Therefore, high attention must be devoted in the preparation of RDF/SRF, to avoid the presence of large and/or heavy/hard components incompatible with the use of screw-type plug feeders.

Combustor

The combustor is the core of a WtE facility. Any significant failure of this component typically requires the shutdown of the treatment line. Sometimes, minor failures can be tolerated also for long operational periods. The potential issues relevant to the combustor typically depends on whether the combustion system is grate or fluidized bed type.

The waste entering a grate combustor must be kept moving and mixed in order to achieve the complete combustion and avoiding high level of CO in flue gas and unburned carbon in bottom ash. Modern grates feature alternate moving and fixed elements that support and transport the waste bed from the inlet section to the ash discharge section. Moving grates are affected by two critical problems: thermal stress and mechanical erosion.

The elements of the grate must be constantly protected against direct radiation by means of a layer of ash and are cooled down by the primary combustion air, which is supplied underneath the grate. Some manufacturers adopt also water-cooled grate elements.

Mechanical erosion is due to the attrition among moving and fixed grate elements, as well as with hard particles (glass, inert materials, hard metals) contained in the waste. Low-melting metals (aluminum alloys, lead, etc.) in the waste can be harmful too.

The hydraulic system used to move the moving elements of the grate is another critical part of the combustor. For water-cooled grates, the flexible pipes connecting the moving elements to the cooling circuit is another source of frequent failures. However, these two systems can often be repaired during short stop or, sometimes, even without the full stop of the line.

In fluidized bed combustors the required moving and mixing of the waste is achieved by means of the bed fluidization, which is caused by the high-velocity injection of the primary combustion air through proper-shaped nozzles. The bed is composed of mainly sand, and only in a minor extend waste.

The most critical aspect in the operation of this type of combustor is the risk of agglomeration of the bed, due to the formation of eutectic mixtures from ash material. Before reaching the full melting of the ash mixture, the appearance of a sticky behavior is typically enough to produce the sintering of some agglomerates. They compromise the fluidification of the bed, implying the forced stop of the line. The consequent required maintenance intervention is rather demanding. To limit as much as possible the occurrence of this event, the content of ash in the treated RDF must be limited, the composition and particle size distribution of the sand bed must be chosen properly and some calcium-based reactants like dolomite can be added to the bed.

Other critical elements of this technology can be the primary air nozzles. In some types of this combustor, they can be blocked typically by small metallic particles contained in the waste. To prevent this failure, a good de-metallization of the RDF is crucial.

Steam generator (i.e. boiler)

For the availability of WtE plants, the pressure parts of the steam generator(s) are the most critical elements. Failures of these parts is rather common and can lead to long unplanned stops and highly expensive maintenance interventions. Similarly, the refractory lining largely used inside waste-fired boilers is another critical element.

Conceptually, any waste-fired steam generator can be divided into two sections: radiant section and convective. In the radiant section, heat exchange surfaces are only waterwalls (i.e. steam evaporators), typically arranged to form the enclosure of the boiler. The convective section is downstream the radiant section and features a different arrangement (typically tube bundles).

In grate-based WtE plants, the volume immediately above the grate is called "combustion chamber". Similarly, in bubbling fluidized bed-based plants, the volume of the bed and the volume immediately above it (called "freeboard") are designed as combustion chamber. In circulating fluidized bed, the identification of the combustion chamber is conventional.

In modern WtE plants, the combustor chamber is integrated with the steam generator / boiler, being the initial part of the radiant section of the boiler. Therefore, the walls around the grate or that confine the fluidized bed are waterwalls, typically refractory-lined. In older plants, the combustor was adiabatic and often called "furnace" instead of "combustor". However, its adiabatic walls were also refractory-lined.

Therefore, in integrated steam generators, the combustion chamber is inside the boiler, whereas in adiabatic combustors, the radiant section of the boiler starts immediately downstream of the adiabatic section.

The volume downstream of the last injection of combustion air is named "post-combustion zone". Its aim is to ensure an adequate residence time to flue gas, above a certain temperature (e.g. in the EU, 2 s above 850 °C, in the USA, 1 s above 950 °C), according to the applicable normative. To meet this requirement, both combustion chamber and post-combustion zone are completely refractory lined even in integrated boilers, to limit heat dispersion.

The main problems experienced by the combustion chamber and post-combustion zone of the combustor/boiler are related to the refractory lining. It can be made just in concrete cast or, more often, with tiles. In both cases, very hard materials, like silicon carbide, are normally used.

The part of the lining in direct contact with a fluidized bed is subject to erosive wearing. However, a proper fluid-dynamic design can prevent the erosive wearing of all the other parts of the lining in both grate- and fluidized bed-based boilers.

Most of the refractory lining failures are due to the slagging behavior of fly ash. Melting of fly ash occurs in hot flue gas and the solidification takes place on colder walls, creating deposits. Chemical diffusion changes in time the composition of the deposits that can melt and solidify again many times, thus reacting with the refractory lining material. Heavy deposits and/or differential thermal expansions can generate significant mechanical stress, up to the breaking of the refractory material. This can potentially lead to a forced stop of the line, typically because of the disturbance induced to the combustion process. Large deposits detaching the walls and falling into a fluidized bed have the same effect of bed agglomeration, with the need of stopping the operation.

Waterwalls underneath the lining are normally made of bare steel, so that the refractory acts also as protection against the highly corrosive flue gas. Small damages of the lining are enough to cause the penetration of flue gas up to the steel surface, where the corrosion takes place with the generation of significant volumes of metal oxides and other salts. Such volumes exert pressure onto the refractory leading to the worsening of the original damage. The corrosion mechanism of all iron-containing alloys, typically named “acidic corrosion”, is based on the high temperature reaction of iron with halogens, mainly chlorine, with the synergic effects of many chemical species that are present in fly ash (e.g. K, Na). The rate of corrosion at the typical HCl concentrations found in waste-fired boilers (hundreds of ppm) is very fast and it increases exponentially with metal temperature.

The reparation of refractory lining is a manual operation, which requires many workers, long times, scaffoldings, etc.

The portion of the radiant section without refractory lining and the convective section of the boiler experience some similar problems, first of which is the acidic corrosion of the hottest parts, exposed to the direct action of acid gases (especially HCl) and fly ash deposits. To protect these parts, iron-free protective coverings are applied. The most common type of protection is the cladding with Inconel® 625 alloy. There exist other thermal spraying techniques less widespread and some ceramic protections start being proposed on the market.

The most critical components are -again- waterwalls, after the end of the refractory lining, and steam superheaters. Cladding, thermal spraying and similar techniques can usually be applied manually or semi-automatically on-site at very high costs. The main components of the boiler, like waterwall panels and superheater bundles, can be protected at the manufacturer shop with fully automated and less expensive processes. However, manual application is always needed on-site to cover welds and special components. The cost of these protections is always relevant, therefore they are economically sustainable only if they last many years. Inconel® 625 cladding on steam superheaters can warrant a reasonable life with maximum steam temperature of about 440 °C and a proper arrangement of tube bundles. Therefore, steam parameters of WtE plants can be considered “conservative” with respect to those adopted in common steam cycles. Moreover, steam reheating is almost never adopted, to avoid doubling the critical components of the boiler.

Excessive fouling is another typical failure of the convective section of the boiler, that is normally designed to manage very different fouling conditions, from clean to very fouled conditions going from the beginning to the end of the operational campaign (which, depending on the design of the boiler, can last six months, one or two years). When fouling is too high, a number of situations can happen: too high pressure drops through the boiler; too high flue gas temperature at boiler exit; too unbalanced flow of flue gas in certain boiler sections. To control fouling, different cleaning system can be used. Convective sections are usually equipped with hammers and/or soot blowers. Radiant sections can use also water cannons. If these systems are not effective enough, controlled micro-explosions can also be used.

Air Pollution Control (APC) system

The Air Pollution Control (APC) system, often called also “flue gas treatment” or “flue gas cleaning system”, is a complex sequence of devices: filters, chemical reactors, dry / semi-dry / wet scrubbers, etc. Each device or group of devices is typically targeted to the abatement of a specific pollutant or family of pollutants. APC is needed to warrant the environmental compatibility of plant operation.

When failures jeopardize the effectiveness of the APC system, the plant manager is commonly obliged, by the permit to operate the plant, to stop the feeding of waste and, if the failure cannot be recovered quickly, going to the full stop of the treatment line.

Many devices of APC are redundant, to warrant continuity of operation and, sometimes, also regeneration of the device effectiveness. This is the case of bag filters, which normally feature multiple parallel cells that can be cleaned separately.

In the presence of an SCR system, a very critical failure is the reversible / irreversible poisoning of the catalyst, which can be caused by failure of other devices, error in the management of the system, or burning of unexpected materials. Reversible poisoning can be recovered by means of thermal regeneration, but only few plants can carry out that operation “online”. Most plants require the temporary replacement of the catalyst and the regeneration carried out at the shop of the catalyst manufacturer. Irreversible poisoning implies the definitive replacement of the catalyst material, associated to very high costs.

Steam turbine, electric generator, fans, pumps

Steam turbine, electric generator, fans, pumps, etc., are all pieces of equipment that are found in all thermoelectric power plants. In the case of WtE plants, more redundancy is adopted, because of both the great continuity of operation required by this type of plants and the safety of operation. Concerning the latter point, special consideration must be applied to grate-based plants. In this type of combustor, a significant amount of waste is present in the combustion chamber so that, in the case of unexpected stop, the process must be managed properly to avoid undesired emissions and the risk of explosion.

A very critical components of WtE plants is the ID fan. Only a few plants have redundancy of such a component. Failures of the ID fan cause at least a temporary stop of the line and can create the aforementioned risky situation.

Control and monitoring systems

Every modern WtE plant adopts a DCS (Distributed Control System), that allows the operators having full control of each part of the plant and, often, includes algorithms for the automated optimal management of the plant.

The effectiveness of the control system is undermined by:

- non-stationary combustion caused by the variability of the chemical properties of the waste and the intermittence with which the feeding system introduces the fuel in the combustion chamber.
- the delay with which the control system and the operators can counteract changes in process conditions (the progress of the production of steam is followed by a much slower dynamics of the combustion process, due to the thermal inertia of the combustor/boiler system).

Typically, DCS is redundant and normal operation and emergency operation are managed by separate systems. So, unplanned maintenance stops due to DCS failures are very rare. Synergic to DCS is the CEMS (Continuous Emissions Monitoring System), which collects and elaborates all the emission data from the plant stack. Like the DCS, it is also redundant, since most legislations on WtE operation set the requirement of stopping the plant in the case emissions are above the limits or cannot be measured.

2.4.2 Results survey on availability in WtE plants

In order to enhance the quality of the review over the challenges of WtE plants operation, specific feedbacks given by plant owners and managers have been elaborated, based on a survey presented by the PREWIN Network[3] in July 2019 [18]. Collected data regard only European plants. However, they cover both the most widespread WtE technologies: grate-based and fluidized bed-based plants. Therefore, most of them can be considered representative of the WtE technologies in general.

[3] *PREWIN (Performance, Reliability and Emissions Reduction in Waste Incinerators) is a European Network with the mission of supporting progress towards improved performance and reliability of European Waste-to-Energy plants (incineration and co-incineration) while maintaining low or reduced emissions to the environment. LEAP has been part of the network since 2016 as R&D unit, participating to the general meetings held twice a year on specific topics.*

A specific questionnaire was prepared with 16 questions including general data about the plant, type of waste input and its main characteristics, availability (hours of unplanned outage and planned outage), time between 2 planned stops (months) and Length of planned stops (days).

In this section the major results conducted by PREWIN survey are reported. The survey has been conducted in 2019, collecting data from 257 lines of the most relevant European WtE plants (242 WtE plants equipped with grate furnace systems and 15 fluidized bed lines burning RDF), obtaining a comprehensive and representative picture of the current European WtE scenario.

Plant Availability is defined as:

$$Availability\ (\%) = \frac{8760 - UO - PO}{8760}$$

where UO = Unplanned outage (hours/year) and PO= Planned outage (hours/year)

All the figures reported in the following charts are accompanied by 3 key values on top of each graph:

1. N = number of datapoints examined;
2. AV = Average value of the analysed variable/properties;
3. MD =Median value of the analysed variable/properties.

Within the 237 WtE line data examined, the average availability registered through the questionnaire has been 90%. Some plants have been able to reach optimal performances, reaching availability values over 95%. 6 availability values have been registered below 70% and these have not been used in analysis, as possible outliers. These results have shown sensible improvements (by some percentage points) with respect to a similar survey carried out in 2016.

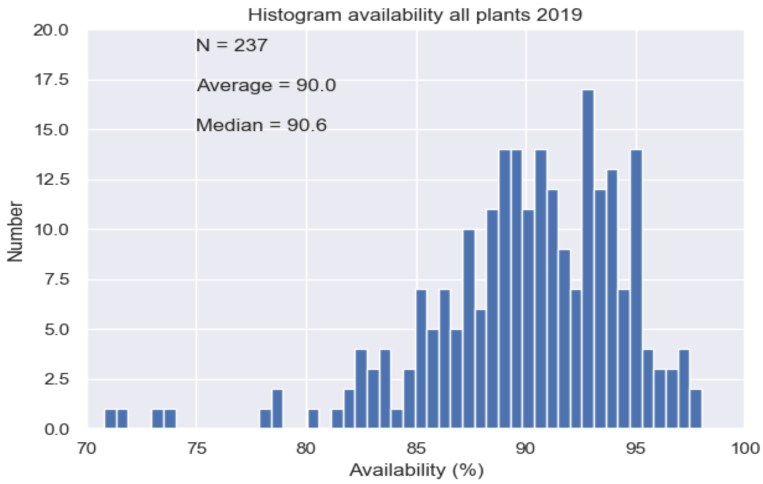

Figure 9: Overall European WtE plants Availability in 2019

Within 112 WtE lines data examined in 2019, the average number of unplanned outages has been **276.5 hours**, i.e. approximately **11.5 days** per year (5 data points of unplanned outage over 1500 hours/year have not been considered in the analysis, as possible outliers).

The average stops for programmed maintenance last **23.8 days**, so roughly 3 weeks and a half overall for a European WtE treatment line.

Asking the operators if they were using any type of protection in the first pass of the boiler, over 120 WtE lines covered by the survey, the answers distribution has been:

- Yes: N=107 → correspondent average availability = 90,8%
- No: N=13 → correspondent average availability = 85,3%

A 5% difference could identify that the adoption of a protection system in the first pass of the boiler can definitely have beneficial results in the availability of the WtE line.

From the data collected in the survey, it doesn't seem that a clear correlation exists between the availability of the plant and the following parameters:

- thermal load, representative of the exploitation of the line capacity.
- age of the plant: younger plants could be more reliable on new components but could have less experience in the ordinary operation, i.e. older plants can have more critical issues due to the effects of aging on various parts, but they can have a better control in the operation overall thank to a stronger experience developed through the years.

3. Overview of regulations relevant to WtE and CCS in the selected countries

The potential for integrating WtE systems with Carbon Capture is also related to the regulatory frameworks in place. For this reason, Wood has carried out a research to make an overview of the regulations relevant to WtE and CCS in the ten countries selected for a more detailed focus throughout the course of the study. The main topics of the research have been the following:

- Air emission threshold limits at chimney stack
- Waste water discharge threshold limits
- Potential feedstock constraints
- Potential opportunities/constraints related to the energy (electrical/thermal)
- Prescriptions for the management of the waste produced
- Relevant laws
- Potential/expected evolution of relevant laws

The following main considerations can be drawn from the review.

European Emission Level Values (ELVs) at the WtE stack are generally more stringent compared to the USA (California) and Japan. Western Australia (Australia) and South Africa demonstrated similar ELVs to the EU countries in terms of ELVs thresholds, whereas India ELVs are slightly higher compared with EU countries

Regarding waste water discharge, only selected European countries (Italy, Germany, The Netherlands, Norway and the UK) have specific ELVs dedicated to waste water discharge from incinerators (requirements applied to waste water from the cleaning of flue gas) while other countries follow their respective general waste water standards for industrial plants.

Selected European countries have developed their respective country regulation for the WtE feedstock control according to the EU Directives on waste and executed through the national laws. USA (California) adopt a BAT approach implementing the MACT criteria for managing wastes fed to the incineration plant. Decentralization in Japan has given more power to municipalities to manage their feedstocks accordingly. In India, the Solid Waste Management policy required that wet and dry wastes should not be mixed. In South Africa, however, specific requirements include having sound design and operating procedure to minimize the release of polluting substances into the environment.

There are many different incentives and CO_2 reduction schemes identified for WtE/CCS units. In Europe, the incentives can be mainly associated with the existing EU ETS. but waste incineration plants processing MSW are excluded[4] from such scheme. However, there are national incentives for CCS application in WtE incinerators, like in Germany, the Netherlands and Norway. The UK are drumming up various different green funding through schemes such as the 2017 Clean Growth Strategy incentives/funding supported by the Government. Australia are working to adopt a new ETS that would replace the current funding system. South Africa are anticipating various different tax-free allowances and public sector funding solutions for WtE. The California cap and trade rules have already involved more than 400 businesses responsible for 85% of California's total GHG emissions. The Japanese JVETS has focused on establishing the J-Credit Scheme and the JCM that aimed to develop and export low carbon technology, products and services outside of Japan. In the meantime, India's Ministry of New and Renewable Energy (MNRE) is working to offer financial incentives applicable to WtE technology.

Barriers to WtE plant construction and operation can be associated with their environmental control (Mainly in Europe, but also in California and Western Australian), the waste management policy (e.g in Western Australia there is no levy on waste disposed to landfill) and/or, the lack of waste supply that can occur in the following scenarios:

- Limited availability and accuracy of waste generation data and waste compositions (South Africa and India);
- Decrease in the volumes of residual waste due to the substantial increase in recycling levels (EU countries and Japan)

As far as more relevant to solid residues acceptance from WtE operation it is worthwhile to highlight that each selected country has defined standards requirement to ensure the appropriate combustion of the treated wastes and to avoid the production of not desired ashes.

Based on the research, all country regulations in the selected countries include provisions related to WtE. However, only European countries have specific provisions on CCS regulations.

To round up going forward, the revised version of the WID calls for more stringent measures on reuse and recycling of materials involving a possible decrease of the residual waste to be incinerated. However, a stricter regulation on landfilling could counterbalance the amount of MSW recovered and not convertible to energy through incineration.It is likely that other countries outside the EU will continue to align their ELVs and regulatory frameworks with the standards set by the European Community though starting at different stage of progression.

[4] Annex 1 of the EU ETS Directive states: "*Combustion of fuels in installations with a total rated thermal input exceeding 20 MW (except in installations for the incineration of hazardous or municipal waste)*"

4. Potential integration of CCU/CCS with WtE facilities

4.1 Ongoing WtE-CCU/CCS initiatives and projects

This section aims at providing a description of the current status (i.e. based on the information available by September 2019) of projects involving the integration of WtE plants with CO_2 Capture and Utilisation/Storage (CCU/CCS) facilities.
The review has followed two steps: first a literature research (based on the screening of scientific articles, technical reports, pdf presentations and websites) has been conducted, in order to retrieve the publicly available information reported by plant owners, technology providers or other authoritative sources on the existing or planned WtE + CCU/CCS plants; afterwards, customized inquiries have been sent (via private e-mails) to relevant plant operators both to acquire additional data (classified as non-confidential) and to check and validate the main technical information retrieved from the literature.

The overview has been focused on the following information (where available):

- List and classification of ongoing CCS/CCU projects integrated with WtE facilities
- Key technical figures on current WtE plants
- Major technical challenges reported by the company managing the WtE
- CCS/CCU Project status (pre-feasibility, feasibility, engineering, under construction, operating, on-hold, stopped, etc.) and projection
- Description of CO_2 Capture technology proposed/under evaluation
- Amount of CO_2 to be captured yearly [t/y], CO_2 removal target (defined as the ratio between the amount of CO_2 removed from flue gases by the capture plant and the amount of CO_2 contained in the flue gases stream entering the CO_2 capture system) and CO_2 capture plant size (defined as the fraction of the total WtE flue gases flow rate sent to capture)
- Captured CO_2 planned destination (storage, EOR or utilisation) and logistics
- Economics and financial information (in case data are publicly available)
- List of major challenges for CCS/CCU implementation

The following seven ongoing WtE projects integrated with CCS/CCU projects from three nations (The Netherlands, Norway and Japan) have been identified and reviewed:

- **The Netherlands**
    - AVR Duiven
    - HVC Alkmaar
    - AEB Amsterdam
    - AVR Rozenburg
    - Twence Hengelo

- **Norway**
    - Fortum Oslo (Klemetsrud)
- **Japan**
    - Saga Municipality Saga City

A summary of their key technical data is reported in Table 5, while Figure 10 depicts a general scheme based on post-combustion CO_2 capture with amine solvent which is the capture technology followed by all of the reviewed WtE+CCU/CCS (with differences on the specific plant configuration, details and solvent formulation).

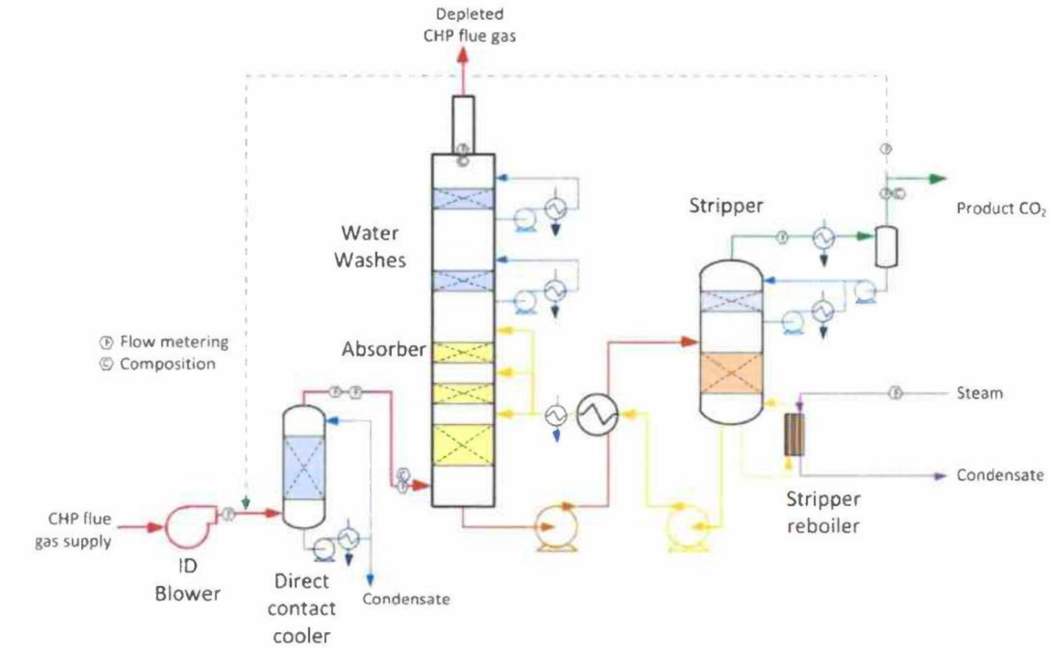

Figure 10: General scheme for amine-based post-combustion CO_2 capture process. Source: D. Thimsen et al., 2014 – Energy Procedia

The total CO_2 emissions produced by the WtE plants include both fossil and biogenic CO_2 and have been assessed as follow:

- In case they have been reported by the plant operator or by another authoritative source (e.g. ISWA report), their value has been taken directly from the source and classified as “reported” and the source has been cited.
- In case they have not been reported by any qualified source, their value has been estimated by assuming a specific CO_2 intensity factor of 0.9875 $kgCO_2$/kg waste, which is representative of the average CO_2 emissions of European WtE plants. In this case the CO_2 emissions are classified as “estimated”.

Country	Plant	Total Waste Processed [t/y]	Total CO_2 Produced [t/y]	CO_2 capture plant type	CO_2 capture plant status	Total CO_2 Captured [kt/y]	CO_2 %mol conc. in flue gases	Removal Target	CCU/CCS Technology
Netherlands	HVC-Alkmaar Project 1	682,412	673,882	Amine technology	Ongoing	4	N.A.	N.A.	Liquefied CO_2 for greenhouse horticulture
	HVC-Alkmaar Project 2	"	"	Amine technology	Feasibility study	75	N.A.	60%	Liquefied CO_2 for greenhouse horticulture
Netherlands	AEB Amsterdam	1,284,164	1,268,112	Amine technology (MEA based)	Feasibility study	450	N.A.	90%	Feasibility study
Netherlands	AVR-Duiven	360,635	400,000 (reported)	Amine technology (MEA based)	Plant Start-up	50-60	10%	90%	Liquefied CO_2 for greenhouse horticulture
Netherlands	AVR Rozenburg	N.A.	1,153,319	N.A.	N.A.	800	N.A.	N.A.	FEED Study ongoing based on the operator's experience in Duiven
Netherlands	Twence-Hengelo	608,000	600,000 (estimated)	Amine Absorption by Aker solutions	Full-scale project under engineering study	100	10-11%	N.A.	Liquefied CO_2 for greenhouse OR for the production of formic acid OR to be mineralized into construction materials
Norway	Fortum-Klemetsrud	375,000-400,000 (reported)	430,000-460,000 (reported)	Shell Cansolv engineered and built by Technip (reported)	Concept study completed. Pilot tests ongoing since Feb 2019. FEED ongoing	414	10-12%	90%	CO_2 to be delivered by truck to the Oslo harbor where it is liquefied and sent by ship to long term storage in the North Sea (logistics under study)
Japan	Saga City-Japan	74,010	54,000 (220 t/day reported)	Chemical absorption based on specific amine solvent	Full-scale plant in operation since 2016	2.5 (10 t/day reported)	8-18%	80-90%	Gaseous CO_2 stored in a 100 m3 buffer and delivered via pipeline to nearby algae cultivation

Table 5 - Summary of WtE + CCU/CCS projects

4.2 Overview of applicable carbon capture technologies and possible destinations of the captured CO_2

In view of a possible integration of CCSU with a WtE facility, the state of art of the CO_2 applicable capture processes and the storage and utilization options are analysed.

4.2.1 Overview of applicable capture technologies

As shown in Figure 11, the technologies for CO_2 removal can be classified according to combustion process in post-combustion, pre-combustion and oxy-combustion. Considering that the aim of this study is to integrate the CO_2 capture with a WtE plant, focusing on a retrofit approach, only the Post-Combustion Capture (PCC) technological methods will be analysed.

The choice of which capture technology use differs across industries, depends on the source of CO_2, the amount and concentration of CO_2, the industrial scaling-up and the technological readiness level, the ease of retrofit to existing industrial plants, the experience in industries other than CCS.

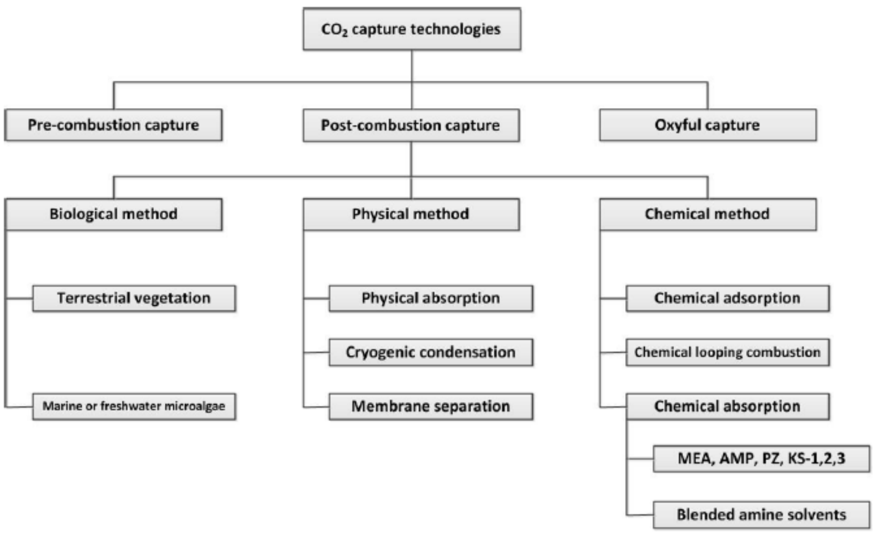

Figure 11- CO_2 capture from post-combustion application **[19]**

The key parameters for membrane separation are the material, shape and geometry of the membrane module, the configuration of the membrane stages (i.e. modules placed in parallel, series, with recycle, etc.), the operating conditions (i.e. volumetric flow rate, temperature, pressure, etc.). This process does not require a separation agent and the gas separation is achieved by applying a pressure difference across the membrane that drives the permeation of the gas. Generally, the membrane materials are inert to O_2 content and has a high tolerance to acid gases. Previous studies (Merkel et al., 2010), conducted on coal-fired power plants, reported CO_2 removal efficiencies with membrane separation up to 90%. The application of membrane technology is very challenging for a post combustion CO_2 capture because of very low pressure of flue gas stream, the high selectivity required and the large membrane surface due to the low pressure, the particulate matter that needs to be removed before membrane purification.

The cryogenic process uses different points of condensation or solidification to separate the CO_2 from gas stream. It consists in either a flash (single or multiple stages) or a distillation column (or a combination of both) at very low temperature and relatively high pressure. The application limit of this method for a post combustion purification is related to the high energy required [20]. The energy expense is limited to reasonable and acceptable levels only if the concentration of CO_2 were very high, much higher than a post-combustion application to air blown boilers for which this capture technology is not convenient.

The adsorption process uses solid sorbent beds with physical and chemical affinity with the CO_2. It is a cyclical process of CO_2 removal and release with the regeneration of the adsorbent bed. The sorbent materials should have a large specific area and a high regeneration ability [20]. The materials are not so expensive as membranes and have a low heat capacityin case of temperature swing adsorption, during the regeneration, the adsorbent bed does not require a large amount of heat, in comparison with the chemical absorption processes described later.. The flue gas can be purified of the CO_2 content by swinging the pressure (PSA) or the temperature (TSA) as driving force to adsorb CO_2 and then release it separately from the flue gas. The main limitation of the PSA method is that the operating pressure levels necessary to make an effective swing are really high compared to the near atmospheric flue gas conditions. On the contrary, the TSA method is applied on small-scale CO_2 capture plant and is on development for industrial applications, because the capture cost is still considered too high to be competitive [20] [21] [22] [23]. The adsorption process could be improved by modifying chemically the adsorbent bed by impregnation with amine, alkali-earth metal or lithium to improve the selectivity and consequently the capture efficiency of the CO_2, but the process is still at pilot-scale.

The most used and ready for industrial application of CO_2 capture is the chemical absorption with amine-based solutions due to the strong affinity between the amines and the Carbon dioxide [22]. The removal efficiency of CO_2 is high (>90%) and industrial large-scale plants are already on-going. Examples of projects to integrate the amine-based post combustion CO_2 capture within existing Waste to Energy are in The Netherlands, where AVR company operates the Duiven CO_2 capture plant, while it plans to build also a new PCC system in Rozenburg; another example is in Norway, where the Fortum Oslo project forecasts a WtE-PCC plant [24] [10].

The challenges of this technology are related to the contaminants in the flue gas and the high energy demand.

Concerning the flue gas composition, the amines are easily degraded in presence of oxygen, SOx and NOx (the latter can lead to nitrosamines and nitramines formation), which are harmful for human health and the environment [20] [25]. This issue can be avoided by purifying the flue gas with adequate technologies (e.g. Selective Catalytic Reduction (SCR) for NOx and scrubbing for SOx removal). In addition, for a carbon capture plant after a Waste-to-Energy, it is necessary to control the HCl content in the flue gas. In fact, the HCl reacts with the amines causing a lower carbon dioxide captured content and corrodes the stainless steel normally used as construction material. The latter problem should be avoided by using a more resistant material but increasing the overall costs. The HCl can be removed in acid gases by scrubbing the flue gas from the boiler.

The high energy demand is mainly related to the regeneration of amines and release of captured CO_2. The energy is supplied by steam sent to the reboiler of the regeneration column. As a rule of thumb, the heat required for a standard PCC (30%wt MEA) in a Natural Gas Combined Cycle application is close to 4 GJ per tonne of CO_2 [25]. The new-developed processes have optimized the reboiler heat duty as MHI and Shell licensed solvents, which have regeneration duty of 2.6 GJ/ton of CO_2 and 2.3 GJ/ton of CO_2, respectively [26] [27]

Several technologies are available from different licensors and the difference among them is mainly the capture efficiency, the type of solvent used and the plant configuration.

The amine-based solvents have a strong affinity with the carbon dioxide and currently represent the most diffused technology in post-combustion capture for both fossil fuels fired plants and WtE plants, as indicated in par. 4.1. However, there are several amine-based solvents: primary and secondary amines have a faster kinetics but a lower loading capacity (mol of amine/mol of CO_2) compared with tertiary amines but require more energy for regeneration; secondary amines have issues with harmful emissions, because they have a greater potential to form nitrosamines after being emitted [28] [29]. Piperazine needs less heat to release the CO_2.

As already mentioned, the CO_2 capture needs a not negligible amount of energy to keep high the temperature in the solvent regeneration column. The heat duty of a carbon capture plant depends on the type of solvent (primary or secondary amine, chilled ammonia or others), the flue gas concentration of CO_2, as well as on the overall process design and configuration.

In last 20 years, the heat duty required for solvent regeneration is reduced from an average of 5.5 to 2.6 GJ/t CO_2. The reduction is due to improvements in chemical structure of the solvent and in capture process configuration.

In Table 6, most recent data about the commercially available licensed amine-based solvents are shown. They are the most recent developed solvent with a heat duty for regeneration lower than MEA.

Table 6 - Comparison of different licensed solvent heat duty

Technology	Licensor	Type of amine	Heat duty, GJ/tCO2
n.a.	**Commercially available**	**MEA**	**~3**
KS-1	MHI	Sterically hindered	2.6 [27]
DC	Shell Cansolv	n.a.	2.2-2.8 [26]
Ecoamine FG	Fluor	Aqueous solution of MEA	3.2-3.6 [30]
n.a.	Aker solution	n.a.	2.8 [31]
TS-1	Toshiba	n.a.	2.6 [32]
H3	Hitachi	n.a.	2.4 [33]

Looking at the WtE facilities that have integrated / planned to integrate CCS, in Duiven (The Netherlands, where the integration of CO_2 capture and locally re-use with a WtE plant is ongoing and the amount of captured CO_2 is roughly 50 ktCO_2/y, which is around 12% of the overall CO_2 produced, including both fossil and biogenic fractions), the CO_2 will be captured by amine-based solvent (commercial MEA) supplied by SIAD group in an absorption-stripper cycle. The CO_2 will be used for horticulture with seasonal arrangement from April to September.
The solvent is regenerated by Low Pressure steam extracted from steam turbine in-plant, that is used for District Heating as well. A similar approach is followed for the FEED study in Rozenburg (NL).

The Fortum Oslo facility is a WtE plant where CO_2 capture based on Shell Cansolv technology has been tested at pilot scale and the full-scale project is at FEED stage. In the latter, the energy produced from WtE is used for district heating and to sustain the energy consumption of capture plant. The captured CO_2 is sent via pipeline first and then via shipping to a storage site in the North Sea. In June 2019, tests focused on emissions and solvent degradation were completed.

A secondary amine sterically hindered is used in PCC technology owned by Toshiba and applied in SAGA facility in Japan. The Saga project is about a WtE plant burning municipal waste. The WtE is composed by 3 parallel grate type boilers that treat on average 100 t/d for each unit. The steam produced is partially supplied to local Health Center and the remaining is used for the regeneration of solvent in PCC. The 5% of total flue gas is treated in the PCC technology to capture about 80-90% of its CO_2, which is sent to farming industry nearby. In this WtE-PCC plant, the steam is not used for district heating thanks to the local warm climate.

4.2.2 Use and destination of CO_2

The captured CO_2 has two possible routes: carbon capture storage (CCS) and carbon capture utilization (CCU). Nevertheless, the carbon capture and storage has been mainly investigated, funded and developed at industrial scale, the gaseous carbon utilization, on the other hand, has progressively earned more visibility as renewable resource, low-cost and not-toxic alternative to GHGs emissions [21].

It is remarked that the environmental benefits of CO_2 storage or utilisation could be different: in case of geological storage, if the well or site is properly selected, managed and monitored, nearly all of the CO_2 stored is likely to remain sequestered and mineralized permanently. On the other hand, in case of CO_2 utilisation, a proper (and not always easy to perform) Life Cycle Assessment should be carried out to identify the direct and indirect CO_2 emissions connected to CO_2 utilisation (for instance in case of CO_2 to fuels).

Looking at national contexts of Italy, Germany, Norway, Netherlands, USA, UK, Japan, India, Australia and South Africa, Figure 12 summarizes the uses of captured CO_2 at 2018 [34].

As it is expected, the major uses of carbon dioxide are the geological storage and the EOR, while the less industrially developed is the fuel production.

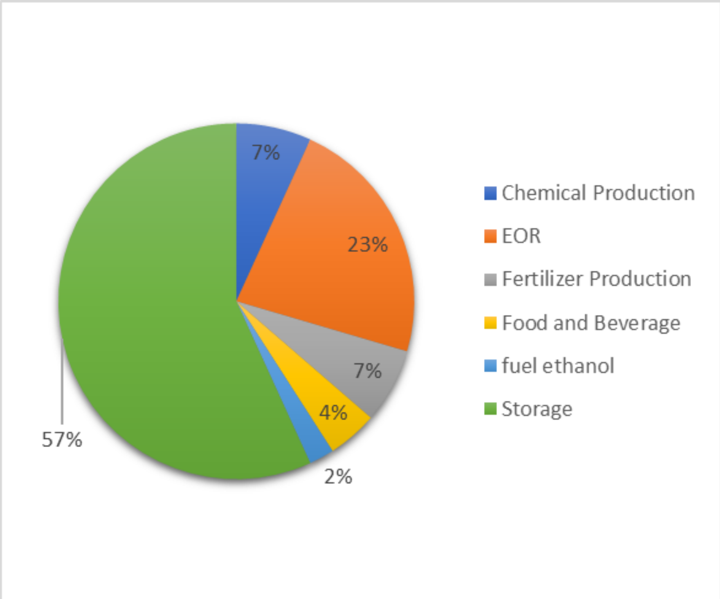

Figure 12- Overview of CO_2 destination for major world countries

The geological storage of the capture CO_2 is the injection of the supercritical CO_2 into depths of 800 and 1000 m under the ground as in deep saline aquifers that have a storage capacity estimated of about 800 Gt of CO_2 or in depleted hydrocarbon fuels. Moreover, the CO_2 could react with the minerals present underground and act as a natural mineral sequestration. The main troubleshooting of geological sites is the leakage of the CO_2 in the environment, and the operating and energy costs of compression and transportation that can be done via pipelines, trucks or ships.

The Global CCS Institute [34] has estimated the potential CO_2 storage capacity for the 80% of world countries. Figure 13 shows the Gtons of CO_2 that could be stored in geological sites for the states chosen as examples in this study.

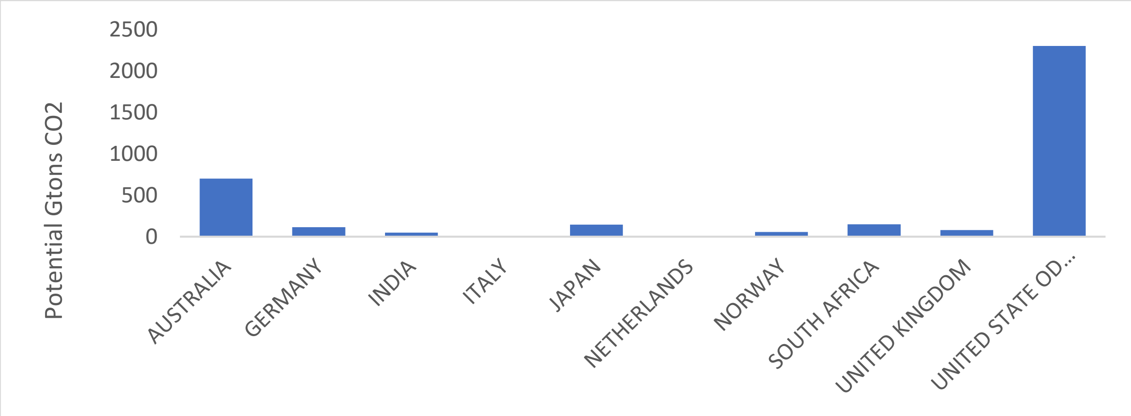

Figure 13- Estimated CO2 storage for the selected countries **[34]**

The USA has the major storage capacity due to the strategic position between the two oceans and its geographic extension, as well as the Australia. For the EU states, public acceptance towards CO_2 storage is much more challenging, and this limits the availability of easily accessible storage sites while increasing the investment costs related to pipelines and transportation. These challenges have stopped many EU members to not push towards the CO_2 storage. In fact, dedicated research and funding programmes have been established in four countries only: France, Norway, Germany and Netherlands.

The Global CCS Institute controls the state of development of CCS and EOR projects and in the following a list of main facilities in national contests is presented, even though the major of them is not integrated with a WtE plant but reflects the local awareness towards the CCS process.

Norway has a demonstration CCS unit for the WtE plant in Klemetsrud [34], run by Waste-to-Energy Agency of Oslo (EGE) that has a capacity of 160,000 ton/year (1 out of 3 WtE lines) and produce electricity (10,5 MWe) and thermal energy (55,4 MWt). Final destination of the CO_2 is an offshore storage planned in *Smeaheia* (saline formation at 1.2-.7 km depth or Johansen formation at 3.3 km depth), both near Troll field, about 600 km from shore. In advanced development is the project of a post-combustion CO_2 capture with partial reutilisation in cement production in the southern Norway. The remaining CO_2 is sent to a geological storage in the Smeaheia area by pipeline and shipping transportations [34]. The CO_2 is obtained from a Waste to Energy and the full chain will be operational in 2023/2024.

In **Germany,** it is worth noting that the coal-fired plant in Essen, North Rhine-Westphalia, is involved in the Align CCU/CCS[5] Project, where an industrial CCU/CCS cluster across five EU countries is foreseen.. The project will develop a unique CO_2 storage in the North Sea basin and their near and mid-term infrastructure facilities by 2025 [35].

In **The Netherlands**, the PORTHOS project is under development. PORTHOS stands for **P**ort **O**f **R**otterdam CO_2 **T**ransport **H**ub and **O**ffshore **S**torage and is a joined initiative of Port of Rotterdam, Gasunie and EBN. The aim is to Capture, Use and Store the CO_2. The CO_2 will be captured from refineries and chemical plants, a portion of CO_2 will be sent to greenhouse farming for plants' growth and the remaining portion will be compressed and stored in a depleted gas field in the North Sea at a depth of approx. 3 km [36]. Aiming at a final investment decision (FID) 2021, PORTHOS will focus on three main issues in 2020: a) Technical development of the transport and storage infrastructure; b) Environmental Impact Assessment and permits; c) Agreements with companies to supply CO_2 and with the government to enable CCU/CCS.

In **UK**, the Caledonia Clean Energy Project (CCEP) captures the CO_2 produced by natural gas fired power plant. The CO_2 is sent by pipeline to a storage site in the Captain sandstone formation. The 95% of required pipeline is existing [37].

In USA the PETRA NOVA plant is the first large US power plant with CCS. The plant captures 5000 tons per day of CO_2 with a post combustion technology applied to a coal-fired electricity generation plant. CO_2 is transported via pipeline to the Rest Ranch oil field where it is injected for EOR. [38]

In Canada, the Boundary Dam plant captures the CO_2 produced for electricity production. The gas is transported via pipeline and stored more than 3 km under the ground in a saline aquifer. [38]

In **Australia**, the Gorgon Project is a large-scale CCS project that aims to capture the CO_2 from natural gas, compress and transport it via pipeline to one of three drill centers where the CO_2 is injected into the Dupuy formation (Barrow Islands). The injection site is continually monitored to observe wells and seismic activity of the area [39].

Based on the outcome of a very recent study carried out by Wood for IEA GHG ("Update techno-economic benchmarks for fossil fuel-fired power plants with CO_2 capture), considering also very high capture rate options (up to 98.5-99%), the process of carbon capture from power applications accounts a global cost of 50-60 €/tCO2 for large coal plants and 70-75 €/tCO2 for large gas-fired palnts, due to capture and compression processes), transportation and storage.

[5] AlignCCUS, About the Project, accessed on 18 June 2019, URL: https://www.alignccus.eu/

The impact of CCS on electricity cost is 40-50 €/MWh for a coal-fired power plant and 20-25€/MWh for a gas-fired power plant.

To offset the costs associated with the CO_2 storage, the interest towards the Carbon Capture Utilization (CCU) is growing and the potential uses of CO_2 are showed in Figure 14.

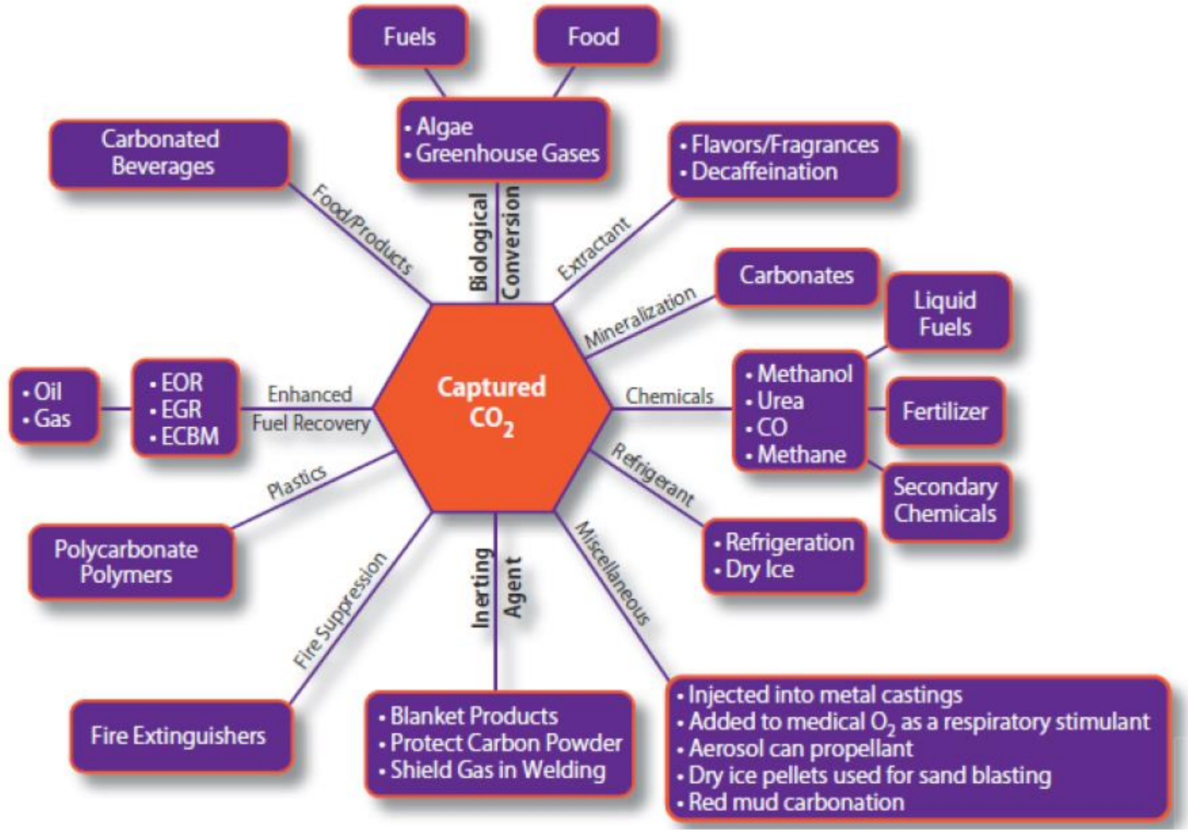

Figure 14- Classification and potential uses of Capture CO_2 [41].

The basic idea is to not treat the CO_2 as waste but as a chemical resource. Among all the applications, just few have overcome the research phase and are ready for the industrial market: the EOR, the chemicals production as urea or methanol, the sodium carbonate production, the use of CO_2 for algae and the biofuel. These processes are associated to different TRLs (Technology Readiness Levels), which ranges from 0 to 9 and indicating the development status of an innovative process and how much it is ready for large-industrial application. The methanol production is at a demonstration level corresponding to TRL 6, while chemicals production as urea synthesis or polymerisation have already entered in the market with a TRL of 8-9. EOR and algae cultivation have a TRL of 9, where values of TRLs higher than 5 indicate that the technology has achieved the prototype/pilot scale [42].

The use of CO_2 as Enhanced Oil Recovery (EOR) is borderline between storage and utilization. In the enhanced oil recovery, the CO_2 is used to extract the oil or natural gas from rocks that otherwise would have been unrecoverable reservoirs, and with the CO_2 storage, it is the main application now developed at large-scale. For example, in Louisiana, the Lake Charles Methanol proposed to capture over 4 Mtpa of CO_2 from syngas used to produce methanol. The captured CO_2 is used in Denbury Resources for Enhanced Oil Recovery in Texas. The operation data of this plant is planned to be 2022 [34].

Figure 15 shows the ditribution of operational installation of large CCU plants other than Storage and EOR (i.e. chemical and fertilizer production, food and beverage industry) in the selected counties, according to Global CCS institue database.

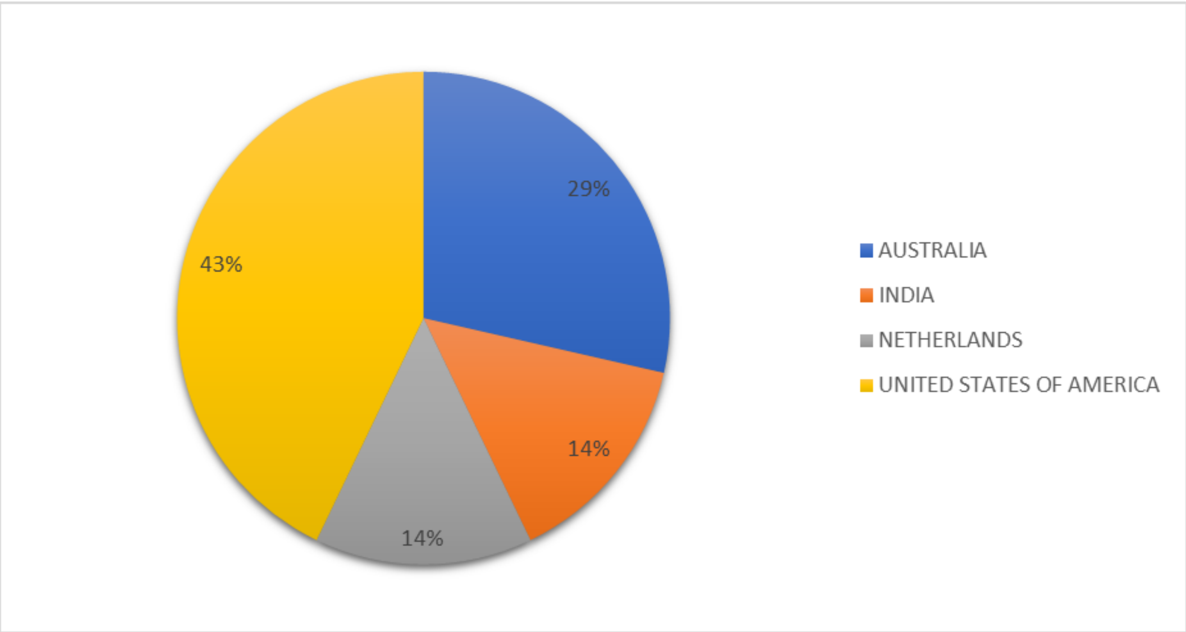

Figure 15- National contest CO_2 uses [34]

For food industry, the USA has operating plants for re-use of capture CO_2 in beverage productions, while in Finland the CO_2 captured from a refinery is sold to food industry after a purification process to reach the necessary CO_2 purity-grade [43].

About the re-use of CO_2 for fertilizers, Australia has one operating plant for fertilizer re-use and another in development, Netherlands and Japan are pointing at reuse of CO_2 for algae production at Twence and Saga city WtE-CCU plants, which are among the most advanced examples in the world [44] [45].

India has an operating plant for chemicals production. MHI signed an agreement with Indian National Fertilizers Limited (NFL) company to develop a CO_2 capture unit from natural gas, where it is used the licensed solvent KS-1. The CO_2 is recovered at 99% purity to be provided as feedstock for urea synthesis from ammonia [46] [47].

In South-Africa, the Swayana engineering firm is collaborating with LanzaTech carbon recycling company to develop a carboncapture and utilization plant in the country. The carbon monoxide (CO) gas, coming from the smelter in a ferroalloy production plant is converted in fuel ethanol in a gas-fermentation technology owned by LanzaTech. A pilot unit has been already tested for the pre-feasibility study successfully [34] [48].

Another example of CO_2 utilisation is represented by the greenhouses. In Duiven WtE (The Netherlands), a project of CO_2 capture integration is ongoing. It captures 50,000 tonnes CO_2 per annum and it has started the operation in 2020 The system uses an improved amine-based post-combustion process that can capture around 90% of the CO_2. The captured and liquefied CO_2 will then be supplied by road tankers to users such as nearby greenhouses, where it will increase the yields of plants and vegetables [44] [45]. Similarly, it is done in Japan, as described in section 2.1. In this plant, the amine used is a secondary sterically hindered solvent, and the CO_2 is transported only few hundred meters far from the WtE-CC plant, reducing significantly the costs of transportation.

4.3 Overview of potential integration issues and operating challenges

4.3.1 Theoretical review energy integration

When the Waste to energy is integrated with a CO_2 capture and storage/utilization system, the auxiliary consumption of the overall system significantly increases. At different degrees, this creates potential conflicts with the main functions of the plant, i.e. producing energy in form of electricity and/or heat.

For a comprehensive technical review of this kind of energy integration issues, Wood has carried out two theoretical study cases (cases 1 and 2), starting from inhouse reference projects, to estimate of the impact of CO_2 capture system on energy production in two WtE plants. The first plant uses a CFB boiler, while the second one is based on a grate incinerator.

One of the most significant parameters is the ratio between the steam required by the CO_2 Capture Unit and the steam produced in the boiler and sent to the Steam Turbine.

The CFB WtE plant of case 1 is non-co-generative, i.e. produces electricity only, with a net electric power output of 20 MW_E and a net electrical efficiency of 25.4%. The flue gas flow rate is 155,000 Nm^3/h with a CO_2 content of approx. 10% vol. and a temperature of 150°C at the stack. The steam cycle throughput is 115 t/h, the steam conditions at the boiler outlet being approx. 60 barg and 430°C.
The amount of CO_2 generated is 31 t/h and, for an assumed average heat duty of regeneration of 3 GJ/tCO_2, the plant would require about 82 GJ/h of energy to separate 90% of the CO_2 from the flue gas. The amount of steam necessary would be approx. 40 t/h. Considering that the plant produces 115 t/h of steam, approx. the 38% of the Steam Turbine throughput should be extracted at a pressure of approx. 6 barg to supply energy for solvent regeneration in the Capture Unit. This would correspond an equivalent electric power of 6 MW_E.
Another major energy penalty is associated with the CO_2 compression and liquefaction (if required). Assuming that liquid should be delivered from the CO_2 capture plant @ 20 barg, the overall electricity consumption of the compression + liquefaction (chiller) would be 2.8 MW_E. Overall,the net electricity production would be almost halved due to the carbon capture energy requirement.

The same technical evaluation is made for the grate-boiler WtE plant of case 2, which is non-co-generative too, with a net electric power output of 20 MW_E and an electrical efficiency of 24.4 %. The flue has flow rate is 186,000 Nm^3/h with a CO_2 content of 8.2% vol. and a temperature of 150°C at the stack. The steam cycle throughput is 101.5 t/h, the steam conditions at the boiler outlet being approx. 61 barg and 420 °C.The amount of CO_2 produced in the WtE is 35.3 t/h and, for an assumed heat duty regeneration of 3 GJ/t_CO_2, the energy required to separate 90% of the CO_2 would be about 95 GJ/h. The amount of steam necessary for a CO_2 capture higher or equal to 90% would be approx. 45 t/h. Considering that the plant produces 101.5 t/h of steam, about the 45% of the Steam Turbine production should be extracted at a pressure of approx. 6 barg to supply energy for solvent regeneration, i.e. an equivalent electric power of 6.8 MW_E would be necessary to sustain the capture unit.
In this case, with same assumptions as case 1, the energy penalty is associated with the CO2 compression and liquefaction would be 3.2 MW_E.
Overall, the net electricity production would be halved with respect to the case with no carbon capture.

The two examples show how significant is the energy penalty associated with the CO_2 separation only.

Hence, it is crucial to find in the WtE plant other heat recovery sources. One potential source is surely the residual energy of the flue gas discharged at the stack

In the considered reference cases, the flue gas is discharged to the atmosphere at approx. 150°C. Usually, the temperature of flue gas is kept high enough to prevent the formation of corrosive deposits and acid condensates typical of municipal waste. However, the heat of flue gas could be recovered by gas condensation, which has become a standard in WtE plants with District Heating, , also considering that with a state of the art flue gas treatment, corrosive deposits and acid condensate should be a less challenging issue. In fact, in the gas condensation, the flue gas is cooled below the water dew point so that the water vapour condenses, and the thermal energy releases are recovered. The flue gas condenser should be placed in the final part of the gas path after the FGT so that the flue gas is already largely purified from contaminants, although some traces of SO_2, HCl and NOx are still present. The condensation of these species could enhance the corrosion risk of duct and heater coils. The risk is analysed and evaluated during the development of the plant, for example by anti-corrosion protection of chimneys and flue gas ducts.

The waste-to-energy plant in Copenhagen, connected to a District heating system, is an example of exploitation of flue gas condensation. The plant has a two-step condensation process. In the first step, the heat is transferred directly to the district heating. In the second one, an absorption heat pump cools the flue gas to 30°C with an increase of heat output from the boiler line of about 20%. [49]

Figure 16 shows a schematic representation of the whole WtE plant.

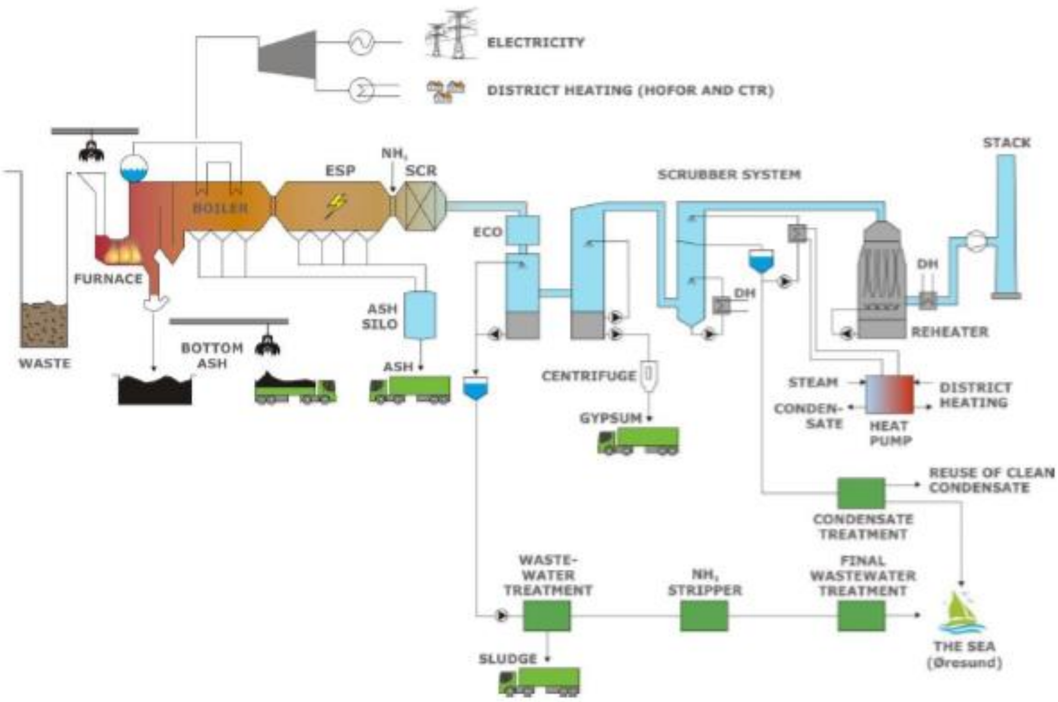

Figure 16- Copenhagen Waste to Energy plant with implantation of Glue Gas Condensation **[49]**

The adoption of such a system could be affective in WtE plants both with and without carbon capture. It has to be remarked that, in case of carbon capture integration, the heat recovered from a flue gas stream of 150°C cannot be effectively used in the CO_2 capture, which typically requires thermal energy for solvent regeneration at approx. 120-140°C. However, in absence of District Heating, a useful alternative would be to recover the heat of flue gas by preheating the Boiler Feed Water (BFW), avoiding the use of steam extraction from the Steam Turbine for this duty and thus contributing to reduce the overall energy penalty in terms of lost electricity production.

To hinder the energy conflict between the district heating and the CO_2 capture, another optional improvement to effectively recover additional energy is to place a heat pump. To this end, Wood carried out a specific evaluation through a third study case (case 3) starting form one of the two study cases described above, namely case 2, and assuming that the plant can be integrated with a District Heating (DH) network. The integration with carbon capture system and the implementation of a heat recovery system, as the heat pump, would get available energy for the district heating, reducing the adverse effect on the overall net energy production of the plant. In this third study case, the heat pump is used for a total recovery, i.e. the DH water temperature is raised to 70°C (a temperature suitable for modern DH systems) in the heat pump itself for a completely new connection to the DH, as the starting plant is non-cogenerative.

For the selected WtE plant, after the boiler, the flue gas is purified of pollutants in a treatment sequence composed by bag filter for dust removal, semi-wet reactor for soluble acid gases and SCR for deNOx. The full scheme of thermal integration of the flue gas cooling with the heat pump and district heating is shown in Figure 17, where the GGH is a Gas-Has Heater and the DCC is a Direct Contact Cooler.

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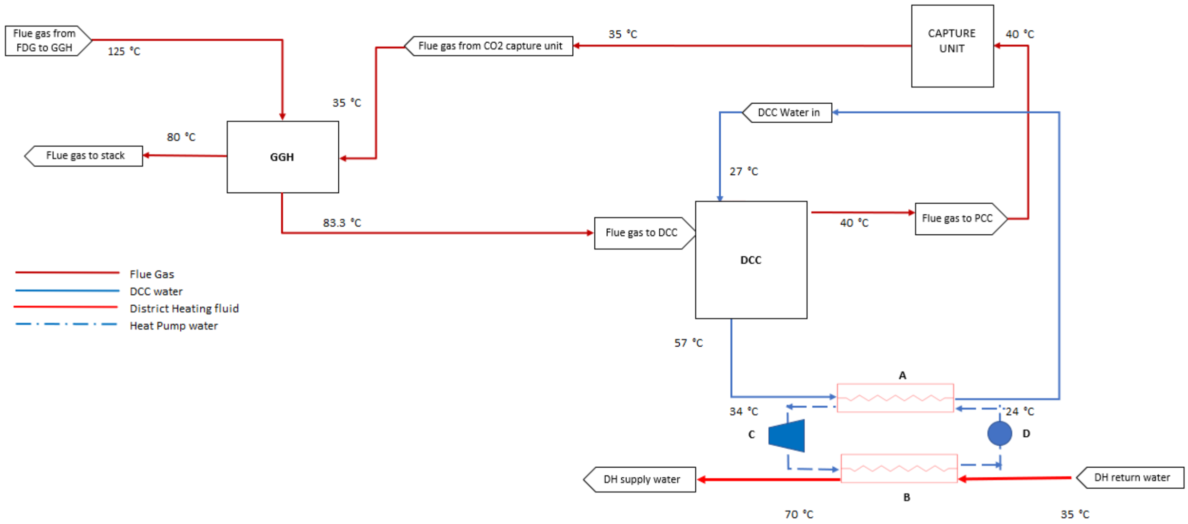

Figure 17- Gas-Gas Heater and Heat Pump integration in the WtE-CC plant of case 3

The heat available from the DCC is estimated to be 12.3 MW_T. This is the net amount that can be transferred to a useful effect, i.e. the District Heating. Assuming a COP of 5.5, the electric power consumed by the heat pump is 2.7 MW_E, the overall thermal output to district heating being 15.1 MW_T.

In addition, with the previous assumption about CO_2 delivery condition (liquid @ 20 barg) the intercooling of the CO_2 offers the possibility to recover heat to the DH system. For case 3, this amount is estimated to be 2.3 MW_T.

Retrieving the energy balance calculation done for case 2, the electric energy penalty is further increased by 2.7 MW_E, leading to an overall penalty of more than 60% with respect to the original plant without carbon capture, but the plant can supply a significant amount of heat (more than 17 MW_T) to the local community, recovering an amount of heat that would be otherwise wasted.

A similar solution has been proposed and is going to be implemented is Klemestrud WtE plant (Oslo), but with a slightly different purpose. In fact, this WtE is a co-generative plant with 112 MW_T output for district heating and about 42 MW_E as available electricity (all the three lines). When the Carbon Capture is added to this plant, the power consumption is reduced to 20 MW_E to sustain the electric consumption of CO_2 capture and CO_2 liquefaction, while 36 MW_T are consumed for solvent regeneration. The thermal consumption is counterbalanced by heat recovery from the Direct Contact Cooler (DCC). The heat pump recovers the heat of water used in the DCC and sustains the district heating. The use of the heat pump introduces an additional electricity consumption which increase the offset of electrical energy available to Norway grid by about further 10 MW_E, however it allows fully balancing the additional heat requirement of the carbon capture, i.e with no penalty on the heat output to the district heating after the integration with the Carbon Capture.

4.3.2 Integration challenges

The integration of a CO_2 capture system on an existing waste to energy facility may require some process modifications or retrofits to meet the operating Requirements for the CO_2 capture.

Examples of process modifications involve the operating costs, the environmental control, the energy integration to cite few of them. In details, the main integration challenges are discussed: the modification of flue gas pre-treatment, the changes in chemicals handling, the energy supply, the stop of operation to interconnect the equipment and the spatial area necessary to build the capture section of the plant.

Gas pre-treatment

The flue gas leaving the boiler of a waste to energy plant is mainly composed by particulate matter (or dust), SOx in form of both SO_2 and SO_3, NOx, HCl, HF, Hg and other heavy metals, which presence or not depends on the type of waste.

The typical flue gas cleaning to comply with environmental regulations in a European waste to energy is generally composed by:

- ESP or bag filter to remove the solid particles;
- SCR or SNCR (in the boiler) for NOx compounds;
- WFGD or Semi-dry FGD for acid gases as Sox and HCl;

A summary of possible typical alternatives in FGT for WtE plants is reported in Table 7.

Table 7- Summary of FGT in WtE plant without CO_2 capture. ESP: electrostatic precipitator; FF: fabric filter; AC: activated carbon

Type of Plant	Flue Gas Cleaning		
w/o CO_2 capture	SNCR	ESP	Wet Scrubber
	SNCR	FF+AC	Wet Scrubber
	SNCR	ESP	Semi-dry scrubber
	SNCR	FF+AC	Semi-dry scrubber

When a post-combustion CO_2 process is added to the existing WtE, the flue-gas pre-treatment is a critical step. In fact, most absorbent liquid used in the process may be affected by flue gas composition. SOx and NOx can react with amine absorbents, forming heat-stable salts, which are difficult to regenerate and reduce the solvent available for CO_2 capture, while particulate matter (PM) can cause equipment blockage, foaming of the liquid absorbent [50]. Reference is also made to the overview carried out in task 3 of the study. The capture solvents impose stringent limitations on the flue gas composition at absorber inlet, to keep the degradation of the solvent to acceptable levels. The following reference values (coming from previous porjects/studies executed by Wood on Carbon Capture, adopting various technologies) are used in the study:

- Maximum SO_2 concentration: 10 ppm
- Maximum NOx (as NO_2) concentration: 20 ppm
- Maximum total dust concentration: 10 ppm
- Maximum HCl concentration: 10 ppm

In existing waste to energy plants, the flue gas cleaning is designed to meet the environmental limit imposed by regulations, Although in many cases the WtE plants emissions are sensibly lower than limit, including the European plants, where the emission limits are the most stringent, their emissions are still too high for the integration with a PCC plant. The more demanding pre-treatment needs would require some modifications/upgrades of the existing flue gas treatment system. Several configurations could be applied, however a few most likely combinations of cleaning technologies can be identified for WtE-PCC plants, as shown in Table 8.

Table 8- Different combination of Flue Gas Cleaning in presence of CO_2 Capture. ESP: electrostatic precipitator; FF: fabric filter; AC: activated carbon

Type of Plant	Flue Gas Cleaning		
With CO_2 capture	SCR	ESP	Wet scrubber multi stage
With CO_2 capture	SCR	FF+ AC	Wet scrubber multi stage
With CO_2 capture	SCR	ESP+ FF+AC	Wet scrubber multi stage
With CO_2 capture	SCR	ESP	Semidry Scrubber

Type of Plant	Flue Gas Cleaning		
With CO_2 capture	SCR	FF+AC	Semidry Scrubber
With CO_2 capture	SCR	ESP+ FF+AC	Semidry Scrubber

The equipment that are mostly subjected to a retrofit are the deNOx and deSOx processes..

As far as NOx emissions are concerned, the majority of existing WtE use the combination of SNCR with flue gas and flue gas recirculation, which reduces NOx by 50-80% [50]. However, the low NOx concentration of inlet of CO_2 absorber can be reached only with a more efficient technology, namely the SCR. In WtE plant that have project of CO_2 capture integration as Alkmaar (NL), Rotterdam (NL), Oslo Fortum (NW) have to consider placing a SCR in the FGT sub-system. The SCR is usually placed after the dust removal unit in a tail-end configuration.

For deSOx, in the carbon capture context, the necessity of very low SOx concentration requires a revamp of existing desulphurization technology or a replacement. The retrofit of an existing abatement system might have significantly different implications depending on the adopted technology. For example, Wood inhouse data for Wet Limestone FGD, available from previous studies on coal power plant with and without carbon capture, suggest that the major equipment dimensions in the design with CCS do not differ from the design without CCS. The difference is mainly related to reagent consumption and by-product generation, and the need for a further water spray plate in the absorber and a new additional slurry circulation pump.

The following highlights from real cases of integration of carbon capture with WtE provide an example of how the flue gas cleaning system upgrade was addressed in relation to this type of retrofit.

In the Hengelo WtE (NL), the flue gas leaving the boiler meets in sequence the electrostatic precipitator, a scrubber reactor with sodium bicarbonate injection, the fabric filter to remove the remaining solid particles and at the end, the SCR.

The Klemetsrud WtE plant in Oslo (NW) has three treatment lines. Two of them are designed with a SNCR deNOx system, while the third line that was built more recently and is undergoing a project for integration with carbon capture. The flue gas cleaning of the third line is composed by an electrostatic precipitator, wet scrubber for acid gases, SCR and activated carbon bed for dioxins [51]. The wet scrubber for acid gases removal is actually composed by 4 scrubbing stages: in the first two, the acidic pollutants as HCl and heavy metals are separated, the SO_2 is removed in the third stage, while the last one is used to capture the remaining particles though a venturi system [51].

Table 9 summarizes the modifications necessary to the operating Flue Gas Cleaning systems as retrofit to meet the CO_2 capture needs in the two mentioned WtE-CCS projects.

Table 9- Retrofit modifications of WtE examples for CO_2 capture plant integration

WtE	Retrofit	Example
Lines 1&2 w/o Carbon Capture: -ESP -Spray Dryer -Wet Scrubber -FF -SCR	Line 3 w/ CC: -ESP -Spray Dryer -ESP -Wet Scrubber -SCR	Hengelo [52] [53] [54]
-SCR -ESP -Wet Scrubber (multi-stage)	No modifications	Klemstrud [51]

Regarding flue gas handling more in general, another implication of the integration of a Carbon Capture with an existing WtE is related to the flue gas blower. The additional pressure drops of a carbon capture, in the range of approx. 80-120 mbar, would require a retrofit of the flue gas blower. Whether this is a revamping of the existing unit or a full replacement should be evaluated case by case.

Chemical handling

When the capture plant is integrated with an existing WtE, the flue gas pre-treatment needs revamping or changes, as described above. In case of revamping, a larger amount of reagents for both deSOx and deNOx have to be handles, as well as, more by-products from FGT are produced.

For reference, Wood estimated from in-house data that the revamp of a reference European existing Flue Gas Treatment would require:

- would require the injection of roughly 10% more of limestone to increase by about 4% the removal efficiency of wet deSOx unit, leading to a 4% increase of gypsum by-production.
- a roughly 10% increase in urea consumption in the SCR to support the increase of deNOx efficiency of about 10% to meet the CO_2 solvent requirements.

The integration of carbon capture system requires a further chemical handling related to the necessity of making-up the operating losses of the capture solvent itself. Based on inhouse data, Wood estimated that, for a plant capturing 35 t/h of CO_2 the solvent make-up requirement (typically the range of 0.2÷1.0 kg of solvent per ton of CO_2 captured) would approx. correspond to just one truck delivery per year.

Spatial Integration

Of course, the integration of CCS/CCU system in an existing WtE requires space for the construction of a new Carbon Capture unit. Based on inhouse data, Wood has estimated that an indicative footprint of an amine-based CO_2 capture unit for the retrofit of a 20 MW_E net power WtE would be approx. 25 m x 40 m (excluding CO_2 compression and liquefaction, if any).

Regarding spatial integration, one of the main issues that can have a significant impact on the retrofit is the possible presence of a gas-gas heater. The installation of a Gas-Gas Heater is necessary when the flue gas temperature after the CO_2 absorber is not high enough to ensure an adequate gas buoyancy and dispersion in the atmosphere and avoid the "plume effect. Its installation, in-between the WtE stack and the absorber, makes the flue gas ducting more complicated. For instance, the straightforward solution of discharging the flue gas directly from the top of the absorber is not possible if the configuration includes a GGH.

Energy supply

For the integrated system WtE-PCC, the solvent used to purify the flue gas of CO_2 is regenerated at high temperatures. The heat duty necessary for the regeneration depends on the type of solvent, but on average ranges between 3 and 4 GJ/t_CO_2. As previously discussed, this means, that an amount of about the 50% of steam produced from the boiler that is exported from the Steam Turbine and supplied to capture reboiler.

To overcome this energy conflicts already described in para 4.3.1, some WtE plants with District Heating have also chosen to capture CO_2 preferably during summer, when the district heating demand is lower, and reduce the CO_2 capture during winter, as is done in Alkmaar plant in the Netherlands. The drawback of this solution would be a peak of CO_2 emissions in atmosphere from the WtE plant during winter, however, depending on the nature of the alternative sources for domestic heating, this may not be a disadvantage in absolute terms.

However, the connection of a CO_2 capture unit downstream an existing WtE generates some other operating challenges that could alter the operation of incinerator, especially when it is designed to produce electricity as main product. Two main types of issues are briefly analyzed:

- Steam throughput (i.e. load) in the last stages of the steam turbine after the retrofit;
- Hardware modifications required to the steam turbine

Making reference to the study case 1 described in para 4.3.1, assuming that the minimum turndown allowable for the condensing section of the steam turbine is approx. 30% of the design throughput (i.e. approx. 24 t/h in the case), in line with Wood experience for previous projects, with the CO_2 capture in operation, there could be limitation in turning down the boiler load, to fulfill the minimum load requirement of the low-pressure section of the steam turbine. This could be an important limitation in terms of operating flexibility of the whole WtE.

As far as the hardware modification required by the retrofit to an existing steam turbine, the following issues may arise from the need to extract a significant amount of steam at a pressure level of around 6-7 bar:

- The distance between stages could be too short in order to allocate the extraction nozzle This aspect could be a main issue especially for a reaction turbine type expansion stages, which are widely used, especially at the low-pressure section of the turbines for power generation.
- The stage downstream extraction would be unbalanced (especially for reaction type turbine this could be again a big issue)

These high-level considerations are very preliminary, being the outcome of an initial brainstorming. Specific evaluations should be developed case by case with the support of the original equipment manufacturer. There could be even the risk that a full replacement of the machine is necessary; for example, at Boundary Dam, the unit 3 retrofit to implement the CCS required the implementation of a new steam turbine [55].

Stop of operation

The integration of CCS/CCU system in an existing WtE needs to stop the WtE plant to allow interconnecting the new CO_2 capture system with the WtE plant and the commissioning/starting-up the CO_2 plant.

During the construction phase of the CO_2 capture unit and relative pipeline to transport the CO_2 in a different geographic area for storage or in an industrial plant for a utilization, the stop of the incineration process is not strictly necessary. The scheduled plant stop for planned maintenance can be exploited to implement in the waste to energy plant some of the modification necessary for the WtE-PCC integration. The actions that can be planned during the scheduled stop of a WtE are mainly the tie-ins (on flue gas duct at the end of FGT, on the WtE stack to connect the CO_2-free flue gas duct, on cooling water circuit and other utilities). The duration of the scheduled maintenance of a Waste-to-Energy plant is typically about 3 weeks on average on a yearly basis. This timeframe is expected to allow the execution of the above listed tie-ins without further stop of operation.

However, other modifications that could be required, namely to the flue gas blower and, especially, to the steam turbine, are more challenging to handle. It is unlikely that a normal planned outage is enough for their realization. As a further general consideration, the construction works of CO_2 capture unit will require some civil works, especially in relation with the foundations of the new equipment. It is crucial that during the design phase any possible interferences with the existing foundations and underground works are checked and avoided as far as possible, as their management during construction phase could lead to a sensible extension of the duration of the WtE shutdown period.

After the completion of CO_2 unit construction and the plant modification in the WtE section, based on Wood experience, a further stop of about 2.5÷3 months would be needed to complete the commissioning of CO_2 capture unit and the initial start-up the integrated plant.

5. Assessment of market potential

The objective of the present study is to understand both the issues and the opportunity pertaining the application of CCS/CCU to WtE plants. This analysis is regarded as an essential first step before proceeding to a more detailed evaluation.

During the execution of the main study tasks, Wood has reviewed various technical, environmental economic, regulatory and social aspects related to this WtE-CCU/CCS combination.
As many of the studied features may have a different impact on WtE/CCS integration depending on the geographical location and local context, the purpose of the study conclusive task is to elaborate a tool to evaluate potentiality of WtE-CCU/CCS integration at a country level, based on criteria depending on the geographical location. The developed tool is then applied to the ten countries selected for this study. However, it is remarked that the tool intended as universal, i.e. it could be potentially applied to any country worldwide.

The study has been focused on the integration of a post-combustion CO_2 capture facility with a Waste-to-Energy plant. The majority of the technical and economical parameters discussed throughout the study were analyzed from a retrofit perspective, i.e. assuming to integrate a new CO_2 capture unit with an existing WtE. Based in the outcome of the previous tasks a number of criteria were identified for an evaluation of the potential in a certain local context (i.e. at country level)

The proposed methodology intends to rank each country against the selected criteria, assigning a weight to each criterion (relative to 100%). For each criterion, a score is given to each country, ranging from 1 to 10. The score of each criterion is then multiplied by its relative weight to obtain the “weighed score” of the criterion. The final score of each technology is the sum of all the weighed scores of the different criteria. The maximum theoretical score that a country could achieve is 10. The final score of each country will be a quantitative indication of the expected country potential in relation to the application of CCS/CCU to WtE, especially in relative terms with respect to the other countries.

5.1 Criteria Overview and application

Based on the review carried out in the previous tasks, the following criteria are identified to have a significant influence in determining the potential of integrating the CCU/CCS in an existing WtE, depending on the geographical location. The weight given to each criterion is also reported

1. Opportunity for CCS/CCU (weight = 20%);

2. Possible integration with District Heating (weight = 10%);
3. Local CO_2 emission factors for power and heat generation (weight = 10%);
4. CCU/CCS regulation and Carbon pricing mechanisms for WtE (weight = 20%);
5. Diffusion of WtE (weight = 15%);
6. Social acceptance of WtE and CCU/CCS (weight = 10%);
7. WtE Regulation: NOx and SOx emission limits (weight = 10%);
8. Average WtE plant size (weight = 10%);

The following criteria are further described below. Also, for each criterion, some possible options are listed and preliminarily ranked to outline the rationale behind the scoring.

5.1.1 Opportunity for CCS/CCU

The criteria "Opportunity for CCS/CCU" relates to the possible destination of the captured CO_2. The availability of storage sites for the captured CO_2 or the presence of CO_2 off-takers in the same geographical area as the plant would make the initiative easier from the techno-economic point of view and increase its potential. For this criterion, the options can range, in increasing scoring order, from no opportunity to store/use the CO_2 nearby the WtE plant, through the availability of Storage site nearby up to the presence of a market for CCU (e.g. EOR, production of chemicals, crops cultivation). The scoring takes into account also the availability of CO_2 pipeline infrastructures in the countries, which is anyway strictly linked to the presence of geological sites and CO_2 off-takers/users.

As discussed in the study, the re-use of captured CO_2 in a different productive process is a further incentive in investing in a capture system, at least in the short term. However, in the medium/long term, when established, the CCU markets will saturate quickly, especially if Carbon Capture from energy and industrial sectors becomes a diffused practice.

In both Netherlands and in Japan there are opportunities for CO_2 re-use, mainly for agricultural fields. However, in The Netherlands (scored with "9"), the development of storage resources and CO2 pipeline infrastructures [56] is more advanced than in Japan (scored with "7.5").

In Germany (scored with "7.5"), there is a remarkable social opposition to CO_2 storage, anyhow there are a few projects for post-combustion capture foreseeing, a re-utilization of the CO_2 in chemical plants as feedstock.

On the contrary, Norway and Australia are focused on under-sea storage thanks to the availability of many storage sites nearby their shores. USA, where the undeground sites are mainly on-shore, is scored higher ("9") than the Norway ("8) and Australia ("7") because the large availability of storage sites is not exploited only for CO_2 storage but for Enhanced Oil

Recovery too, as done in PetraNova project in Texas, and there is a considerably larger number of existing CO_2 pipeline, some of which are hundreds of kilometers long [56].

The UK has shown a hybrid behavior, going towards both CCS (with six large scale projects trials and several storage sites identified) and CCU.

The score for South-Africa and India is sufficient ("6") due to the ongoing development projects and pilot plants on re-use of captured CO_2 from fossil sources as feedstock for ammonia synthesis or to produce fuel-ethanol, despite there are no operating WtE and many projects to build WtE plants and change the waste management are ongoing.

Italy, scored with a "6", is characterized by the scarce incentives in CCS, but also by the development of the few projects on reuse of CO_2 as feedstock.

5.1.2 Integration with District Heating

The Waste-to-Energy plants can be three different outputs: electrical generation (EL), heat generation (HP) and combined electrical and power generation (CHP). Among the options including the supply of heat, the integration with District Heating (DH) is one of the most common.

When a CO_2 capture plant is constructed downstream a WtE, as deeply discussed in the report, the integration with a capture unit requires further flue gas cooling (typically in a Direct Contact Cooler - DCC) that represents an additional heat source. It is of primary importance to understand whether and how this heat can be effectively utilized, assuming that the heat potentially recoverable from the DCC cannot be elevated to the temperature level required by the solvent regeneration in the CO_2 Capture Unit, with reasonably acceptable energy efficiency solutions. If the WtE plant is originally integrated with a DH system, DCC heat can be elevated at the temperature levels typically required by modern DH systems via a heat pump.

For evaluation of this criterion each country is analyzed against its trend to utilize WtE for DH, which is also related to the local meteorological conditions

The evaluation is firstly based on the percentage of WtE plant combining heat generation with electricity production (i.e. Combined Heat and Power, CHP) with respect to the overall number of existing WtE facilities in the ten countries.

Table 10- Percentage of existing WtE plant with CHP output- Source LEAP database

	Italy	The NL	UK	Norway	South Africa	Germany	Australia	Japan	India	USA
# WtE	39	13	42	17	1	81	0	1141	8	78
% CHP	24	38	14	100	0	51	0	n.a.	0	21

The figures are self-explaining however it is worth to raise a few comments to better explain the scoring against this criterion. In Japan, there are CHP-WtE facilities, but they are less widespread than in Europe, and it is unknown a specific number of CHP plants. In Australia, there are no operating WtE plants and, among the on-going projects, just one (Pilbara-New Energy) is designed for a combined output. In South-Africa, of course, the district heating is not present at all, while in India there are projects to improve the country development with more WtEs-CHP facilities.

5.1.3 Local CO_2 emission factors

The CO_2 emission factor represents the grams of CO_2 emitted per kWh of electricity produced. The energy generated by WtE facilities replaces the generation form other sources, including fossil fuels. As the waste has a significant biogenic fraction (typically 50%), an avoidance of net CO_2 emissions is associated with the use of WtE. The higher the local CO_2 emission factors for electricity and heat generation in a country, the higher is the CO_2 avoidance benefit associated with WtE, especially if integrated with CCSU. Accordingly, with emission savings opportunity, the lowest and highest marks were assigned to low and high emission factors, respectively. However, it has to be noticed that, even in national energy markets that are already decarbonized, the electricity production from WtE coupled with CCS, can be effectively utilized to stabilize the electrical system, thanks to the programmability features that is lacking in several renewable sources. For this reason, the countries with the lowest CO_2 emission factors are not penalized excessively penalized in the scoring (i.e. the minimum score is 5).

The ranking evaluation of ten countries for the CO_2 emission factor is based on emission factor published by IEA for electricity production including CHP systems in 2017 and 2018 [57] [58], listed in Table 11.

Table 11- CO_2 emission factor for national contexts in 2017 and 2018 published by IEA **[57] [58]** n.a.= not available

	Electricity (incl. CHP) gCO2-eq/kWh	
Country	**2017**	**2018**
Australia	742.9	714.3
Germany	416.7	404.8
India	718.1	n.a.
Italy	325.7	301.9
Japan	522.3	485.0
Norway	8.3	8.3

	Electricity (incl. CHP) gCO2-eq/kWh	
Country	***2017***	***2018***
Netherlands	437.0	420.3
South Africa	899.6	n.a.
UK	245.3	228.1
USA	421.1	409.4

5.1.4 CCU/CCS regulation and Carbon pricing mechanisms for WtE

The Carbon pricing is a terminology that covers all Carbon Tax and Cap&Trade programs relative to GHGs emissions. Nowadays, several Cap and Trade programs are active, and they cover the same types of process emissions from power generation, civil aviation and waste incineration.

Cap&Trade programs (also known as ETS; Emission Trading Systems) entail the distribution at participating states of "emission credits", each covering 1 ton of CO_2 emitted. All tons of CO_2 emitted and not covered by the emission credits must be paid.

It is worth noting that even if an ETS is in place and is extended to WtE facilities, this would make it a driver for the investments in combined system WtE- CO_2 capture only assuming a future consistent increase in demand for CO_2 quotes. Four main options are considered for this criterion. The total absence of an Emission Trading System is valuated with lowest mark, while the highest value is assigned to an ETS program that includes both the Waste-to-Energy sectors and incentives for Negative Emission Technologies (NET) .In the middle, there are the Cap and Trade systems that cover the WtE but not the NETs, and the programs, which do not include neither of them.

In India, there is no kind of Emission Trading System and the lowest value was assigned, accordingly with Table 3. South-Africa, Japan and USA have different Cap and Trade systems, all of them applicable to Waste Incinerators as well, but not considering the Negative Emission Technologies. It is worthy specify that the American Cap and Trade program is actually active only in California State. The EU member states participate to, the EU-ETS, a similar one being followed by Australia as well. The EU-ETS is about the GHGs emissions from energy-intensive industry, civil aviation and power generation and does not presently include the WtE sector, at least for Municipal Solid Waste and Hazardous Waste (whilst plants fed with other special wastes can be included). For this reason, the EU-ETS, is scored with "6".

5.1.5 WtE diffusion

The Waste-to-Energy diffusion has been selected as a criterion for the WtE-CCU/CCS market potential because the higher the diffusion of WtE plants, the higher is the potential of the local market.

The ranking comparison among the ten countries for the WtE diffusion is based on the figures reported in Table 12. The main indicative parameter is the amount of waste burned in WtE plant in the country per year.

Table 12- Evaluation of WtE diffusion

	Italy	The NL	UK	Norway	South Africa	Germany	Australia	Japan	India	USA
# WtE	39	13	42	17	1	81	0*	1141	8	78
Amount of Waste burned in WtE, #/Mtons/y	6.1	7.0	10.9	1.5	0	22.6	0*	54.6	2.2	27.8

(*) There is actually no operating plants in Australia, but 5 important project are under development to be in operation within 3-4 years for a total capacity of 1.8 MTPA.
(*) In the next 5-7 years several WtE plants can be put in operation for an overall potential treatment capacity of 33000 t/d (9.6 MTPA).

The following remarks further help in understanding the scoring associated with tis criterion. South-Africa has one WtE plant (bio-methane production) in operation since 2019 nearby Cape Town and it is, in fact, the country with less WtE diffusion due to the high rate of landfilling in the country. In Australia, there are no operating WtE plants but 5 important projects are under development, so they are considered but with a lower weight in scoring the country. In India, nowadays just 8 WtE plants burn municipal waste, while the 80% of waste is sent to landfilling. In USA, in spite of the large amount of waste produced, the landfilling and the recycling are the two main waste management solutions, which explains the low WtE diffusion in the nation. Even though the landfilling is banned in Germany, the WtE diffusion is not at very high levels, because the waste is mainly recycled and/or composted.

5.1.6 WtE and CCU/CCS social acceptance

The social acceptance of WtE and, mainly, of CCS can be at same time a barrier or an incentive for relative projects. In fact, public movements as "Not in My Back Yard" and the negative advertisement of CCS due to risk of CO_2 leakages has influenced the diffusion of WtE-CCS technology worldwide. For this criterion, two main options were considered, i.e. "High" and "Low". However, ad-hoc campaign have helped in some countries to reduce the social opposition to this kind of initiatives, so there is a number of intermediate scores that can be considered.

Table 13 summarizes the percentage of social acceptance towards CCS in ten countries. Data in Table 17 are results of social surveys, reviewed throughout the course of the study.

Table 13- Public acceptance of CCS

	Italy	The NL	UK	Norway	South Africa	Germany	Australia	Japan	India	USA
Public Acceptance, %	18%	43%	29%	54%	Very Low	24%	45%	10%	Very Low	13%

Norway, UK, The Netherlands and Australia, which are investing a lot in CCS are the countries with the higher social awareness and acceptance towards the geological injection of CO_2. The 13% of public acceptance in USA indicates the exploitation of storage site widely spread outside American shores mainly for EOR, because of social fear of CO_2 leakages from CO_2 sites. The Netherlands is the European country with the highest public knowledge of what is the carbon capture and storage (52%) which explains the high acceptance of such technology. Italy and Germany are in similar scenario, where people are not well informed and, for those who are aware of global warming issue and benefits associated with CCS, the risks associated with the technology overcome its utility. This negative trend becomes more relevant in Japan, India and South-Africa, which have the lower acceptance levels.

5.1.7 WtE Regulation: NOx and SOx emission limits

The Flue Gas Treatment sequence of equipment downstream the boiler of WtE is designed in a way to respect the pollutants emission limits from waste incinerators. When the post-combustion CO_2 capture system is integrated with the existing WtE, a retrofitting of FGT is required. In fact, the solvent used to purify the flue gas of CO_2 has generally a very low tolerance towards dust particles, SOx, NOx, HCl and HF, and lower pollutants concentrations are necessary at the back end of FGT system. Especially the SOx and NOx removal system may be subject to some modifications, depending on the adopted technology.
The extent of these upgrades, in a retrofit perspective, is expected to be lower if the initial SOx and NO_X emissions limits for the WtE are stricter.

The emission limits of NOx and SOx for the ten countries are shown in Table 19, which is an extrapolation of Table 1 in Task 2, where detailed emission limits are reported.

Table 14- SOx and NOx emission limits. USA values are referred to California State

	Italy	The NL	UK	Norway	South Africa	Germany	Australia	Japan	India	USA
SOx, mg/Nm^3	50	40	50	50	50	50	50	60	200	30
Nox, mg/Nm^3	200	180	200	200	200	150	200	217	400	150

Note: the emissions limits refer to dry flue gas @ 11% O_2 in EU, whilst in the other countries the reference O_2 content is 10%.

California in USA is the country with lower emission limits for NOx and SOx, while India is the worst in this scenario. It means that an eventual integration of a PCC system would require an intensive upgrade of the FGT. The remaining states stay on average values as it is expected that the fulfilment of the CO_2 capture systems requirement can be achieved through slight modifications. It is anyway important to remark that in EU countries, the permitting process for WtE plants requires the emission limits to be in line with the Best Available Technologies (BAT), the new version having been approved very recently. This could generate further synergies with the possible integration with carbon capture, however, the single countries may adapt their emission limits in different manner and extent.

5.1.8 Plant capacity

The plant capacity stands by the average amount (tons/year/plant) of waste burned by the WtE plants operating in each country. From a financial standpoint, considering that the implementation of a post-combustion CO_2 capture system represents a significant investment, larger-scale WtE plants are favoured by the economies of scale, i.e. the countries with larger plant on average get higher scores.

It is remarked that, although the specific carbon capture cost is expected to be lower for larger plants, the higher absolute investment cost may represent a barrier. However, in such a case, a possible solution could be to design the CO_2 capture unit only for a slip stream of flue gas existing the boiler.

The plant capacity, expressed as ton/day burned, was estimated as average of all operating WtE plants in each country. For Australia, where no operating plants are present, but there are important projects under development, the value is just a projection into the near future and its weight is smoothed in scoring the country against this criterion.

Table 15- Average plant capacity for each country

	Italy	The NL	UK	Norway	South Africa	Germany	Australia	Japan	India	USA
Plant Capacity, t/d	524.7	2001.2	1012.6	304.6	550	1036.9	1096.1	237.4	1087	1217.1

5.2 Overall results

Table 16 summarizes the outcome of the application of all the criteria discussed in the previous paragraphs.

Table 16- Overall WtE-CCU/CCS relative country-based potential

Criteria	weight %	Italy	The NL	UK	Norway	South Africa	Germany	Australia	Japan	India	USA
Opportunity for CCU/CCS	20%	6	9	8	8	6	8	7	7.5	6	9
Integration with DH	10%	7	8	5	10	1	9	3	4	2	6
CO2 emissions factor	10%	7	8	6	5	10	8	9	8	9	8
CCUS Regulation: Carbon pricing for WtE	20%	6	6	6	6	9	6	6	9	1	9
WtE diffusion	15%	6	6	7	4	1	8	3	10	5	8
WtE and CCUS social acceptance	10%	3.5	8	5.5	10	1	4.5	8.5	2	1	3
WtE Regulation: NOx/SOx Emission limits	10%	7	8	7	7	7	8	7	6	1	9
Plant Size	5%	4	10	5	2	3	6	5	1	7	9

The overall potential estimated for each country is shown in Table 17. It is calculated as weighted sum of all the scores for each considered criterion.

Table 17- WtE-CCU/CCS market potential

Italy	The NL	UK	Norway	South Africa	Germany	Australia	Japan	India	USA
5.95	7.60	6.45	6.70	5.20	7.25	6.05	6.85	3.80	7.85

The countries with the highest potential in WtE-CCU/CCS are USA, The Netherlands and Germany, thanks to generally high ranking for most of the adopted evaluation criteria. A very good potential is also expected for Japan, Norway and UK.
The lowest potential is envisaged for India, mainly penalized by the lack of environmental policies regulating CO_2 capture and the relatively low WtE diffusion.

5.3 Other than location factors

During the various analyses carried out in the course of this study work, it has come out that other than location aspects may also affect the feasibility of integrating a WtE plant with a carbon capture unit. Two main factors have been identified and are briefly described in the following paragraphs:

- Incineration technologies – The most significant differerence between the two most diffused incineration tehcnologies, i.e. the grate combustion and the fluidized bed (mainly circulating) combustion, is represented by the environmental performance. The fluidized bed technology, especially in the Circulating (CFB) version, is typically characterized by lower thermal NOx and SOx emission from the boiler itself, making easier to achieve the stringent limitations required by CO_2 capture solvents to prevent degradation.

- Greenfield vs retrofit, as the study has been executed from a retrofit perspective, i.e. assuming to integrate a new CO_2 capture unit with an existing WtE, but it is worth to explore the differences that could arise in case an entirely greenfield integrated facility. The comparison between greenfield and retrofit scenarios in the integration of a WtE facility with a carbon capture unit shows some advantages for the greenfield, mainly related to the possibility to face more easily some challenges like the spatial integration, the optimized and ad-hoc design of flue gas cleaning, the work out of strategies for energy integration with the boundaries, Steam Turbine design and operating philosophy in relation to the significant steam export to the CO_2 capture.

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TASK 1.1 - REVIEW OF WTE PLANTS

1. Introduction

Waste management is a very scattered and complex system made up by different plants and facilities that treat / recover / dispose different types of waste (e.g. "municipal" or "special"), based on the policies adopted in each country and the available technologies.
According to the recent modification (Directive (EU) 2018/851 - EU, 2018) of the European Waste Framework Directive (WFD, 2008/98/EC), Municipal Solid Waste (MSW) is defined as:

- mixed waste and separately collected waste from households, including paper and cardboard, glass, metals, plastics, bio-waste, wood, textiles, packaging, waste electrical and electronic equipment, waste batteries and accumulators, and bulky waste, including mattresses and furniture;
- mixed waste and separately collected waste from other sources, where such waste is similar in nature and composition to waste from households.

On the other hand, the updated WFD defines as "special" all the wastes that cannot be classified as MSW, like the waste generated by large offices and commercial activities, as well as industries, agriculture, Construction & Demolition (C&D), mines, etc. As stated, industrial waste, commercial waste and extractive waste have extremely diversified compositions and volumes, depending on the economic and industrial structure of the single country.
The overall production of "special" waste in industrialized countries is significantly higher than that of MSW: for example, in the European Union, MSW is estimated to represent 7 - 10 % of the total waste generated (EU, 2018). This is mainly due to the relevant amounts of C&D waste, as well as, in certain countries, to the waste from mining activities or from the maintenance of woods and forests.

1.1 MSW focus

While the management of MSW is the result of public planning, the management of special waste is typically dispersed and depends, for a large extent, on the initiatives of waste producers and private waste management companies. As a result, plants for MSW recovery are relatively large plants equipped with energy recovery facilities, whereas special waste is often incinerated in medium-small plants that feature energy recovery only in very limited cases[1].
Since very often these latter plants are not considered in detail in the official accounting of the individual states, the investigation presented in the next chapters focuses on MSW and plants

[1] For example, in Italy in 2017 the 40 operating WtE plants for MSW have treated 6.1 Mt of mixed waste, mainly MSW, whereas additional 1.5 Mt of special waste was incinerated in more than 150 other smaller facilities.

devoted to its treatment. However, even limiting the analysis to only WtE plant, several missing data had to be retrieved and the focuses on some selected countries are done by presenting data from sources referring to different years. The investigation on WtE plants and their characteristics started from the reports from the International Solid Waste Association (ISWA, 2013) and the Confederation of European Waste-to-Energy Plants (CEWEP, 2012), where quite comprehensive data on European countries were retrieved.
Nevertheless, many data on heat and electricity production were not updated or even missing, due to reluctance of plant owners/managers to disseminate data or to discrepancies among the different countries in accounting and processing such data. Where available, specific country reports were considered (e.g. Japan, UK, Italy) or even reports/datasheets from plant owners in case of poor or controversial data.

1.2 Country focus

A general overview of the framework of WtE plants worldwide is represented in Chapter 3, but the analysis focuses on a restricted group of countries that have been selected depending on several parameters, like:

- the geographical zone and the urbanization level;
- the branching of the electricity/heat network;
- the presence of large scale WtE plants;
- the type of waste incinerated and the type of energy recovery;
- the potential for CCS/CCU applied to WtE plants;
- the availability of potential destinations for the captured CO_2.

As a result, 10 significant countries have been selected to represent the possible trends worldwide in terms of energy recovery from waste and CCS/CCU potential. The selected countries, from the five continents, are:

- Africa: South Africa;
- America: USA;
- Asia: India, Japan;
- Europe: Germany, Italy, The Netherlands, Norway, UK;
- Oceania: Australia.

Despite the only WtE plant operating in Africa is located in Ethiopia, South Africa has been selected because of the higher level of urbanization and the more effective electricity grid.
Among the countries of the American continent, USA is the reference nation in terms of installed WtE plants and the one with the greater potential for enhancements also regarding CCS/CCU.
Japan and India are two opposite cases in Asia, with the former representing a pioneer country in waste incineration and CO_2 capture from WtE, while the latter can be considered an arising country for WtE diffusion on large scale.

Regarding Europe, several countries have been selected because there are significant differences between North-Western countries like The Netherlands and Norway, where most of the WtE plants produce both heat and electricity, and South Europe countries like Italy, where often the energy output of WtE is only electricity.

Australia has been chosen as a focus country for Oceania because there are several ongoing projects of WtE facilities and, as a growing country, potential applications in the future.

2. Global MSW production and composition

The production of MSW is strictly related to the economic development, the industrialization level and the local climate (World Bank, 2018). Countries with higher GDP tend to produce greater amounts of waste as levels of consumerism are higher. Even the level of urbanization plays a key role, since urban population generates twice the amount of waste produced by its rural counterpart.
Municipal Solid Waste generated worldwide is estimated to be approximately 2.02 billion tons[2] (year 2016): the lowest productions are recorded for the Middle East and North Africa Region (129 million tons), while the highest values are noted in the East Asia and Pacific Region (468 million tons). Values for the different regions are shown in Figure 1.
The average generation per capita settles on 0.74 kg of waste per day, with the lowest values recorded for the Sub-Saharan Region (0.46 kg/capita/day) and the highest values noted in the North American Region (2.21 kg/capita/day). Values for the different regions are shown in Figure 2.

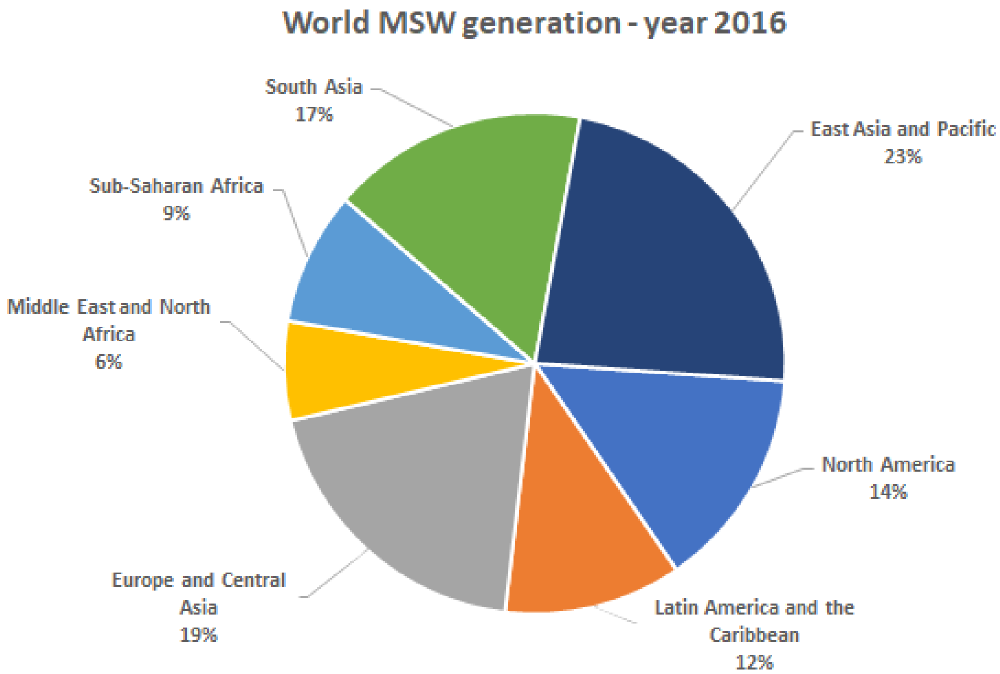

Figure 1: Municipal Solid Waste production worldwide (year 2016, data from World Bank, 2019)

[2] Throughout the whole report, mass amounts are reported in metric tons: 1 [t] = 1000 [kg].

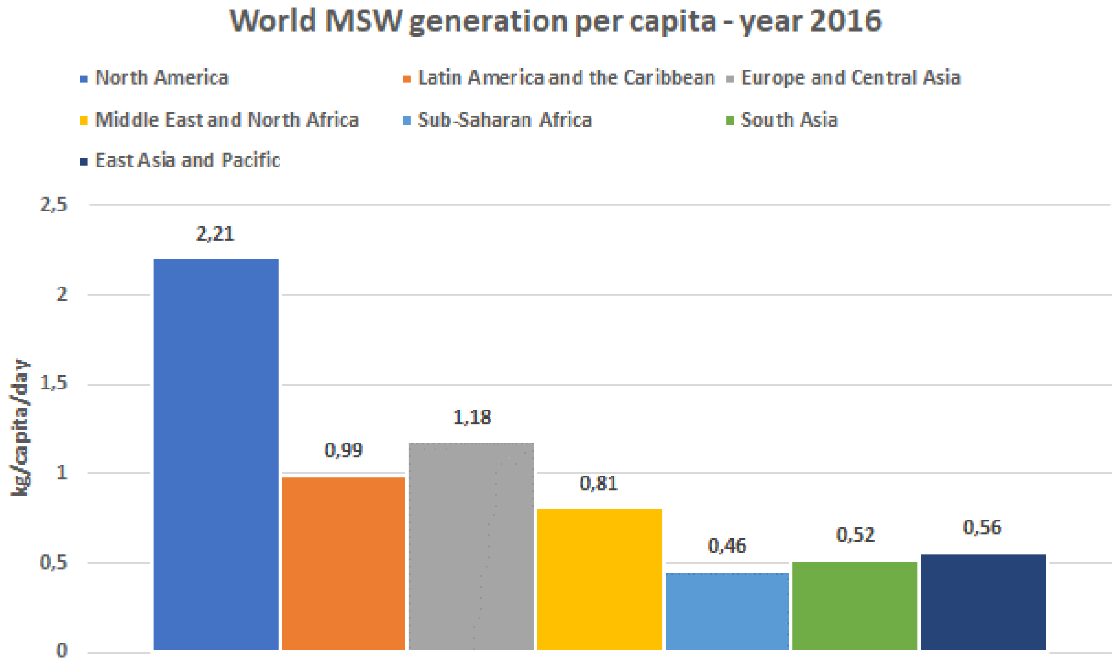

Figure 2: Municipal Solid Waste production per capita worldwide (year 2016, data from World Bank, 2019)

Projections on MSW generation worldwide, linked to the evolution of the Gross Domestic Product per capita throughout the years, lead to an increase to 2.59 billion tons by 2030 and to approximately 3.4 billion tons by 2050 (Figure 3).

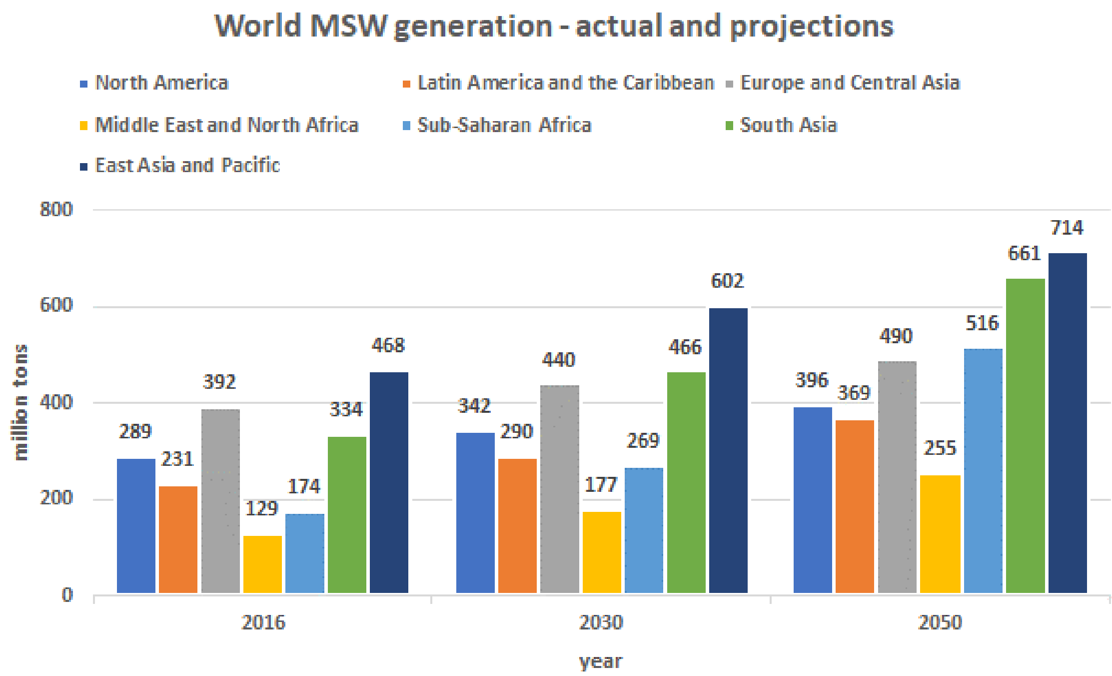

Figure 3: Municipal Solid Waste production worldwide - actual and projections (data from World Bank, 2019)

Figure 4 shows the average composition of MSW worldwide (data from World Bank, 2018): the main contributions are given by food and green (44%), paper and cardboard (17%) and other/plastics (14% and 12%). Typically, the higher the income level of the Region, the lower the percentage of organic matter. Moreover, the high rate of food and green is related to food loss and waste (1.3 billion tons per year according to the Food and Agriculture Organization of the United Nations).

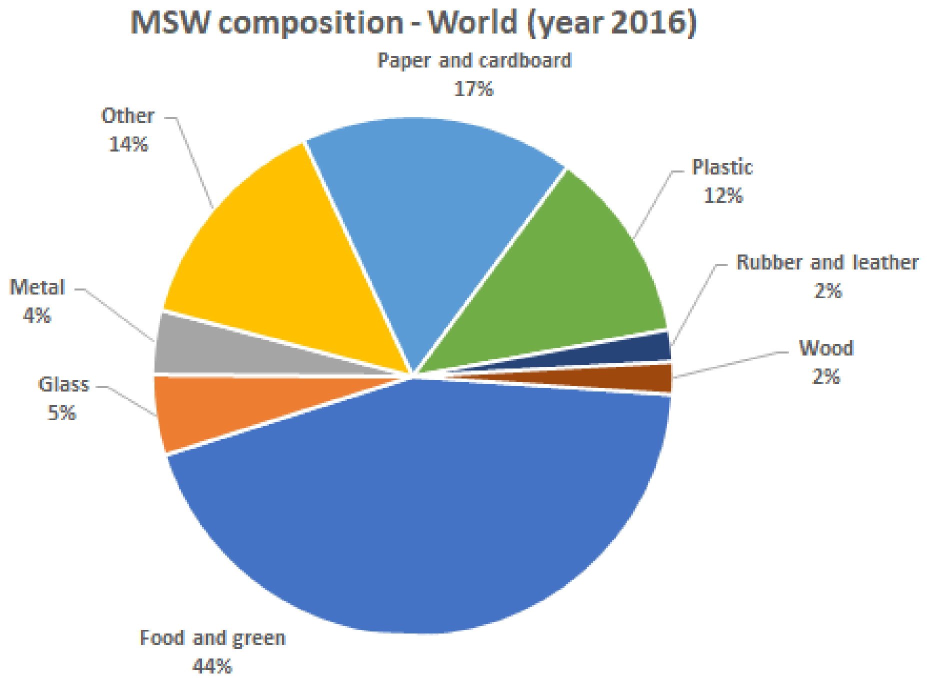

Figure 4: Municipal Solid Waste composition worldwide (year 2016, data from World Bank, 2019)

3. Global WtE framework

The diffusion of WtE plants in the world encompass the presence of around 2,100 facilities in 42 countries. They have a treatment capacity of around 360 million tons of waste per year. Asia and Europe lead the way with respectively more than 1,500 and 490 plants in operation in 2018 (Table 3-1).

Region	Number of plants
Africa	1
America	92
Asia	1,503
Europe	492
Oceania	1
TOT.	**2,090**

Table 3-1: Number of WtE plants worldwide (source Geosyntec and Deltaway Energy, 2018)

3.1 Africa

Only one WtE plant is reported to be active, located in Ethiopia (Addis Ababa). A biogas-from-waste facility has been built in South Africa (Cape Town).

3.2 America

All the WtE plants are located in North America (USA and Canada). No WtE facilities in South America, apart from an ongoing project of a 14 MW_E WtE in Brazil.

3.3 Asia

Japan and China lead the way with respectively more than 1,100 and 250 plants. Most of Japan facilities are incineration-only. It is important to underline that in Japan there are many incineration plants of small capacity scattered all around the country that together bring to that high number of plants for all Asia. This distributed development is due to historical decisions taken in Japan.

Another Asian country with a significant presence of WtE facility is South Korea (35 plants), whereas several plants have been built in different countries (e.g. Baku in Azerbaijan, Ladang Tanah Merahin in Malaysia) and a number of WtE projects are ongoing in Middle East (e.g. UAE), Russia, Indonesia, Thailand, etc.

3.4 Europe

Around 492 WtE plants are currently working in Europe (year 2017) for a total amount of incinerated waste of approximately 96 million tons. The majority of them are located in Germany, France, Italy and the UK.

3.5 Oceania

Currently no WtE plant results to be in operation. The construction of a 36 MW_E facility in Kwinana is ongoing.

4. Country focus

For each selected country, an analysis of waste generation and treatment has been carried out, focusing on Municipal Solid Waste, followed by an examination of the WtE framework (number of plants, amount of waste treated, installed capacity, electricity/heat production).
For the countries with more than 20 WtE plants, some examples have been reported, relating to the most significant plants in terms of size and characteristics.

4.1 South Africa

According to Department of Environmental Affairs (DEA) of the Republic of South Africa, South Africa generated approximately 108 million tons of waste in 2011, of which 49 million tons was general waste, 1 million tons was hazardous waste and the remaining 58 million tons was unclassified waste (Figure 5).

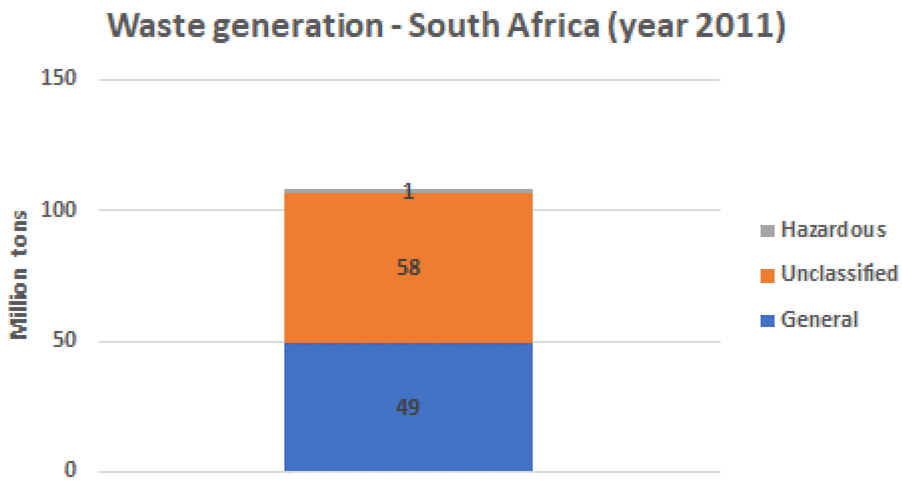

Figure 5: Waste generation in South Africa (year 2011 - data from DEA, 2011)

Considering data for 2012, the overall general waste composition (Figure 6) is made up by non-recyclable municipal waste (35%), followed by construction and demolition waste (20%), metals (13%), organic waste (13%), paper (8%), plastic (6%), glass (4%) and tires (1%).

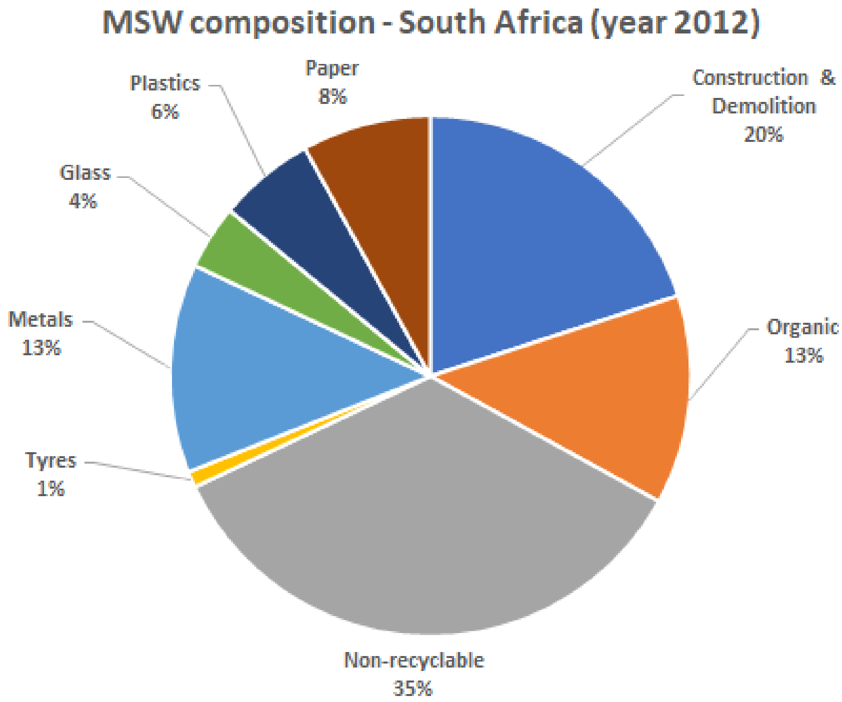

Figure 6: MSW composition for South Africa (year 2011 - data from DEA, 2012)

4.1.1 *Waste management*

Waste management services rely heavily on landfills for the disposal of waste. In 2011, 90% of all South Africa's waste was disposed into landfill sites, whereas the remaining 10% was recycled. In 2012, There were many landfill sites that were operating without license (Table 4-1), resulting in poor levels of operation and negative impacts on the environment.

Facility	Number of plants	Number of licenced plants
General waste landfill site	1,203	432
Hazardous waste landfill site	77	86
Healthcare risk waste storage facility	25	25
Recycling facility	9	44
Transfer station	35	88
TOT.	**1,336**	**675**

Table 4-1: Waste disposal facilities in South Africa (year 2012 - data from DEA, 2012)

4.1.2 WtE plants

No conventional WtE plants for MSW treatment are active in South Africa by now. In 2012, there were, however, 11 licensed treatment facilities for waste from public and private health care institutions, providing an annual treatment capacity of approximately 56,400 t/y. Some of such facilities were incineration plants, as shown in Table 4-2.

Licenced technology	Treatment capacity (t/month, theoretical)
Incineration	1,660
Non-combustion	3,084
TOT.	**4,744**

Table 4-2: Waste treatment facilities in South Africa (year 2012 - data from DEA, 2012)

In 2019 the first energy recovery plant in South Africa has been installed in the neighborhood of the city of Cape Town. The Afrox/New Horizons Energy complex is made up by two treatment section, one Mechanical Biological Treatment (MBT) and one Anaerobic Digestion (AD) coupled with an upgrading section for the biogas-to-biomethane conversion. The AD section will treat 500 t/day of organic waste from the City of Cape Town and will generate 760 Nm^3/hr of bio compressed natural gas (250 bar, compressed gas trailers), 18 t/day of carbon dioxide (24bar, -17 deg C for dry ice makers, industrial cleaning and refrigeration) and 100 t/day of organic fertilizer.

4.1.3 WtE potential

The WtE potential of the country is related to the implementation of the waste management hierarchy (art. 4 of WFD), which leads, as first step for a sustainable waste management treatment, to avoid dump sites. In 2011, the Department of Environmental Affairs of the Republic of South Africa issued the National Waste Management Strategy document, which is based on the following principles:

- providing a methodology for the classification of waste and standards for the assessment and disposal of waste for landfill disposal;
- implementing baseline regulatory standards for managing waste at each stage of the waste management hierarchy;
- identifying categories of waste that require special waste management measures due to the risks of these wastes to human health and the environment.

4.2 United States of America

According to the USA Environmental Protection Agency (EPA), the MSW generation in the country reached 262.4 million tons in 2015 and a specific production of 2.03 kg per capita per day.

However, it is fundamental to underline that the methodology adopted by the USA EPA for the evaluation of the MSW generation cannot be easily comparable with other countries. Europe (Eurostat) applies a "site-specific" methodology, which is a direct approach that relies on the measurement of MSW collected at waste treatment facilities. The USA EPA instead applies a materials flow methodology (indirect approach) where MSW amounts are not measured directly but they are calculated based on industry production data. The calculation hence for MSW generation in the USA is quite complex and it could contain estimations and missing gaps. Moreover, the US EPA and Eurostat define MSW treatment categories differently, so the full comparison of MSW statistics could become very critical.

The composition of US MSW is reported in Figure 7: the main contribution is given by paper and cardboard (26%), followed by organic waste (15%) and plastics (13%). Given the shares of the different fractions, the LHV is expected to be around 10 MJ/kg.

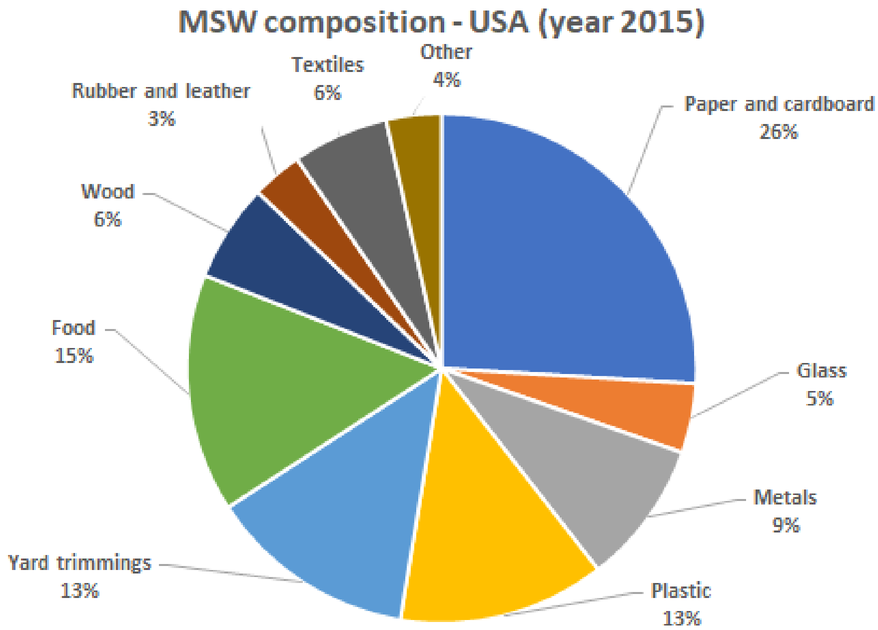

Figure 7: MSW composition for USA (year 2015 - data from US EPA, 2018)

4.2.1 *Waste management*

Figure 8 shows the breakdown of MSW management into the different treatment / disposal options, based on year 2015 data from US EPA.

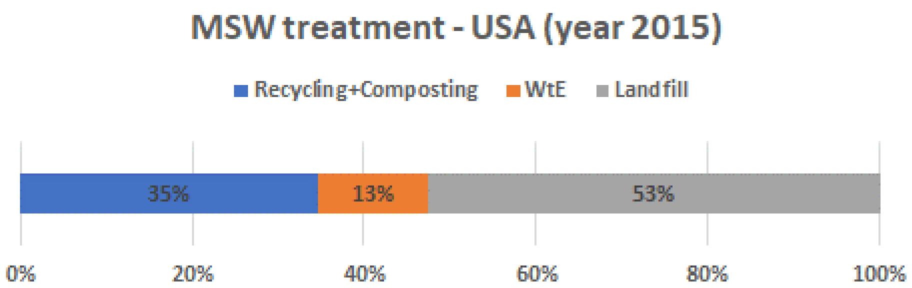

Figure 8: MSW treatment overview in USA (year 2015, data from US EPA, 2018)

Due to the large amount of free land, landfill disposal has been and still is the most used method for waste management at the expense of material and energy recovery.

4.2.2 *WtE plants*

According to the 2016 Directory of Waste-to-Energy facilities, 7877 WtE plants were operating in the country, located in only 22 out of the 50 States, with Florida and New York leading the way with 11 and 10 facilities respectively.
The total amount of waste treated is approximately 27.8 million tons per year, for an average plant capacity of 357,200 t/y.
60 WtE plants, out of 77, are grate furnace plants and they are fed with MSW or MSW+industrial waste or sewage sludges. The other 13 plants out of 77, such as the ones in Hartford, West Palm Beach, Ames, Orrington, West Wareham, Detroit, Red Wing, Portsmouth Virginia, LaCrosse, Mankato, Honolulu, are fed instead with Refuse Derived Fuel (RDF). The 4 WtE plans left are considered modular, meaning that they can be moved from site to site. Modular systems burn unprocessed, mixed MSW but they differ from mass burn facilities in that they are much smaller and portable.
The typical output of US WtE plants is electricity only to the grid (59 plants), with the combined production of heat and power limited to 15 facilities and the heat-only production (i.e. steam export) limited to 3 plants.
The total amount of electricity production reached 20,850 GWh/y in 2016, with an installed Gross Electric Capacity higher than 2,500 MW_E and with an installed Equivalent CHP Capacity higher than 2,700 MW_T.
The characteristics of some of the most interesting plants are shown below.

- *Reference plant: Palm Beach Renewable Energy Facility (PBREF) No.2*
  - Location: West Palm Beach (Florida)
  - Ownership: Solid Waste Authority of Palm Beach County
  - Start-up: July 2015
  - Daily capacity: 3 process lines (1000 ton/day each)
  - Annual capacity: 1,000,000 ton/year
  - Fuel: Unprocessed MSW
  - Technology: B&W Volund DynaGrate traveling grates
  - Electrical gross power output: 95 MW_E

  Data source: ERC, 2016, Babcock & Wilcox

- *Reference plant: H-POWER (Honolulu Resource Recovery Venture) WtE Plant*
  - Location: Kapolei (Hawaii State, Oahu Island)
  - Number of Lines: 3
  - Fuel: RDF (line 1-2), MSW and sludges (line 3)
  - Capacity: 3,000 t/day
  - Electrical power output: 59 + 32 MW_E
  - Electrical production: 513’000 MWh/y
  - Technology: CE traveling grates (line 1-2), reverse-reciprocating grate (line 3)

  Data source: ERC, 2016, Covanta

4.2.3 WtE potential

The MSW landfill disposal ratio in the US is still today quite significant (53%), with 28 out of the 50 states still without WtE plants. Henceforth there is a huge potential for energy from waste enhancement. The proper application of the waste management hierarchy that requires waste diversion from landfills is possible only in the presence of an adequate WtE capacity.

4.3 India

As there are no reliable estimates of municipal solid waste generation in India, all the alternative estimations made by different subjects through the years have been presented in Table 4-3. The latest available official estimates of MSW generation from the Central Pollution Control Board and the Ministry of Urban Development, Government of India are for 2014-15 and they place annual generation of MSW at 52 million tons. The Report of the Task Force on Waste to Energy of the Planning Commission in 2014 estimates MSW generation at 62 million tons in 2013-14. Assuming urban population of 440 million in 2017 (based on projections from United Nations population estimates) and per capita daily waste generation of 0.45 kg, the MSW generated for 2017 comes to 72 million tons. If the assumption with respect to per capita daily waste generation is lowered to 0.4 kg, the estimate of MSW generated for 2017 is lower, i.e., below

64 million tons. This does not include electronic waste which is estimated at close to 2 million tons in 2017 and a major unknown, i.e., Construction and Demolition waste for which the estimates range from a mere 10 million tons per annum to an enormously larger volume of 520 million tons per annum, with someone suggesting that C&D waste is about 30% of the total waste.

Year	Source	Annual Generation (million tons)
2017	**Our estimate 1** based on 0.45 kg per capita daily generation and urban population of 440 million*	72
2017	**Our estimate 2** based on 0.40 kg per capita daily generation and urban population of 440 million*	64
2014-15	**Central Pollution Control Board**	52
2014-15	**Ministry of Urban Development**	52
2013-14	**Task Force on Waste to Energy, Planning Commission**	62
**Based on projections from United Nations estimates*		

Table 4-3: Alternative estimates for MSW generation in India, *Source: Central Pollution Control Board, Ministry of Urban Development, and Planning Commission elaborated by the INDIAN COUNCIL FOR RESEARCH ON INTERNATIONAL ECONOMIC RELATIONS*

In conclusion there is still a high variability in the Indian MSW generation that can be estimated in a wide range between 50 and 70 million tons per year.

Concerning the average Indian MSW composition, some data have been retrieved from CPCB (Figure 9): the main contribution is given by compostable matter (42%), followed by inert (40%) and paper (6%). Given the shares of the different fractions, CPCB estimated an average LHV value around 7.3 MJ/kg. It is important to underline that these data must be considered relatively reliable as well.

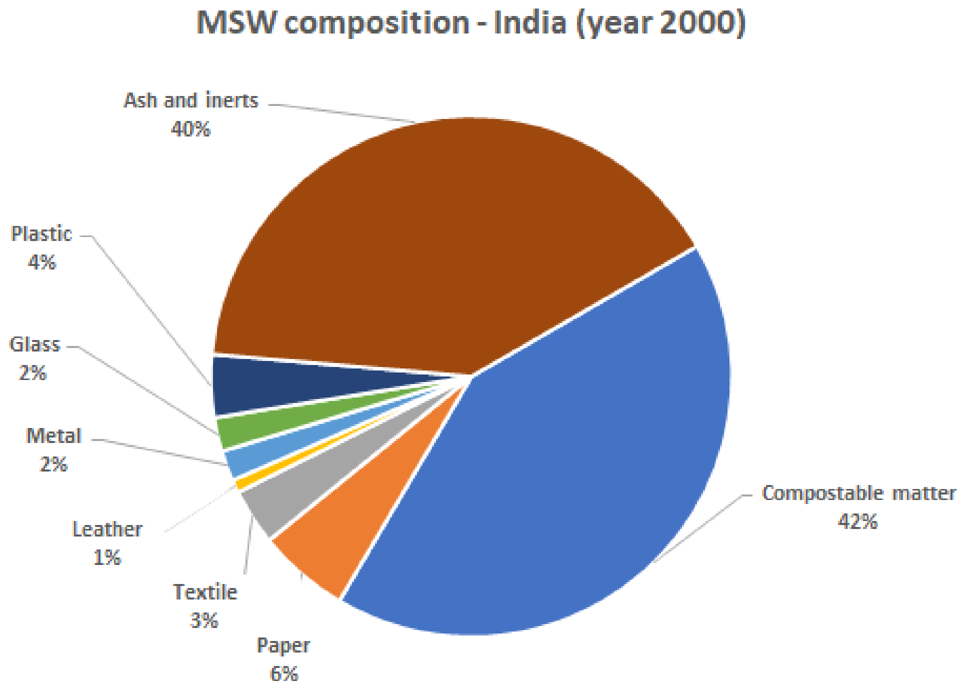

Figure 9: MSW composition in India (year 2010 - data from Central Pollution Control Board, 2000)

4.3.1 *Waste management*

Based on the information available for the year 2012 by the Central Pollution Control Board (CPCB), municipal authorities have set up so far in the country only 279 compost plants, 172 bio-methanation plants, 29 RDF production plants (such as Mechanical-Biological Treatment - MBT - plants) and 8 Waste-to-Energy plants that mainly burn RDF. However, it is also reported that many of the overall facilities above are not even working. In any case the current most severe fact is that these facilities allow to treat only the 19% of the total production of MSW, while the remaining 81% is disposed indiscriminately at dump yards in an unhygienic manner by the municipal authorities leading to problems of health and environmental degradation. (Figure 10).

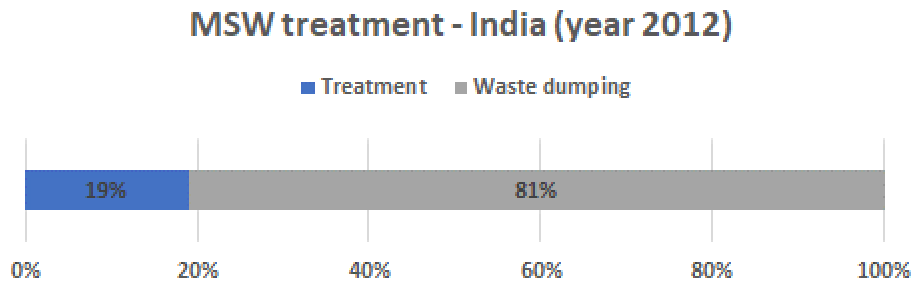

Figure 10: MSW treatment overview in India (year 2012, data from Central Pollution Control Board, 2012)

According to the final Draft Background paper *"A 21st Century Vision on Waste to Energy in India"* (May 2018), India currently suffers an alarming landfill urgency: assuming a current 62 million tons annual generation of MSW that continues to be dumped without treatment, it will need 3,40,000 cubic meter of landfill space every day. Considering the projected waste generation of 165 million tons by 2031, the requirement of land for setting up landfill for 20 years could be as high as 66,000 hectares of precious land (considering 10-meter-high waste piles).

4.3.2 WtE plants

Only 8 WtE plants are operating in the country (2 in the province of Maharashtra, 3 in the province of New Delhi, 1 in Madhya Pradesh and 1 in Himachal Pradesh). The total installed capacity is equal to 94.1 MW_E.
The main features of some of the most interesting plants are shown below.

- *Reference plants: Timarpur Okhla WtE Plant*
  - Location: Okhla, South Delhi
  - Constructor: OP Jindal Group
  - Operator: TIMARPUR-OKHLA Waste Management Company Pvt Ltd's
  - Daily capacity: 1,350 t/day (RDF)
  - Rated power: 16 MW_E
  - Year of commissioning: 2012

  Data source: OP Jindal Group

- *Reference plants: Ghazipur WtE Plant*
- Location: Ghazipur, East Delhi
- Constructor: IL&FS Environment
- Operator: East Delhi Municipal Corporation (EDMC)
- Daily capacity: 1,200 t/day (RDF)

- Rated power: 12 MW_E
- Year of commissioning: 2016

Data source: IL&FS Environment

- *Reference plants: Ramky WtE Plant*
  - Location: Narela-Bawana, East Delhi
  - Constructor: Ramky Enviro Engineers Limited (REEL)
  - Daily capacity: 1,200 t/day
  - Rated power: 24 MW_E
  - Year of commissioning: 2017

Data source: Ramky Enviro Engineers Limited

- *Reference plants: Essel Jabalpur WtE Plant*
  - Location: Jabalpur, Madhya Pradesh
  - Operator: Essel Infraprojects Ltd.
  - Daily capacity: 660 t/day
  - Technology: Stoker-type incinerator (Hitachi Zosen)
  - Rated power: 11.5 MW_E
  - Year of commissioning: 2016

Data source: Essel Infraprojects Ltd.

4.3.3 WtE potential

According to the Task Force on Waste to Energy of the Planning Commissioning of the Government of India, in a foreseeable future of 5-7 years the non-recovered waste has a potential of generating 440 MW_E of power from 32,890 ton/day of combustible wastes including Refuse Derived Fuel (RDF), 1.3 million cubic meters of biogas per day or 72 MW_E of power capacity from biogas and 5.4 million metric tons of compost annually to support agriculture. The potential for new WtE installations is hence significantly important and in a longer projection (2050) it has been estimated that the number of energy recovery facilities can increase up to 2,780 MW_E in terms of electric capacity.

Finally, according to the final Draft Background paper *"A 21st Century Vision on Waste to Energy in India"* (May 2018), around 50 WtE projects have been left incomplete through the years, held up at different stages or stranded for a variety of reasons (legal complications, lack of financial support from banks, non-availability of land, etc.). A quick completion of these 50 WtE projects, which have already been initiated, could help many cities and towns to tackle effectively the waste issue (the full list of these plants is available in the cited report).

4.4 Japan

Based on the data from the Japanese Ministry of the Environment, the national production of MSW hit 44 million tons in 2014, as shown in Figure 11.

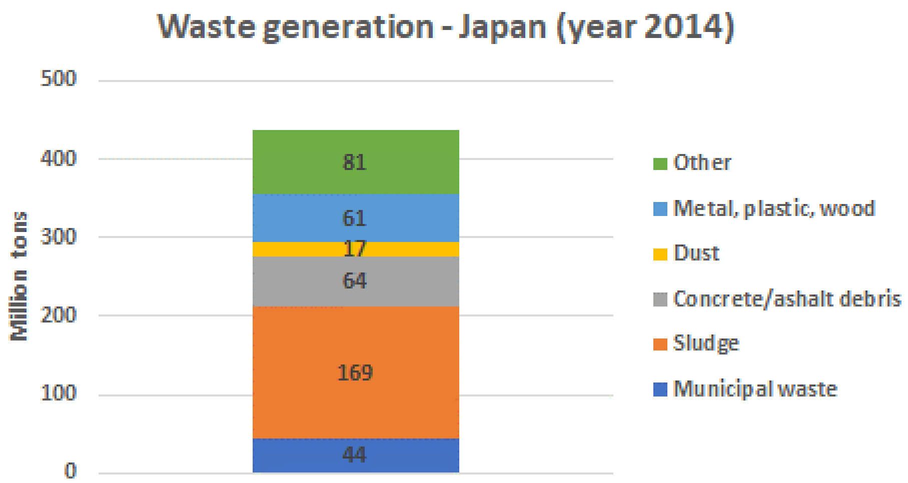

Figure 11: Waste generation in Japan (year 2015 - LEAP processing data from the Japanese Ministry of the Environment, 2017)

A composition of the Municipal Solid Waste generated in the municipality of Kyoto have been retrieved from literature (Source: Asia Biomass Energy Cooperation Promotion Office) and, given the shares of the different fractions, the LHV is expected to be around 10 MJ/kg. The main contribution is given by organic waste (36%), followed by paper and cardboard (30%) and plastics (11%).

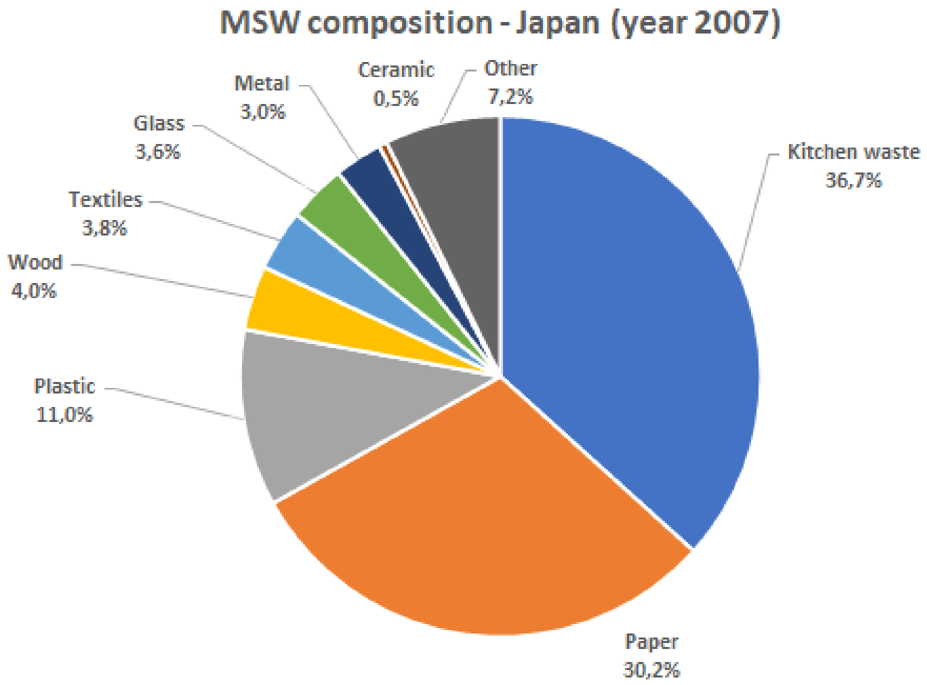

Figure 12: MSW composition for Japan (year 2007 - data from Asian Biomass, 2007)

4.4.1 Waste management

Figure 13 shows the breakdown of MSW management into the different treatment / disposal options, based on data from the World Bank for the year 2015.

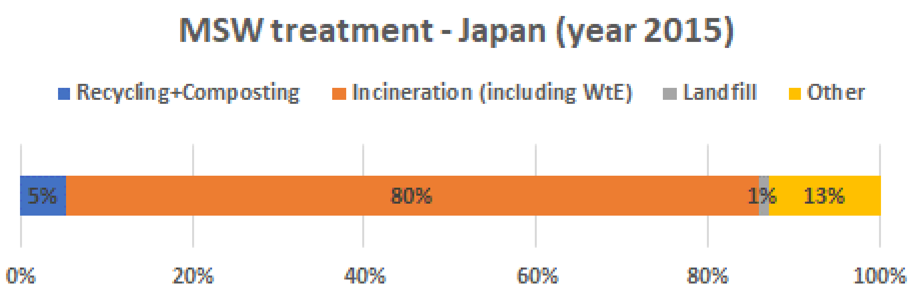

Figure 13: MSW treatment overview in Japan (year 2015, data from World Bank, 2019)

Due to the lack of free land for waste disposal and the obligations to treat waste locally, the primary objectives of waste incineration in Japan has always been the volume reduction and the ease of the disposal process. Japan has historically been a pioneer of waste incineration, resulting in many small-scale disposal-only plants for the use of individual municipalities.

As a consequence of the peculiar history of Japan, incineration (including WtE) rate is the highest in the world, being around 80%.
However, although the modernization of installations has improved energy recovery from MSW incineration and modern Waste-to-Energy plants are now incentivized to recover energy on a larger scale, Japan is still very far from European’s records.
As a matter of fact, 64-67% of Japanese incineration facilities have a heat recovery system, which has been a percentage almost constant in the last ten years. More specifically, in 2013, there were in the country 778 plants recovering residual heat, but only 328 of them (28.0%) were equipped with power generation facilities.
In 2015, a slight increase through the years has been registered with approximately 350 facilities equipped with power generation as well.

4.4.2 WtE plants

With regard to 2015, 1,141 waste incineration plants are operating in the country, evenly located across the Japanese territory.
The total amount of waste treated is approximately 181,899 t/day, for an average plant capacity of 159.4 t/day.
Table 4-4 shows the outline of the different thermal processes used in Japanese waste incineration plants. Of the 1’141 facilities in operation, 89% are incineration plants, and 9% (103 plants) are gasification plants.

WtE facilities	Number of plants	Number [%]	Capacity [t/day]	Capacity [%]
Incineration	1,020	89%	161,140	88.6%
Gasification & Melting	103	9%	19,412	10.7%
Carbonization	5	0.4%	206	0.1%
Other	13	1.1%	1,141	0.6%
TOTAL	**1,141**	**100%**	**181,899**	**100%**

Table 4-4: Main features of WtE plants in Japan (year 2015 - data from Takaoka, M. 2017)

As a matter of fact, Japan has been one of the few countries in the world that historically has developed a significant number of gasification facilities for waste treatment, mainly due to the potential benefits that may justify their adoption related to material recovery and operation/emission control such as recovery of metals in non-oxidized form, collection of ashes in inert-vitrified form and lower generation of some pollutants. With a focus on the Japanese slagging gasification technologies, the 6 leading companies, that in 2013 as reference year, have licensed, developed and constructed gasification plants in Japan are Nippon Steel (as largest supplier), Kobelco-Eco, JFE, Hitachi Zosen, Ebara, Mitsui Engineering & Shipbuilding. One of the main gasification-based technologies adopted in Japan is the Direct Melting System (DMS) offered by the Nippon Steel and implemented for example in the Shin-Moji WtE plant, one of the largest waste gasification and ash melting plants in the world.

However, combustion remains the most predominant way of WtE and Table 4-5 shows the outline of the different technologies installed in combustion-type waste incineration plants. Among the different technologies installed in these plants, grate combustors lead the way (71% in number) followed by fluidized bed reactors (17% in number).

WtE facilities furnace type	Number of plants	Number [%]	Capacity [t/day]	Capacity [%]
Grate	814	71%	137,046	75%
Fluidized bed	197	17%	29,652	16%
Fixed bed	31	2.7%	212	0.1%
Other (includes Shaft type)	99	8.7%	14,982	8%
TOTAL	**1,141**	**100%**	**181,892**	**100%**

Table 4-5: Main features of furnace type WtE plants in Japan (year 2015 - data from Takaoka, M. 2017)

The characteristics of some of the most interesting plants are shown below.

- *Reference plant: New Suginami WtE Plant*
- Location: Suginami, Tokyo
- Operator: Clean Authority of Tokyo
- Daily capacity: 600 t/day = 300 t/day x 2 units
- Annual Capacity: 220,000 ton/y
- Power: 24 MW_E
- Activity since: 2017
- Technology: Moving grate furnace (Hitachi Zosen)

Data source: Hitachi Zosen Corporation

- *Reference plant: Ota WtE Plant*
- Location: Keihinjima, Ota-ku, Tokyo
- Operator: Clean Authority of Tokyo
- Daily capacity: 600 t/day = 300 t/day x 2 units
- Annual Capacity: 220,000 ton/y
- Power: 22.8 MW_E (Design LHV: 14.8 MJ/kg)
- Activity since: 2014
- Technology: Stoker type incinerator with plasma melting of ash (Takuma SN)

Data source: Clean Authority of Tokyo

- *Reference plant: Maishima WtE Plant*
- Location: Konohana Ward, Osaka
- Operator: Osaka City Environment Bureau
- Daily capacity: 900 t/day = 450 t/day x 2 units
- Annual Capacity: 300’000 ton/y MSW
- Power: 32 MW_E
- Activity since: 2001
- Technology: Moving grate furnace (Hitachi Zosen)

Data source: Hitachi Zosen Corporation

- *Reference plant: Shin-Moji gasification WtE plant*
- Location: Kitakyushu City, Fukuoka Prefecture
- Daily capacity: 720 t/day = 240 t/day x 3 units
- Annual capacity: 216,000 ton/year
- Waste type: MSW (LHV 10.9 MJ/kg) + Sludge
- Gross Power: 23.5 MW_E
- Activity since: 2007
- Technology: Direct Melting System (DMS) Gasification process (Nippon Steel)

Data source: Nippon Steel Engineering

4.4.3 WtE potential

In 2009, the Japanese Ministry of the Environment made a subsidy system and a guidebook to promote the construction of incinerators for Municipal Solid Waste with high power generation efficiency. In the guidebook, various existing technological options and combinations were recommended to achieve more than 20% of power generation efficiency in MSW plants with a capacity of 500 ton/day. As a result, the power generation efficiency raised from 15.8% (weighted mean for years 2003-2007) to 20.2% in newly constructed facilities.
Although the modernization of installations has improved energy recovery from MSW incineration, Japan is still very far from European’s records: one of the reasons of the poor results is the small size of the facilities in Japan.
In addition, most of the heat cannot be used because of the lack of district heating infrastructure. In fact, central/district heating is not widespread as it is in Europe.

4.5 Germany

According to the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), the MSW generation in the country reached 52 million tons in 2015 (Figure 14, data from the Federal Statistical Office).

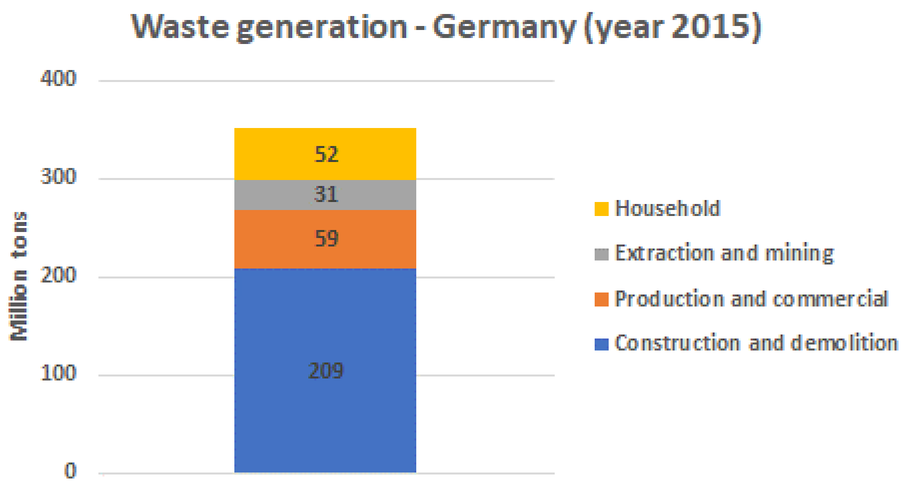

Figure 14: Waste generation in Germany (year 2015 - data from Federal Statistical Office, 2017)

Some data on MSW composition have been retrieved for the Hamburg district (Figure 15): the main contribution is given by organic waste (33%), followed by paper and cardboard (16,5%). Typical values for LHV of the residual waste range from 8.5 to 10 MJ/kg, while water and ash content are respectively 30% and 28%.

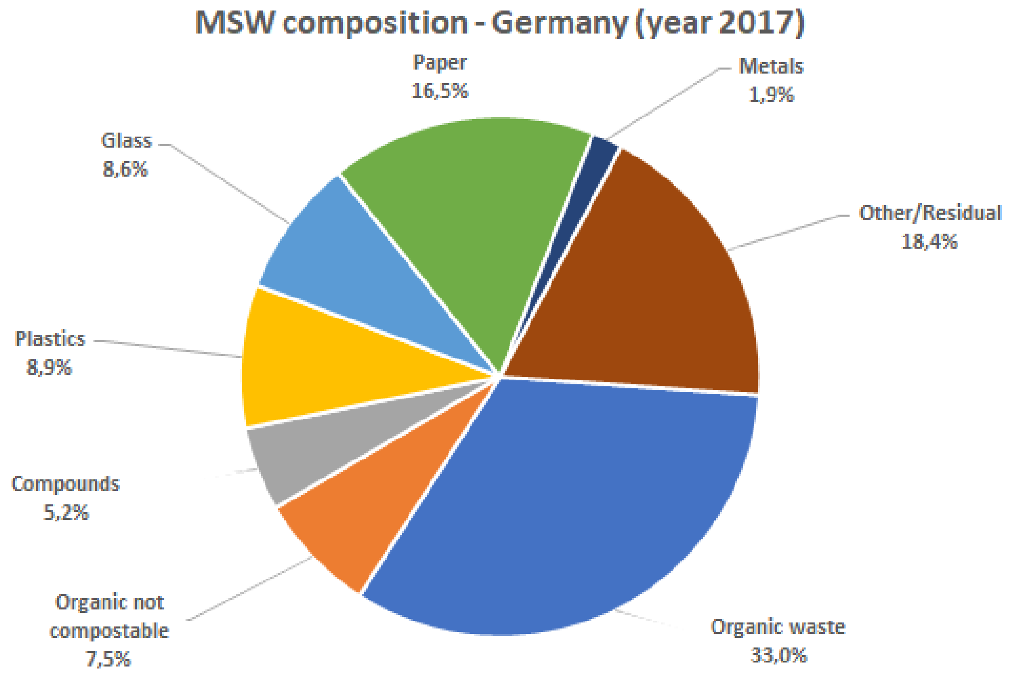

Figure 15: MSW composition for Germany (year 2013 - data from Stadtreinigung Hamburg, 2017)

4.5.1 *Waste management*

The share of recycling (including composting), Waste-to-Energy and landfilling of municipal waste in Germany is shown in Figure 16, based on year 2017 data from CEWEP.

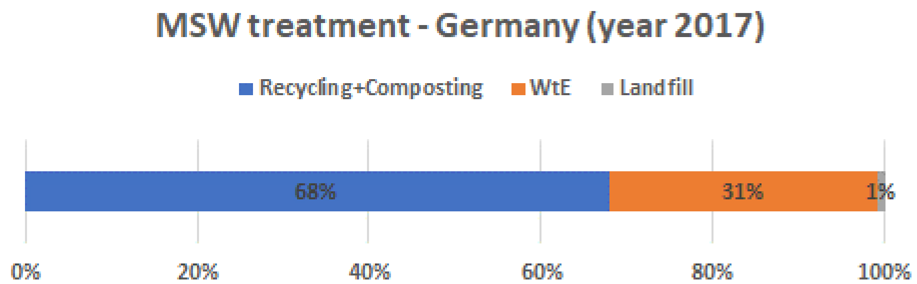

Figure 16: MSW treatment overview in Germany (year 2017, data from CEWEP, 2019)

Among the European countries, Germany is the one with the highest rate of recycling and composting (68%) and the one with the lowest rate for landfill disposal (1%). This brings to a good balance between material and energy recovery from waste.

4.5.2 WtE plants

According to ISWA and CEWEP, globally 81 WtE plants are operating in Germany, evenly distributed all over the country and with a major concentration in North Rhine–Westphalia.
The total amount of waste treated is approximately 22.6 million tons per year, for an average plant capacity of 305,000 t/y.
Most of the plant are fed with a mixture of MSW and commercial waste or sludge, and are grate-based, whereas a few plants uses only RDF in fluidized bed combustors.
The nominal LHV of the processed waste ranges from 8.5 to 12 MJ/kg for grate-based incinerators, from 14 to 18 MJ/kg for fluidized bed reactors.
The typical output of German WtE plants is the combination of electricity to the grid and heat for district heating.
The total amount of electricity production reached 5,768 GWh/y, with an installed electricity production capacity of 1,925 MW_E (2016).
Data on heat production are available for 40 plants, with a total amount of 11,800 GWh/y (2013).
The main features of some of the most interesting plants are shown below.

- *Reference plant: Mühlheizkraftwerk München Nord WtE Plant*
  - Location: Munich
  - Technology: Moving grate
  - Annual capacity: 680,000 t (rated capacity)
  - Electrical production: 131,514 MWh of electrical power (2013)
  - Heat production: 744,772 MWh of heat for district heating (2013)

  Data source: ISWA 2013, CEWEP 2015, AWM Munich

- *Reference plant: AVA Frankfurt Nordweststadt WtE Plant*
  - Location: Frankfurt
  - Number of Lines: 4
  - Fuel: Household Waste, Household-Type, Industrial Waste
  - Heating Value (min/max/nom): 8.0 / 14.0 / 11.3 MJ/kg
  - Fuel Throughput (min/max/nom): 12.0 / 22.0 / 20.0 t/h
  - Rated Thermal Input (each line): 62.8 MW
  - Steam Capacity (each line): 67.2 t/h
  - Steam conditions: 59.0 bar (g), 500 °C
  - Year of Commissioning: 2006 / 2008

Data source: Standardkessel Baumgarte

- *Reference plant: MHKW Ruhleben WtE Plant*
  - Location: Berlin (Ruhleben)
  - Number of Lines: 5 (1-4 + A)
  - Fuel: Household Waste
  - Heating value: 8,5–9,0 MJ/kg
  - Annual capacity: 520,000 t/y
  - Technology: Moving grate
  - Steam production: 1,114,000 t/y
  - Electrical production: 180,000 MWh
  - Heat production: 640,000 MWh (district heating)
  - Year of Commissioning: 1967 (line 1-4), 2012 (line A)

Data source: ISWA 2013 and CEWEP, 2015, BSR.de

4.5.3 WtE potential

As Germany imports some waste from UK, Norway and Ireland to full load its WtE plants, the ratio of landfill disposal is very limited (1%) and the thermal treatment rate is relevant (31%) no significant developments in the number of installed WtE plants or in the amount of waste treatment capacity are foreseen, even in the case of energy recovery of combustible discards from material recovery.

4.6 The Netherlands

Based on the data from Statistics Netherlands (CBS), the national production of municipal solid waste hit 9 million tons in 2016, as shown in Figure 17.

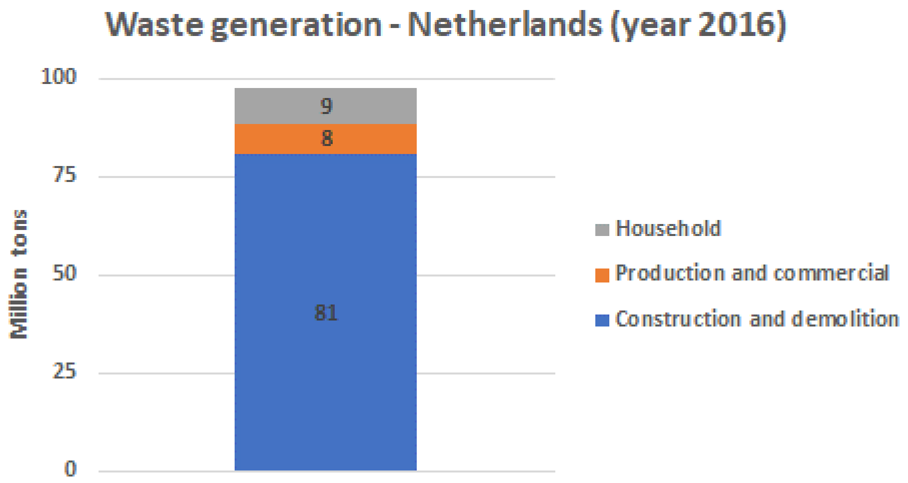

Figure 17: Waste generation in The Netherlands (year 2016 - data from Statistics Netherlands)

A MSW composition has been retrieved from literature (World Bank, 2012) and, given the shares of the different fractions, the LHV is expected to be around 10 MJ/kg. The main contribution is given by organic waste (36%), followed by paper and cardboard (28%) and plastics (14%).

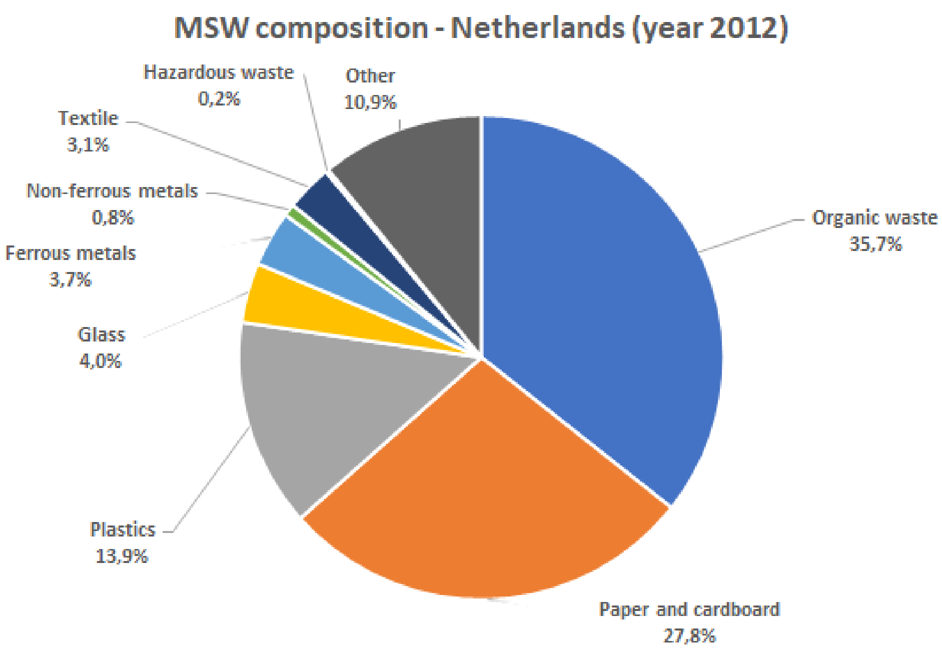

Figure 18: MSW composition for The Netherlands (year 2012 - data from World Bank, 2012)

4.6.1 Waste management

Figure 19 shows the breakdown of the different activities in MSW management, based on year 2017 data from CEWEP.

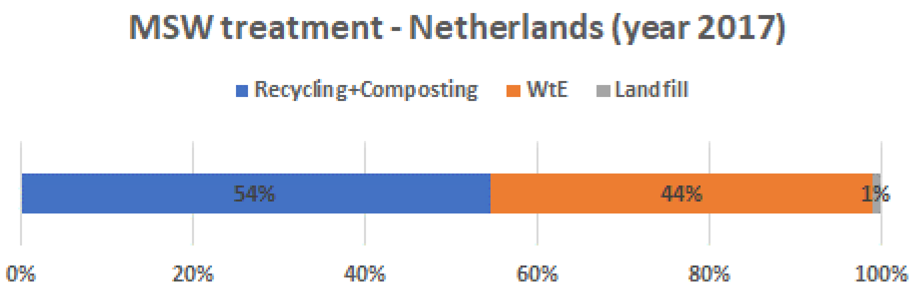

Figure 19: MSW treatment overview in The Netherlands (year 2017, data from CEWEP, 2019)

Like in Germany, the waste management system in The Netherlands is based on a good balance between material and energy recovery, with a small residual rate of landfill disposal (1%).

4.6.2 WtE plants

Globally 13 WtE plants are operating in the country. The plants are evenly distributed, with the biggest facilities located in the most urbanized Western part of the Netherlands.
The total amount of waste treated is approximately 7 million tons per year, for an average plant capacity of 540,000 t/y.
Most of the plants are fed with a mixture of MSW and industrial waste, and are grate-based, whereas only 2 plants (Beuningen, Midden-Drenthe) use RDF in fluidized bed combustors.
The nominal LHV of the treated waste ranges from 8.4 to 13 MJ/kg for grate-based plants, while it is approximately 14 MJ/kg for fluidized bed combustors.
The typical output of Dutch WtE plants is the combination of electricity to the grid and heat for district heating.
The total amount of electricity production reached 1,997 GWh/y in 2016, whereas data on heat production are available for 5 plants, with a total amount of 962 GWh/y (2013).
Table 4-6 shows the list of WtE plants installed and operating in the country.

Location	Operator	First year of operation	Combustion Technology	Plant size (t/y)	Waste Type
Amsterdam	AEB	1917	Grate combustion	1,400,000	MSW, industrial waste
Alkmaar	HVC Group	2005	Grate combustion	660,000	MSW, industrial waste
Rozenburg	Van Gansewinkel	1992	Grate combustion	1,300,000	MSW, industrial waste, sludges, biomass, other
Moerdijk	Attero	1997	Grate combustion	1,000,000	MSW, industrial waste
Hengelo	Twence BV	1997	Grate combustion	600,000	MSW, other
Midden-Drenthe	Attero	1996	Fluidized bed	625,000	RDF
Duiven	Van Gansewinkel	1990	Grate combustion	400,000	MSW, sludges
Beuningen	ARN B.V.	NA	Fluidized bed	267,620	RDF
Delfzijl	E.ON Energy from waste	2008	Grate combustion	275,000	NA
Dordrecht	HVC Group	1992	Grate combustion	189,413	MSW, other
Dordrecht	Zavin C.V.	1972	Grate combustion	7,648	Hazardous sanitary waste, Non Hazardous sanitary waste

Table 4-6: List of WtE plants in The Netherlands (year 2015 - data from ISWA, 2013 and CEWEP, 2015)

4.6.3 WtE potential

Through the years The Netherlands has achieved a significant thermal treatment rate. Moreover, like Germany, they import waste from the UK to full load their WtE plant fleet. For this reason, together with the very limited amount of landfill disposal, no significant developments in the WtE sector are foreseen in The Netherlands, in terms of number of plants and waste treatment capacity, even in the case of the possible recovery of combustible discards from the recycling sector.

4.7 Norway

According to Statistics Norway, the MSW generation in the country reached 2.42 million tons in 2017 (Figure 20).

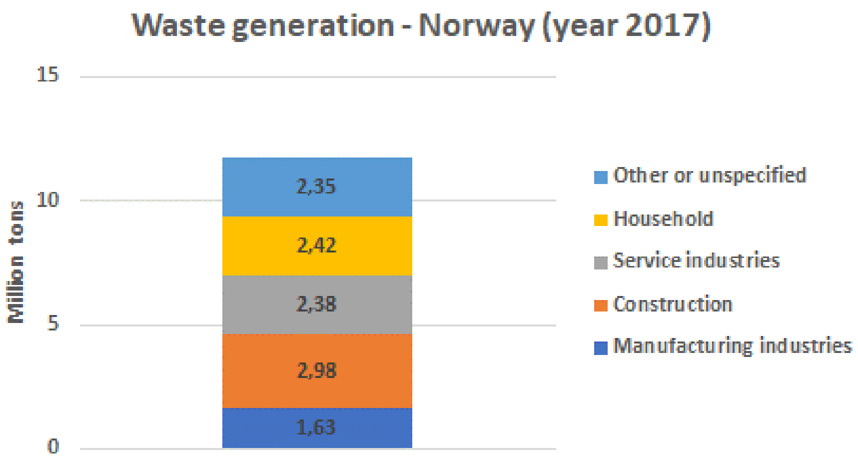

Figure 20: Waste generation in Norway (year 2017 - data from Statistics Norway, 2017)

Figure 21 shows the MSW composition that have been retrieved from literature (European Environmental Agency): the main contribution is given by paper and cardboard (27%), followed by wood (17%) and food/garden waste (15% each). Given the shares of the different fractions, the LHV is expected to be around 10 MJ/kg, whereas an estimation of the biogenic fraction of the residual waste is about 52% on energy basis (Avfall Norge, 2010).

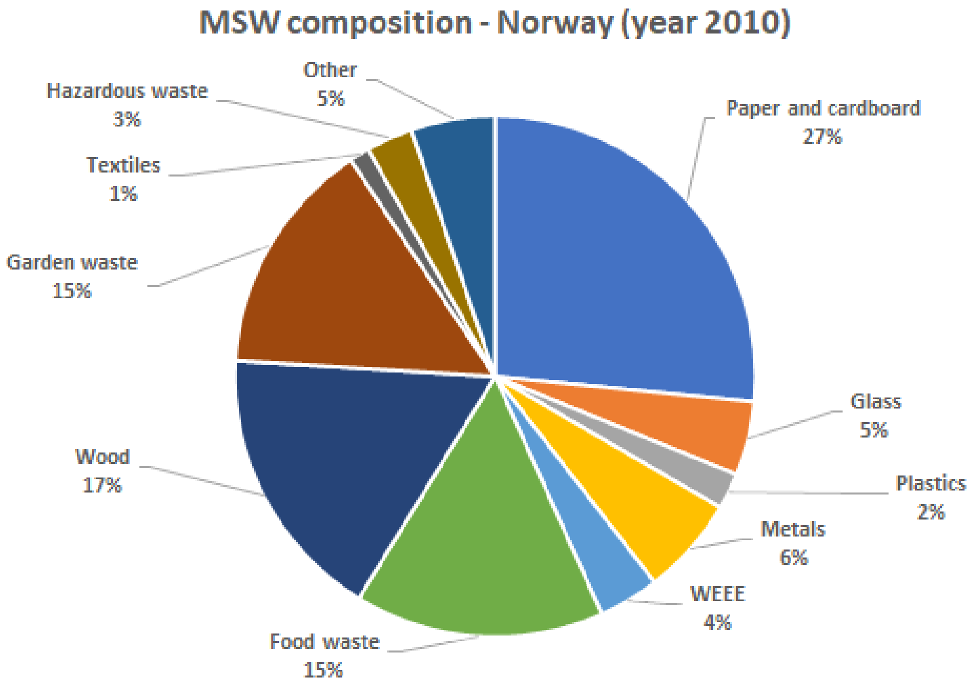

Figure 21: MSW composition for Norway (year 2010 - data from European Environmental Agency, 2013)

4.7.1 Waste management

The share of recycling (including composting), Waste-to-Energy and landfilling of municipal waste in Norway is shown in Figure 22, based on year 2017 data from CEWEP.

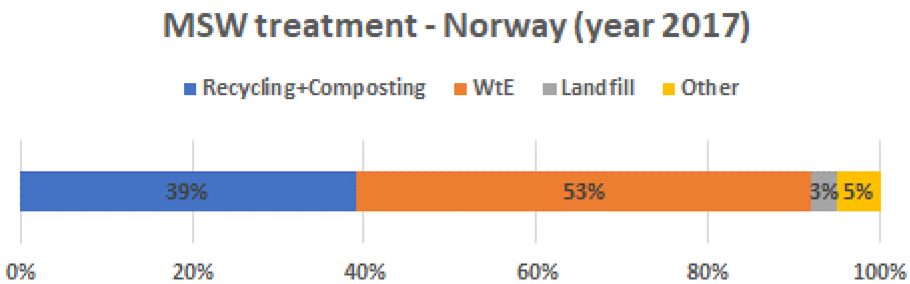

Figure 22: MSW treatment overview in Norway (year 2017, data from CEWEP, 2019)

Norway is one of the European countries (together with Finland, Sweden and Denmark) with the highest rate of thermal treatment (53%), which overcomes the recycling rate mainly because

WtE plants are massively exploited to supply heat for the district heating networks. Nevertheless, the overall result is a correct balance between material and energy recovery, ensuring almost zero use of landfilling.

4.7.2 WtE plants

Globally 17 WtE plants are operating in the country, most of them located in the major urban centers of the southern part of the country.
The total amount of waste treated is approximately 1.53 million tons per year, for an average capacity of 85,000 t/y.
Most of the plant are fed with a mixture of MSW and industrial or commercial waste and they are grate-based, whereas only 1 plant (in Oslo) uses RDF in a fluidized bed combustor.
The nominal LHV of the treated waste ranges from 10.5 to 12 MJ/kg for grate-based plants, whereas it is around 13 MJ/kg for the fluidized bed combustor.
The typical output of Norwegian WtE plants is heat for district heating, with the production of electricity limited to half of the facilities.
The total amount of electricity production reached 430 GWh/y in 2015 as a result of the average plant capacity of 61 MW_E, whereas the total heat production reached 3,800 GWh/y in 2015.
Table 4-7 shows the list of Norwegian WtE plants operating in the country.

Location	Combustion Technology	Plant size (t/y)	Waste Type
Averøy	Gasification	**30,000**	Mixed MSW, commercial waste
Bergen	Grate combustion	**210,000**	MSW, industrial waste
Finnsnes	Grate combustion	**11,000**	NA
Frederikstad	Grate combustion	**92,000**	MSW, commercial and industrial waste
Fredrikstad	Grate combustion	**50,000**	NA
Hamar	Grate combustion	**80,000**	NA
Kristiansand	Grate combustion	**130,000**	NA
Lenvik	Grate combustion	**5,050**	MSW, commercial and industrial waste
Oslo (Haraldrud)	Fluidized bed	**99,500**	MSW, industrial waste
Oslo (Klemetsrud)	Grate combustion	**148,694 (320,000)**	MSW, industrial waste
Rakkestad	Grate combustion	**10,000**	MSW, industrial waste

Sandnes	Grate combustion	**110000**	NA
Sarpsborg	Grate combustion	**78,000**	MSW, commercial waste
Trondheim	Grate combustion	**220,000**	NA
Tromso	Grate combustion	**55,000**	MSW and RDF
Ål	Grate combustion	**24,000**	NA
Alesund	Grate combustion	**100,000**	NA

Table 4-7: List of WtE plants in Norway (year 2015 - data from ISWA, 2013 and CEWEP, 2015)

4.7.3 WtE potential

Although Norway has an unexploited capacity for WtE, it exports waste to Sweden due to lower gate fees and significantly higher revenues from energy sales than the ones achieved by Norwegian WtE plants.
No significant developments in the number of installed WtE plants or waste treatment capacity are foreseen. The major cities in Norway (Oslo, Bergen, Trondheim and Stavanger) have already a well-developed infrastructure for district heating. The remaining district heating market is limited and only for small-scale applications. This makes difficult to build new WtE plants that can ensure the full utilization of the recovered energy.
Concerning RDF plants, a 2x15 MW_T facility is planned to be constructed in Ranheim (no electricity production, 8,000 hours/y of running time, total cost approximately 420 M€).

4.8 Italy

Based on the data from “Catasto Nazionale Rifiuti” managed by the “Istituto Superiore di Protezione e Ricerca Ambientale (ISPRA)”, the national production of MSW hit 29.6 million tons in 2017, as shown in Figure 23.

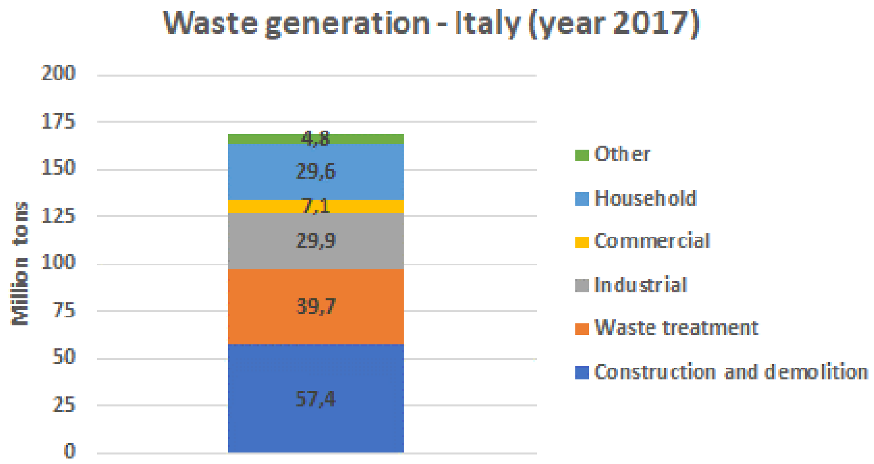

Figure 23: Waste generation in Italy (year 2017 – data elaboration by LEAP from ISPRA Report 2018)

Some data on MSW composition have been retrieved from ISPRA (Figure 24): the main contribution is given by organic waste (36%), followed by paper and cardboard (23%) and plastics (13%). Given the shares of the different fractions, the LHV is expected to be around 10 MJ/kg.

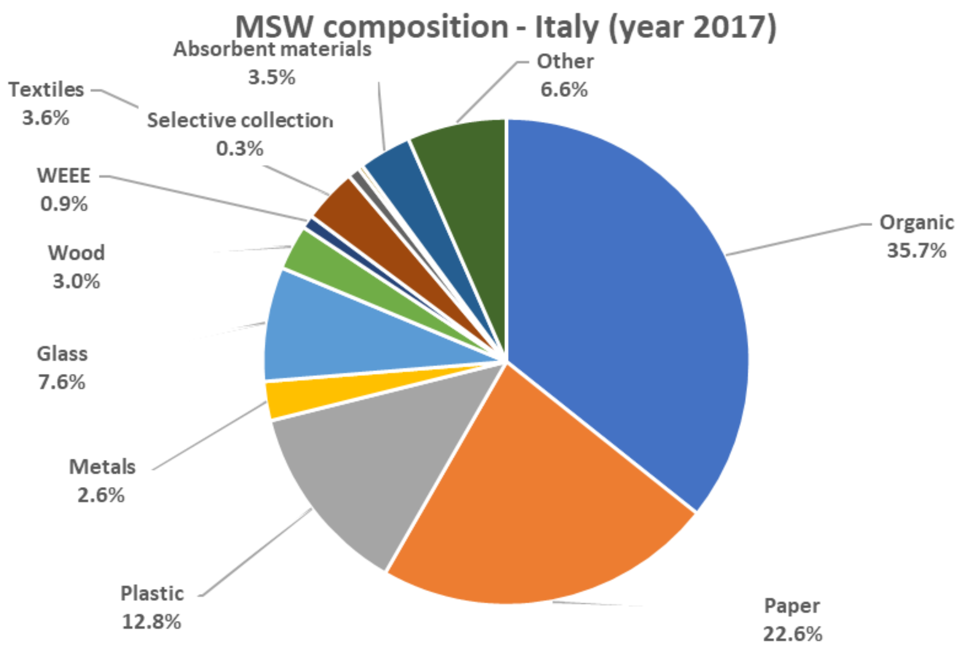

Figure 24: MSW composition for Italy (year 2017 - data from ISPRA Report 2018)

4.8.1 Waste management

The share of recycling (including composting), Waste-to-Energy and landfilling of municipal waste in Italy is shown in Figure 25, based on year 2017 data from CEWEP.

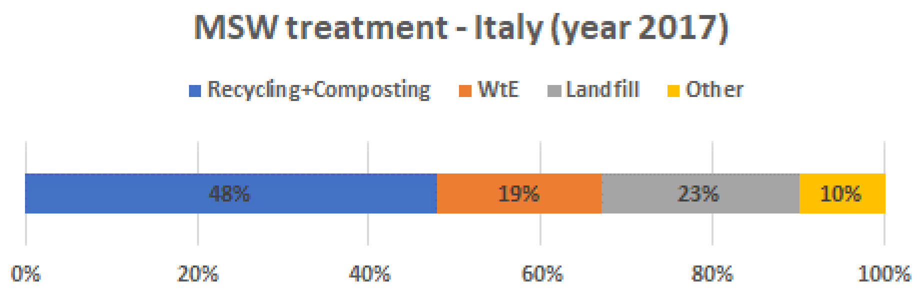

Figure 25: MSW treatment overview in Italy (year 2017, data from CEWEP, 2019)

Among the selected European countries, Italy is yet the one with the highest rate of landfill disposal (23%) and the lowest rate of thermal treatment (19%). The recycling rate is growing year by year, being very close to the standards set by the European Union (50% by 2020).

4.8.2 WtE plants

In total, 39 WtE plants are operating in the country: 26 of them are located in the northern part of Italy, while only 7 and 6 can be found in the center and southern regions respectively.
The total amount of treated waste is about 6.1 million tons per year, for an average plant capacity of 153,000 t/y. According to ISPRA, in 2017 the 26 plants in northern Italy treated 4'469'251 ton. More specifically these plants are concentrated in the regions of Lombardia (13 plants) and Emilia Romagna (8 plants) and in 2017 these two regions have treated 3,4 ml tons of MSW, covering about half of the whole national WtE treatment.
The central and southern part of Italy are currently the ones suffering a relevant WtE deficit together with the fact that there aren't new plants scheduled to enter in operation in the near future.
In general, most of the plants are fed with a mixture of unsorted MSW and pretreated waste from MBT (Mechanical Biological Treatment), and they are grate-based, whereas 7 plants (Bergamo, Corteolona, Gioia Tauro, Manfredonia, Massafra, Parona, Ravenna) uses only RDF in fluidized bed combustors.
The nominal LHV of the processed waste ranges from 9.2 to 11.5 MJ/kg for grate-based plants, whereas it is around 14.5 MJ/kg for fluidized bed reactors.

The typical output of Italian WtE plants is the electricity to the grid, with the combined production of heat and power limited to a quarter of the facilities, especially in northern Italy. The total amount of electricity production reached 1,750 GWh/y in 2017 as the result of an average plant capacity of 22 MW_E. The total heat production reached 1,150 GWh/y in 2017. The main features of some of the most interesting plants are shown below.

- *Reference plant: Torino WtE Plant*
- ➢ Operator: IREN Ambiente
- ➢ Daily capacity: 1,600 t/day (3 processing lines)
- ➢ Annual capacity: 520,000 ton/y
- ➢ Waste type: MSW + Industrial waste (nominal LHV of 11 MJ/kg)
- ➢ Total nominal thermal load: 206 MW_{LHV}
- ➢ Minimal annual availability: 7,800 h/y
- ➢ Activity since: 2014
- ➢ Technology: CNIM/Martin grate
- ➢ Rated electric power: 55.5 MW_E (when district heating not active)

Data source: Trattamento Rifiuti Metropolitani (TRM), Iren Ambiente

- *Reference plant: Parona Energia WtE plant*
  - ➢ Operator: Lomellina Energia Srl (LGH, a company of A2A group)
  - ➢ Annual capacity: 380.000 ton/y (2 lines)
  - ➢ Waste type: pretreated MSW + Industrial Waste + RDF
  - ➢ Activity since: 2000
  - ➢ Net electric power: 25 MW_E (gross), full electric- no district heating
  - ➢ Combustion Technology: Circulating Fluidized Bed (Foster Wheeler)

Data source: Lomellina Energia

- *Reference plant: Brescia WtE Plant*
- ➢ Operator: A2A Ambiente
- ➢ Daily capacity: 880 t/day per line (3 process lines)
- ➢ Annual capacity: 710’000 ton/year
- ➢ Waste type: MSW + Industrial Waste + RDF (LHV 10 MJ/kg)
- ➢ Total nominal thermal load: 304.5 MW_{LHV}
- ➢ Activity since: 1998
- ➢ Net electric power: 85 MW_E (when no district heating)
- ➢ Combustion Technology: Moving Grate (MARTIN GmbH)

Data source: A2A Ambiente

- *Reference plant: San Vittore del Lazio WtE plant*
- Operator: Acea Ambiente
- Annual capacity: 397,200 t/y (3 processing lines)
- Waste type: RDF (LHV of 15 MJ/kg)
- Total nominal thermal load: 160 MW_{LHV}
- Activity since: 2011
- Net electric power: 41.5 MW_E

Data source: Acea Ambiente

- *Reference plant: Acerra (Napoli) WtE plant*
- Operator: A2A Ambiente
- Daily capacity: 1,650 t/day (3 processing lines)
- Annual capacity: 725,000 ton/y
- Waste type: Dry Fraction of Regional MSW (LHV of 15 MJ/kg)
- Total nominal thermal load: 340 MW_{LHV}
- Activity since: March 2009
- Net electric power: 91.8 MW_E (full electric-no district heating)

Data source: A2A Ambiente

4.8.3 WtE potential

Unlike other more virtuous EU countries (like Sweden, Denmark, Netherlands or Germany), still today the MSW landfill disposal ratio in Italy is quite significant (23%).
The distribution of WtE plants is very fragmented, with some regions in the north with overcapacity and some regions in the south with no facilities at all.
Significant improvements in energy recovery from waste are theoretically possible, both in South Italy (installation of WtE plants dedicated to electricity production) and in North Italy (integration with district heating networks).
In 2016, the Italian Government estimated a need for additional WtE capacity for 1.8 million t/y, based on a number of very optimistic assumptions. Such an estimate clashes with the current use of landfilling of almost 7 Mt/y.

4.9 United Kingdom

Based on the data from the UK Department for Environment Food & Rural Affairs (DEFRA), the MSW generation in the country hit 27 million tons in 2016, as shown in Figure 26.

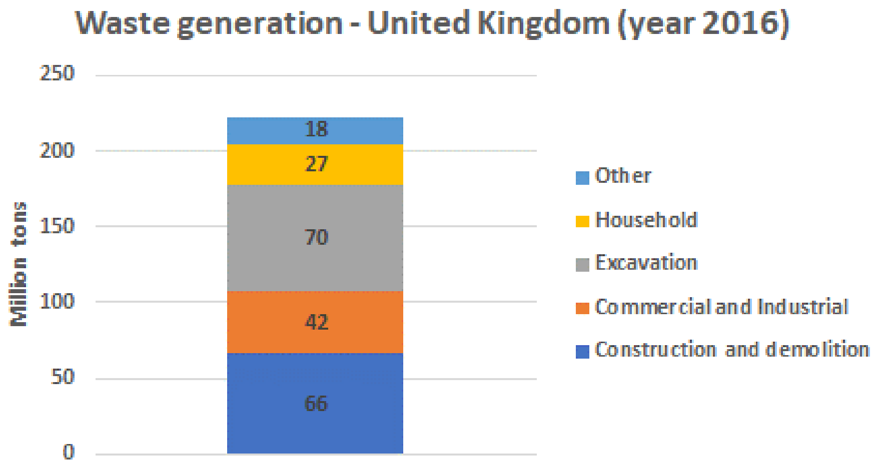

Figure 26: Waste generation in the United Kingdom (year 2016 - data from DEFRA Statistics, 2019)

Some data on MSW composition have been retrieved from literature (Zero Waste Scotland): the main contribution is given by food waste (23%), followed by paper and cardboard (20%) and garden waste (17%). Typical values for LHV of the unsorted waste range from 8.9 MJ/kg for household waste to 11 MJ/kg for commercial & industrial waste.

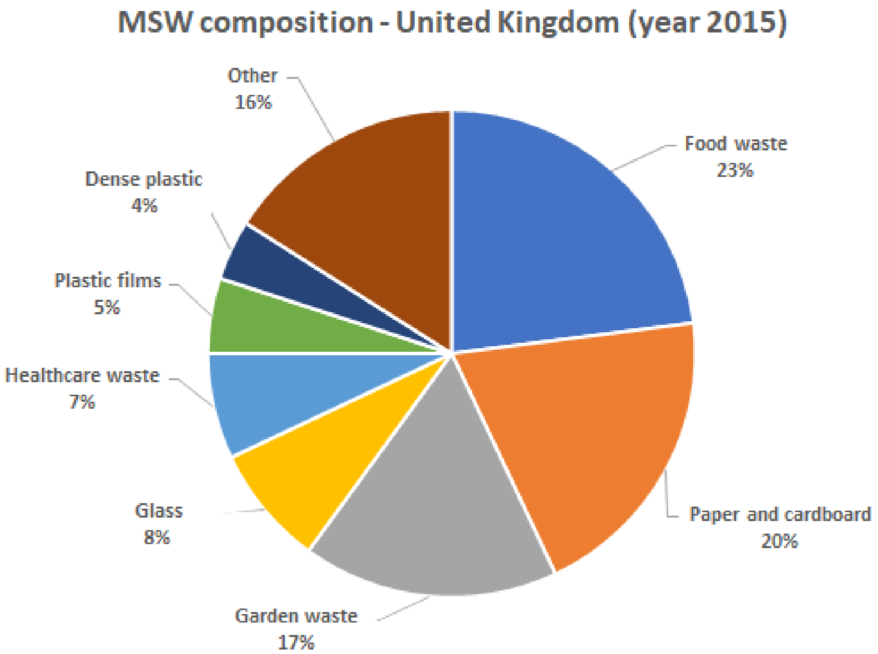

Figure 27: MSW composition for the United Kingdom (year 2015 - data from Zero Waste Scotland, 2017)

4.9.1 Waste management

Figure 28 shows the breakdown of MSW management into the different treatment / disposal options, based on year 2017 data from CEWEP.

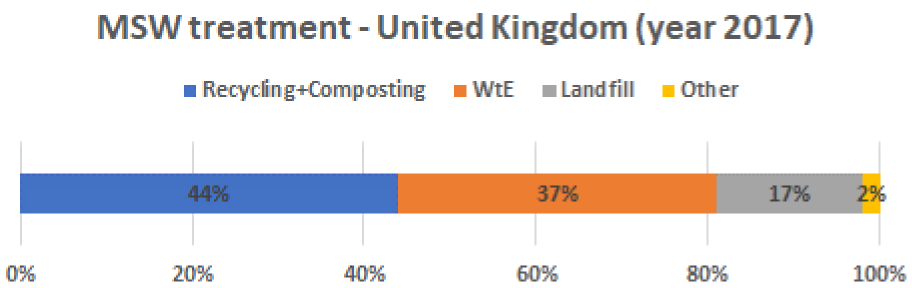

Figure 28: MSW treatment overview in the United Kingdom (year 2017, data from CEWEP, 2019)

Like the Italian case, in the United Kingdom a significant amount of MSW is disposed into landfills (17%), with a recycling rate that stood below the EU28 average (46%), while the thermal treatment is higher than the European average value (29%).

4.9.2 WtE plants

In total, 42 WtE plants are operating in the country: most of them are located in England, especially in the central and southern part, while no plants can be found in Wales.
The total amount of waste treated is approximately 10.9 million tons per year, for an average plant capacity of 260,000 t/y.
Most of the plants are fed only with MSW or MSW + commercial waste. They are grate-based plants and there is no fluidized bed-based plant using RDF.
The nominal LHV of the treated waste ranges from 8.5 to 10.5 MJ/kg.
The typical output of UK WtE plants is electricity to the grid, with the combined production of heat and power limited to 6 facilities (Lewisham, Middlesborough, Coventry, Plymouth, Sheffield, NE Lincolnshire).
The total amount of electricity production reached 7,146 GWh/y in 2017, with a net export of 6,187 GWh/y and an installed capacity higher than 920 MW_E. The total heat production reached 865 GWh/y in 2017.
The characteristics of some of the most interesting plants are shown below.

- *Reference plant: Runcorn Energy Recovery Facility*
  - Location: Halton (Liverpool)

- Number of Lines: 4
- Fuel: RDF (from household and commercial waste)
- Annual capacity: 850,000 t/y
- Technology: Moving grate
- Electrical power output: 70 MW
- Electrical production: 564,000 MWh/y
- Heat power output: 51 MW

Data source: Tolvik Consulting, 2017, Viridor

- *Reference plant: Riverside Resource Recovery Facility*
- Location: Bexley (Greater London)
- Number of Lines: 3
- Fuel: household and commercial waste
- Heating value: 7,0–13,0 MJ/kg
- Annual capacity: 750,000 t/y
- Technology: Moving grate
- Rated Thermal Input (each line): 79.5 MW
- Steam Capacity (each line): 96.5 t/h
- Steam conditions: 72.0 bar (g), 427 °C
- Electrical power output: 65 MW
- Electrical production: 525,000 MWh
- Heat power output: 51 MW

Data source: Tolvik Consulting, 2017, Cory Riverside Energy, Hitachi Zosen INOVA

- *Reference plant: South East London Combined Heat & Power plant*
  - Location: Lewisham (London)
  - Number of Lines: 2
  - Fuel: household and commercial waste
  - Heating value: around 9.2 MJ/kg
  - Annual capacity: 438,000 t/y
  - Technology: Moving grate
  - Steam conditions: 46.0 bar (g), 395 °C
  - Electrical power output: 35 MW
  - Electrical production: 246,000 MWh
  - Year of Commissioning: 1993

Data source: Tolvik Consulting, 2017, Veolia

4.9.3 WtE potential

UK exports over two million tons of RDF for energy recovery mainly to The Netherlands, Norway, Denmark and Germany. The absence of RDF recovery facilities combined with a rising landfill tax and high gate fees at the relatively few operating facilities were justifiable economic drivers for the UK to export RDF. However, this is not for sure the most desired or straightforward waste management solution to pursue. Strategically, in a national waste management perspective, the UK still has a significant gap to be filled potentially with WtE technologies.
Scarlat et al. estimated the need of approximately 20 new plants able to treat more than 5.6 million tons per year of waste (for an average plant capacity of 225,000 t/y).

4.10 Australia

According to data processed by Blue Environment Pty Ltd for the Department of the Environment and Energy of the Australian Government, the MSW generation in the country reached 13.8 million tons in 2017, as depicted in Figure 29.

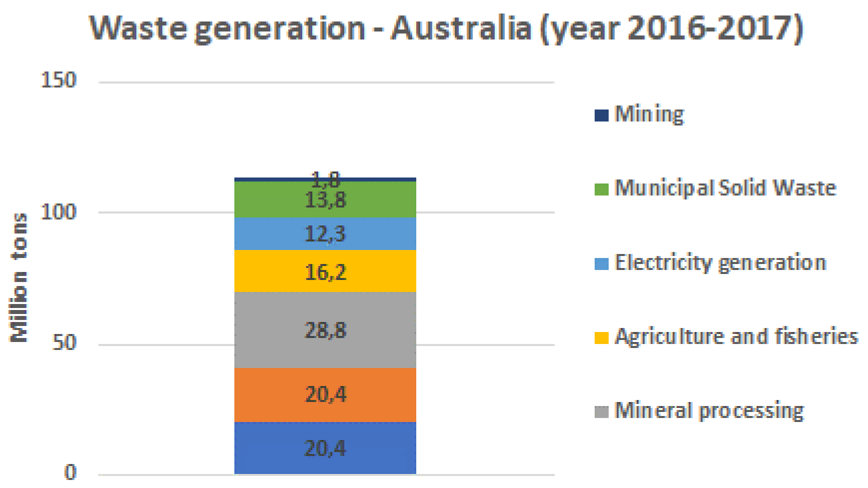

Figure 29: Waste generation in Australia (year 2016-2017 - data from Blue Environment Pty Ltd, 2018).

Figure 30 shows the MSW composition that have been retrieved from literature (Blue Environment Pty Ltd): the main contribution is given by food (39%), inert waste like metals or glass (21%) and garden/green waste (19%). No data on the calorific value nor on the biogenic fraction of the waste have been found but, given the shares of the different fractions, the LHV could be between 8 and 9 MJ/kg.

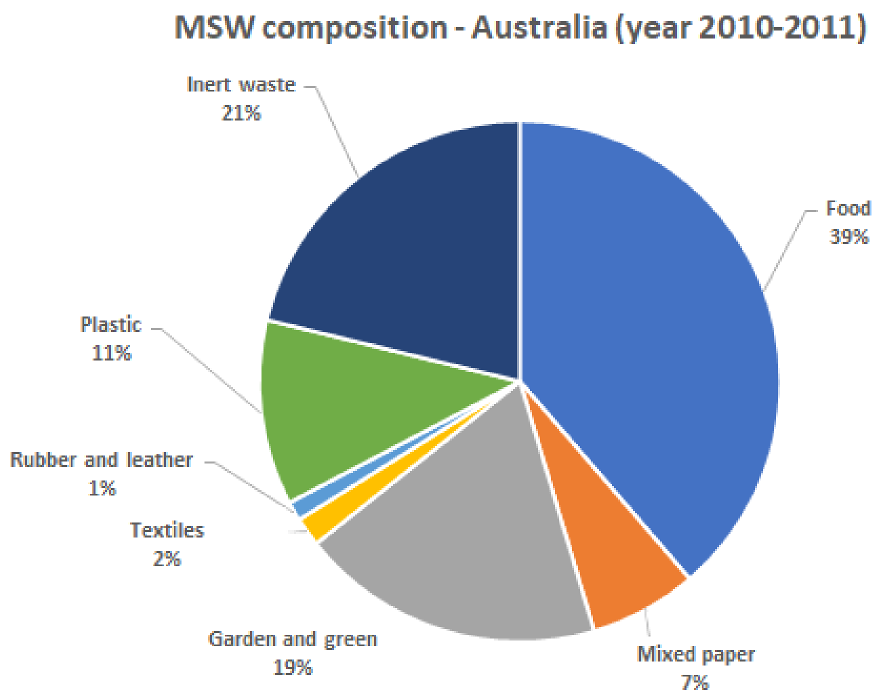

Figure 30: MSW composition for Australia (year 2010-2011 - data from Blue Environment Pty Ltd, 2014)

4.10.1 *Waste management*

Figure 31 shows the breakdown of MSW management into the different treatment / disposal options, based on year 2016-2017 data from Blue Environment Pty Ltd.

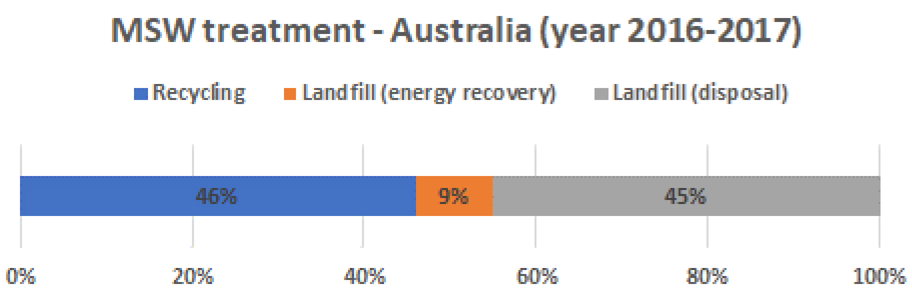

Figure 31: MSW management in Australia (year 2016-2017 – data elaboration by LEAP from Blue Environment Pty Ltd, 2018)

Currently no incineration/WtE plants are operating in Australia, whereas the landfill disposal represents the most adopted option for waste management (54% overall). This figure includes some landfills with biogas collection and energy recovery based on internal combustion engines. Such landfills receive around 9% of the overall waste generation.

4.10.2 WtE plants

Table 4-8 shows a list of ongoing projects for new WtE plants in Australia.

Location	***Companies involved & Operator***	***First year of operation/ Status***	***Technology***	***Plant Size [t/y]***	***Waste type***
Port Hedland (WA)	New Energy Corporation	Project (construction planned for January 2019)	Gasification process (Entech)	86,000	MSW C&I C&D
East Rockingham, Perth (WA)	NewEnergy, Hitachi Zosen Inova, Tribe Infrastructure Group + SUEZ (EPC)	Project (Construction in 2019)	Combustion technology, HZI grate	300,000	MSW C&I
Swanbank landfill, Ipswich (Qld)	Remondis (German company)	Project (Begin construction end of 2021 - Planned for 2023/2024)	Combustion	300,000 - 500,000	MSW C&I

Kwinana Industrial Area, Perth (WA)	Kwinana WTE Project Co (Phoenix Energy Power Plant company, Green Investment Bank, and Green Investment Group) + ACCIONA (EPC)	Project (construction started 2019, beginning operation end of 2021)	Moving grate (Keppel Seghers technology)	400,000	MSW C&I C&D
Latrobe Valley mill, Melbourne (Vic)	Australian Paper + SUEZ (EPC)	Project (construction beginning by mid 2020, beginning operation by 2024)	Combustion	650,000	MSW C&I

Table 4-8: List of possible WtE plants in Australia under development/planning in the near future

The main features of some of the most interesting projects are shown below.

- *Reference project: Pilbara WtE Site*
  - Location: Pilbara, Port Hedland (WA)
  - First Waste to Energy Project approved by EPA in Australia
  - Overall Materials Recovery Facility capacity: 225,000 t/y
  - WtE Plant capacity: 86,000 t/y (gasifier inlet)
  - Gasification technology: ENTECH-Renewable Energy Solutions (600 - 875°C, fixed bed, mechanical agitation, sealed ash bins with water quench)
  - Thermal Capacity: 72 MW_{LHV}
  - Electricity generation: 15.5 MW_E to grid

Data source: New Energy Corporation

- *Reference project: East Rockingham Resource Recovery Facility*
  - Location: East Rockingham, Perth Metropolitan Area (WA)

- Developer: Hitachi Zosen Inova (HZI), New Energy Corporation, Tribe Infrastructure Group, SUEZ
- Operator: JV between HZI and New Energy
- Waste type: Residual waste (municipal and commercial)
- Number of lines: 1 (grate type)
- Annual capacity: 300,000 t/y
- Plant throughput: 37.5 t/h
- Plant thermal capacity: 101.8 MW_{LHV}
- Flue gas treatment: SNCR, Dry system
- Construction: planned to begin in 2019

Data source: New Energy Corporation

- *Reference project: Kwinana WtE Plant*
- Location: Kwinana, Perth Metropolitan Area (WA)
- Engineering, design and procurement: Ramboll Group
- Waste type: MSW, Commercial & Industrial Waste and pre-sorted Construction & Demolition Waste
- Capacity: 400,000 t/y
- Number of lines: 2 (600 t/day each)
- Combustion technology: integrated moving grate fired furnace/boiler
- Electric power Generation: 36 MW_E
- Flue gas treatment technology: SNCR and semi-dry system
- Commercial operation: expected by October 2021.

Data source: Ramboll Group

4.10.3 WtE potential

As the energy recovery is only guaranteed by the waste disposed to landfills equipped with biogas recovery systems, which in any case represents an absolutely minority share of the total waste landfilled, there is considerable interest within government and industry in expanding energy recovery from waste. All the possible alternatives have been taken into account and analyzed (traditional mass-burn incineration, gasification and pyrolysis, anaerobic digestion, mechanical-biological treatment).

Therefore, several proposals for large-scale Waste-to-Energy facilities treating MSW are at various stages of development, mainly in the States of West Australia, Queensland and Victoria, while the State of New South Wales recently declined another large-scale proposal.

Based on typical household waste composition in Australia, about half energy recovered would be biogenic and half fossil: combustion of this type of waste would result in greenhouse gas emissions at about half rate of bituminous coal per unit of power generated (estimated by Blue Environment Pty Ltd, 2018).

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TASK 1.2 - UPDATE OF WTE PLANTS WITH CCS/CCU

5. Introduction and task methodology

This section aims at providing a description of the current status (i.e. based on the information available by September 2019) of projects involving the integration of WtE plants with CO_2 Capture and Utilisation/Storage (CCUS) facilities.
The review has followed two steps: first a literature research (based on the screening of scientific articles, technical reports, pdf presentations and websites) has been conducted, in order to retrieve the publicly available information reported by plant owners, technology providers or other authoritative sources on the existing or planned WtE + CCUS plants; afterwards, customized inquiries have been sent (via private e-mails) to relevant plant operators both to acquire additional data (classified as non-confidential) and to check and validate the main technical information retrieved from the literature.

The overview has been focused on the following information (where available):

- List and classification of ongoing CCS/CCU projects integrated with WtE facilities
- Key technical figures on current WtE plants
- Major technical challenges reported by the company managing the WtE
- CCS/CCU Project status (pre-feasibility, feasibility, engineering, under construction, operating, on-hold, stopped, etc.) and projection
- Description of CO_2 Capture technology proposed/under evaluation
- Amount of CO_2 to be captured yearly [t/y], CO_2 removal target (defined as the ratio between the amount of CO_2 removed from flue gases by the capture plant and the amount of CO_2 contained in the flue gases stream entering the CO_2 capture system) and CO_2 capture plant size (defined as the fraction of the total WtE flue gases flow rate sent to capture)
- Captured CO_2 planned destination (storage, EOR or utilisation) and logistics
- Economics and financial information (in case data are publicly available)
- List of major challenges for CCS/CCU implementation

The next paragraph summarizes the main outcomes of this task, while its subsections report further details on each of the listed WtE + CCUS projects.

6. Overview on current status of WtE plants with CCUS

The following seven ongoing WtE projects integrated with CCS/CCU projects from three nations (The Netherlands, Norway and Japan) have been identified and reviewed:

- **The Netherlands**
    - AVR Duiven

    - HVC Alkmaar
    - AEB Amsterdam
    - AVR Rozenburg
    - Twence Hengelo
- **Norway**
    - Fortum Oslo (Klemetsrud)
- **Japan**
    - Saga Municipality Saga City

A summary of their key technical data is reported in Table 9, while Figure 32 depicts a general scheme based on post-combustion CO_2 capture with amine solvent which is the capture technology followed by all of the reviewed WtE+CCUS (with differences on the specific plant configuration, details and solvent formulation).

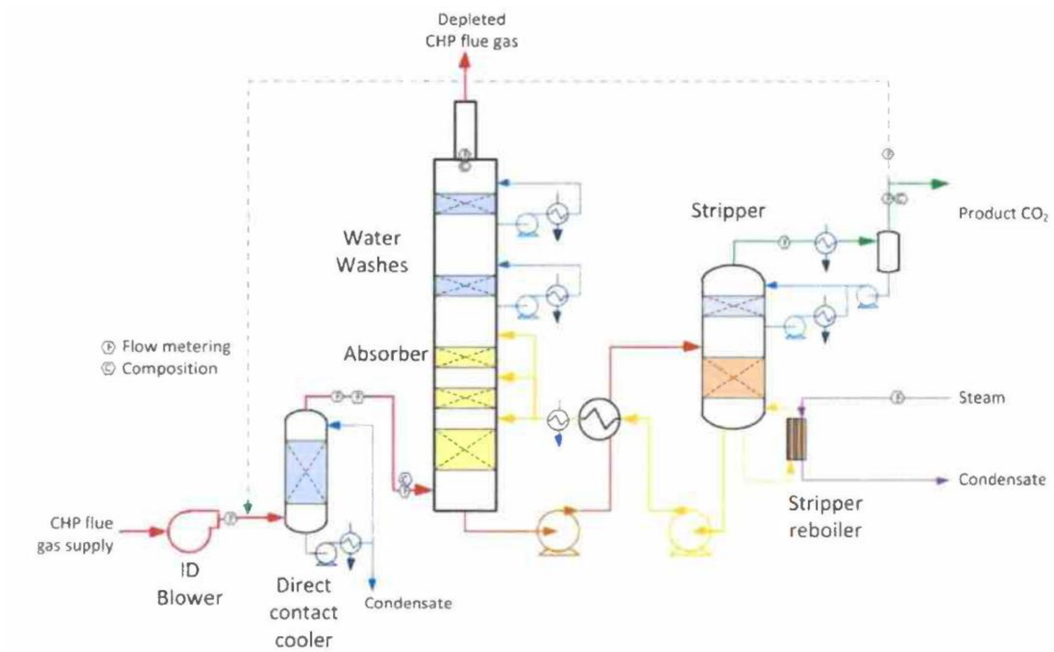

Figure 32: General scheme for amine-based post-combustion CO_2 capture process (solvent reclaimer, solvent drainage/make-up, CO2 compression and dehydration package not showed). Source: D. Thimsen et al., 2014 – Energy Procedia.

The total CO_2 emissions produced by the WtE plants include both fossil and biogenic CO_2 and have been assessed as follow:

- In case they have been reported by the plant operator or by another authoritative source (e.g. ISWA report), their value has been taken directly from the source and classified as "reported" and the source has been cited.

- In case they have not been reported by any qualified source, their value has been estimated by assuming a specific CO_2 intensity factor of 0.9875 kg_{CO2}/kg_{waste}, which is representative of the average CO_2 emissions of European WtE plants. In this case the CO_2 emissions are classified as "estimated".

Country	Plant	Total Waste Processed [t/y]	Total CO_2 Produced [t/y]	CO_2 capture plant type	CO_2 capture plant status	Total CO_2 Captured [kt/y]	CO_2 %mol conc. in flue gases	Removal Target	CCUS Technology
Netherlands	HVC-Alkmaar Project 1	682,412	673,882	Amine technology	Ongoing	4	N.A.	N.A.	Liquefied CO_2 for greenhouse horticulture
	HVC-Alkmaar Project 2	"	"	Amine technology	Feasibility study	75	N.A.	60%	Liquefied CO_2 for greenhouse horticulture
Netherlands	AEB Amsterdam	1,284,164	1,268,112	Amine technology (MEA based)	Feasibility study	450	N.A.	90%	Feasibility study
Netherlands	AVR-Duiven	360,635	400,000 (reported)	Amine technology (MEA based)	Plant Start-up	50-60	10%	90%	Liquefied CO_2 for greenhouse horticulture
Netherlands	AVR Rozenburg	N.A.	1,153,319	N.A.	N.A.	800	N.A.	N.A.	FEED Study ongoing based on the operator's experience in Duiven
Netherlands	Twence-Hengelo	608,000	600,000 (estimated)	Amine Absorption by Aker solutions	Full-scale project under engineering study	100	10-11%	N.A.	Liquefied CO_2 for greenhouse OR for the production of formic acid OR to be mineralized into construction materials
Norway	Fortum-Klemetsrud	375,000-400,000 (reported)	430,000-460,000 (reported)	Shell Cansolv engineered and built by Technip (reported)	Concept study completed. Pilot tests ongoing since Feb 2019. FEED ongoing	414	10-12%	90%	CO_2 to be delivered by truck to the Oslo harbor where it is liquefied and sent by ship to long term storage in the North Sea (logistics under study)
Japan	Saga City-Japan	74,010	54,000 (220 t/day reported)	Chemical absorption based on specific amine solvent	Full-scale plant in operation since 2016	2.5 (10 t/day reported)	8-18%	80-90%	Gaseous CO_2 stored in a 100 m3 buffer and delivered via pipeline to nearby algae cultivation

Table 9: Summary of WtE + CCUS projects.

6.1 Alkmaar Plant (HVC)

Figure 33: Alkmaar facility **[https://www.hvcgroep.nl/over-hvc/interactieve-locatiekaart/locatie-alkmaar]**.

Table 11: Processed waste composition in Alkmaar

HVC Alkmaar – Waste Composition	Amount [t/y]	%
TOT	682.412	
Domestic	352.527	51,66%
Industrial	329.144	48,23%
Pellet	0	0,00%
Sludge	329	0,05%
Hospital	0	0,00%
Biomass	0	0,00%
Other	412	0,06%

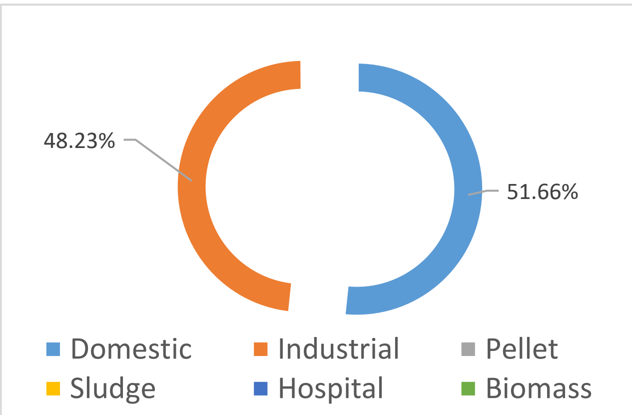

Figure 34: Processed waste composition breakdown in Alkmaar [ISWA Report].

The WtE plant by HVC in Alkmaar (AEC-afvalenergiecentrales) [Jaarverslag Report] is endowed with 4 incineration lines: the first three date back to 1996, line 4 has been operating since 2005. Grates are movable and supplied by De Shelde (lines 1-3) and EisenWerk Baumgarte (line 4). HVC-Alkmaar site is also provided with a biomass energy plant (BEC) [HVC 2018].

The AEC plant has two steam turbines (50 + 50 MW_E), it grants 418.000 MWh/y of electricity with 2.228.000 tons of steam produced every year in average and 12.222 MWh/y thermal [ISWA Report].
Domestic and industrial waste constitute the main inlet of the Alkmaar facility (details in Table 11, Figure 33 and Figure 34), which emits an estimated amount of CO_2 equal to 673.882 t_{CO2}/y (fossil + biogenic).

Shifting towards decarbonization, HVC is currently lunching 2 different initiatives to perform CO_2 capture from WtE flue gases: Ambience, Ambition (project 1) and Amazing (project 2) [HVC CATO 2018]. The selected CCS technology is based on amine absorption and the isolated CO_2 will be liquefied, transported via truck and supplied to greenhouse horticulture companies [CATO Event].
Project 1 envisages the construction of "Ambience" capture unit (Alkmaar biomass energy carbon capture use, 12 m height absorber column) and "Ambition" liquefaction unit (Alkmaar Bio- CO_2 liquefaction for greenhouses) which are pilot scale facilities associated to low

financial risk. The two sections will run together, and the CO_2 capture facility has been built in November 2018 in the BEC Alkmaar waste incineration site. Start of operations is planned in 2019 (measurement program activity) and the targeted capture rate is in the order of 0,5 t/h with estimated 4.000 t_{CO2}/y. The plant is expected to operate for 12 years, with main CO_2 production in summer time.

Another initiative to be carried out in the Alkmaar facility is the “Amazing” project (Alkmaar haalbaarheidsstudie grootschalige demo zuiver CO_2 afvang en vervloeiing). It consists in the construction of a large demo scale facility for CO_2 capture and liquefaction and it will be connected to both BEC and AEC WtE Plant-line 4. Currently the project is at the feasibility study stage, which was scheduled to end in 2019 [CATO Event].

The "Amazing" project will build a larger scale CO_2 capture plant, producing 75.000 tons of liquid CO_2 per year, with a capture rate of 15 t/h. More specifically, approximately 60% of the CO_2 from AEC-line 4 or BEC will be captured, preferably in summer season.

6.2 Amsterdam Plant (AEB)

Figure 35: Amsterdam facility [**AEB Amsterdam**].

Since 1993, the City of Amsterdam's Afval Energie Bedrijf (Waste and Energy Company-AEB) has run a WtE Plant (Figure 35) located in the city's western port district, processing more than 800.000 t/y of waste with an investment of 450 M€ for site construction.

In 1998, a master plan for an advanced Waste-to-Energy Plant has been developed by AEB. The new facility offers additional incineration capacity of approximately 500.000 t/y. The new high-efficiency Waste Fired Power Plant (WFPP) also provides a total increase of electrical efficiency from 22% to 30%. WFPP realization (370 M€) is part of the Eco-Port® concept, a sustainable industrial complex based on recycling and processing waste from urban regions [AEB brochure].

WFPP has been added to the existing WtE plant and it can operate independently from the previous facility, mainly processing combustible household and industrial waste within an LHV range of 7300-16000 kJ/kg. Links between the two units are limited to process utilities (e.g.: chemicals, water, etc.).

The two lines that compose WFPP show a conventional structure (waste supply, incineration grate, boiler, flue gas cleaning and stack) and they can operate separately. However, in order to achieve 30% electrical efficiency, the plant has been designed to produce steam at higher conditions (440°C and 130 bar), which frequently activate chlorine corrosion; consequently, critical heat-exchange surfaces have been covered with Inconel® allowing better corrosion control. Moreover, an external heat exchanger has been placed for re-heating of the high-pressure turbine discharge with saturated steam from boiler's drum.
Reheating the turbine steam and cooling the condenser with harbor water are associated to maximum turbine efficiency.
More details on reheating and water-steam cycle are reported in Figure 36.

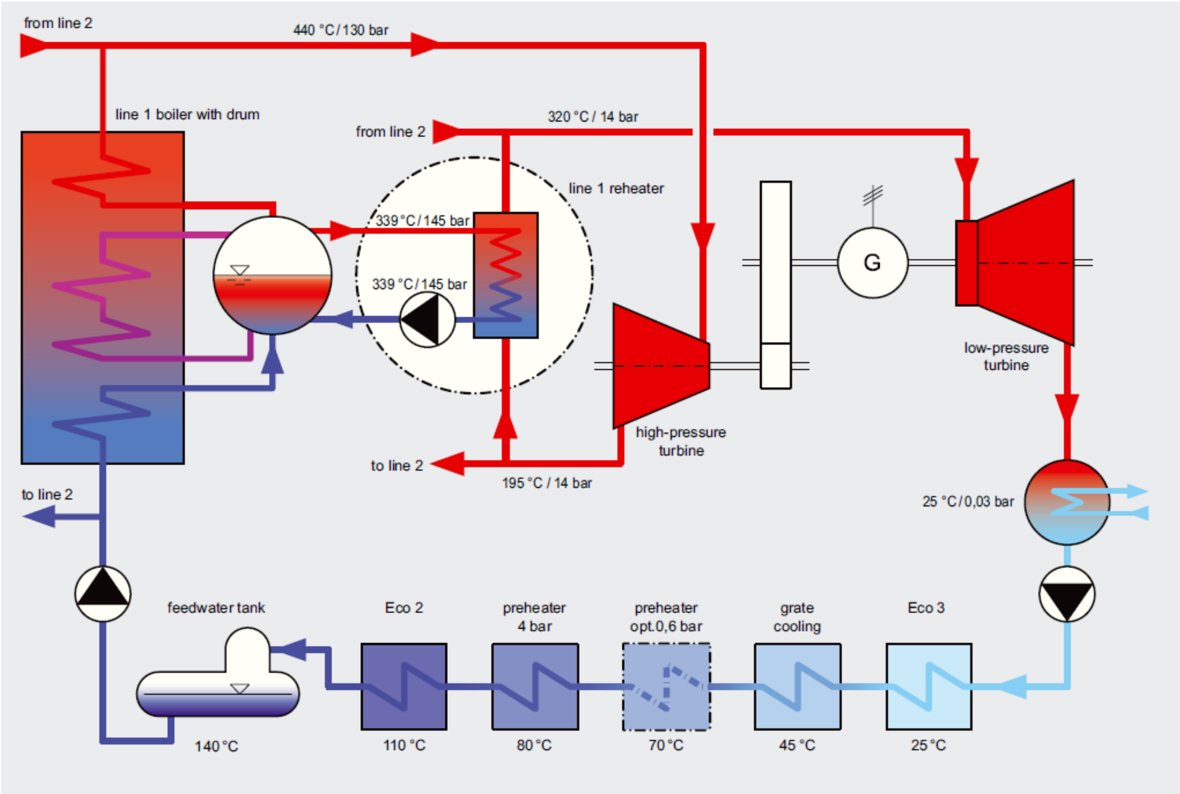

Figure 36: Reheating and water-steam cycle scheme [AEB brochure].

Table 12: Processed waste composition [ISWA Report].

AEB Amsterdam – Waste Composition		
	Amount [t/y]	%
TOT	1.284.164	
Domestic	1.221.544	95,12%
Industrial	8.829	0,69%
Pellet	0	0,00%
Sludge	5.573	0,43%
Hospital	0	0,00%
Biomass	6.570	0,51%
Other	41.648	3,24%

Nowadays, the Amsterdam AEB plant is composed of 6 incineration lines (lines 1-4 from 1993 and lines 5-6 from 2007), with movable grate supplied by W&E (lines 1-4). Domestic waste is the prevalent material processed by the facility; nevertheless, further details on waste composition and total flowrate are reported in Table 12 and Figure 37.

The Amsterdam plant shows a total electric power generated of 125 MW_E with an electricity production equal to 888.000 MWh/y (up to 1.000.000 MWh/y) and 4.612.000 t/y of steam. Heat production accounts for 70.278 MWh/y and the CO_2 released every year from the facility is estimated to be 1.268.112 t_{CO2}/y (fossil + biogenic). With regards to district heating, AEB is planning an expansion of the system that will principally involve the high efficiency plant.

AEB is currently building a sustainable energy plant in the Amsterdam port area that will run entirely with biomass, offering double the heat generation capacity to the city's district heating network. This biomass power plant provides around 67.000 tons of avoided CO_2 per year [https://www.aebamsterdam.com/innovation/].

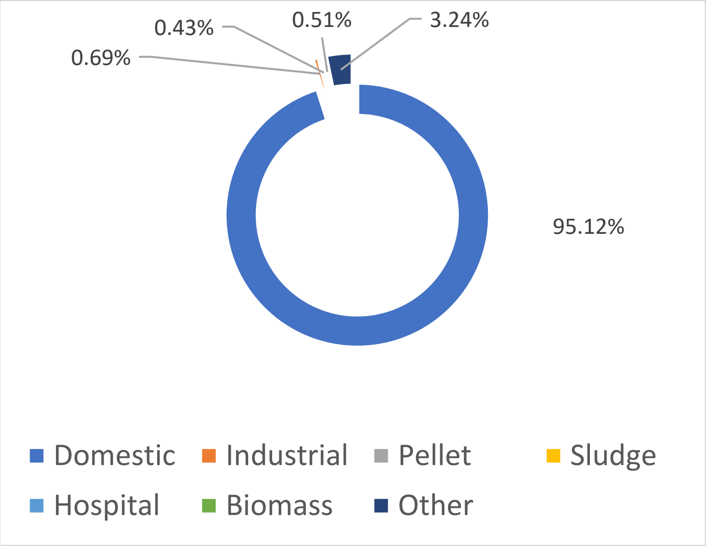

Figure 37: Processed waste composition breakdown in Amsterdam [ISWA Report].

Moreover, the operator intends to capture CO_2 from the waste plant's flue gas and deliver it as pure CO_2 to glasshouse horticulture companies in the Westland. After capture, the CO_2 can be transported by an existing pipeline (OCAP) to Rotterdam at 20 bar. Additionally, the operator, together with OCAP, are negotiating the erection of a centralized liquefaction plant that should also process CO_2 from Shell and Alco companies; this alternative option is still under evaluation but it would be beneficial in order to supply off-takers not connected to the grid.

Among the current initiatives, AEB is trying to booster the utilization route via greenhouses as an alternative to CCS; in fact, the Netherlands also constitute a suitable region for the captured CO_2 to be stored in depleted gas fields in the North Sea during winter time. Therefore, AEB, together with OCAP, the Dutch waste management sector and the Dutch greenhouse association, are discussing with the Dutch Government to subsidize the proposed CCU route via greenhouses.

Since 64% of AEB's CO_2 stems from biogenic sources, another field of interest from AEB involves trading with other industrial, fossil sources in order to lower emissions.

With regards to the main facility (high efficiency plant), the capture process under investigation will be connected to both the existing two lines where CO_2 concentration is roughly 10% and it will benefit from the utilities already in place. The foreseen capture technology would consist in a post combustion solvent scrubbing unit working with MEA solutions and associated to an estimated investment cost of 120 M€. Targeted amount of CO_2 to be captured from the main plant is 450.000 ton/y; however, technical and economic feasibility of the project is under evaluation together with Linde Engineering, it has reached FEED level but further development of the business case is still required.

NOTE: The information reported for the AEB Amsterdam Plant have been partially provided by the owner.

6.3 Duiven Plant (AVR)

Figure 38: Duiven facility [**https://www.avr.nl/en/about-us**].

The WtE plant in Duiven (Figure 38) is operated by AVR and it is composed of 3 incineration lines dating back to 1975, with rotatory furnaces supplied by De Shelde (lines 1-2) and Stork Ketels (line 3). The net electricity production is equal to 147.000 MWh/y, with 452.000 tons of steam produced every year (average) meanwhile heat production accounts for 163.889 MWh/y. The Duiven facility mainly processes domestic waste, however fraction of sludge, biomass and industrial waste have been detected. A more accurate breakdown of processed waste composition is shown in Table 13 and Figure 39.

Table 13: Processed waste composition in Duiven [ISWA

AVR Duiven – Waste Composition		
	Amount [t/y]	%
TOT	360.635	
Domestic	337.652	93,6%
Industrial	2.604	0,7%
Pellet	0	0,0%
Sludge	13.299	3,7%
Hospital	0	0,0%
Biomass	6.197	1,7%
Other	883	0,2%

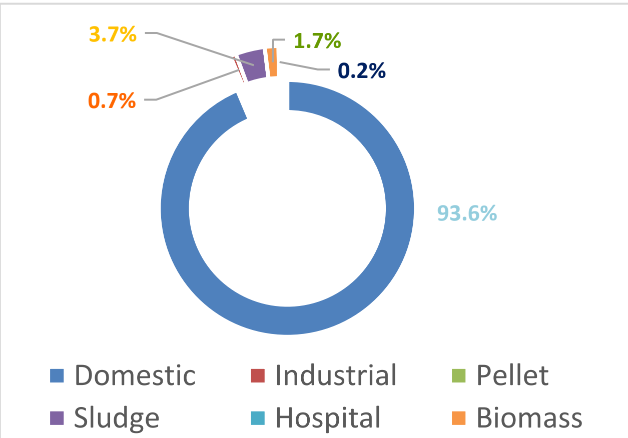

Figure 39: Processed waste composition breakdown in Duiven [ISWA Report].

The Duiven facility produces a reported amount of CO_2 equal to ~400 kt_{CO2}/y (fossil + biogenic) over the three lines. In May 2018 AVR decided to invest in a CO_2 capture plant in Duiven, processing WtE flue gas. The separated CO_2 is delivered at 20 bar and -30°C in a liquid state, and it will be supplied for greenhouse horticulture (accelerated cultivation of plants) via truck [private communication with AVR, AVR Report].

The selected CCS technology implemented by AVR is amine absorption and the facility is supplied by TPI (MEA based process) [AVR Report]. The plant is expected to be ready for delivery and commissioning in mid-2019 with first supply scheduled in August 2019. AVR also concluded an agreement with Air Liquide for the purchase of the CO_2.

Starting from the initial WtE configuration, flue-gas flowrate coming from 1 out of 3 lines will be sent to the CO_2 capture facility with a targeted removal of 90% of the CO_2 and an average CO_2 concentration of roughly 10% in every stream. However, connection with all the 3 lines will be in place.

Considering the current amount of flue gas flowrate produced by each line, the targeted capture capacity is equal to 50-60 kt_{CO2}/year, corresponding to roughly 12-15% of the overall carbon dioxide production.

From the separation process, exhaust solvent is produced, and its regeneration is carried out with low pressure steam from the existing facility (which is also used for district heating). The overall cost of the CCS unit has been estimated to 20 M€.

Following this initiative, AVR intends to start the construction of a much bigger version of the Duiven plant in Rozenburg during the upcoming years, and a FEED study for a 250 kt/y is ongoing.

The 2018 annual report from AVR shows that the primary process releases CO_2 for a total amount of 2,231,000 $t_{CO2}/year_{2018}$ at group level, and a share of biogenic CO_2 equal to 59.8%. In comparison with CO_2 emission in 2017, an increase of 0.5% of the recorded CO_2 emission has been detected in 2018 and related to the liquid waste treatment plant.

NOTE: The information reported for the AVR Duiven Plant have been partially provided by the owner.

6.4 Rozenburg Plant (AVR)

Figure 40: Rozenburg facility [https://www.avr.nl/en/visit-avr].

Table 14: Processed waste composition [ISWA Report].

AVR Rozenburg– Waste Composition		
	Amount [t/y]	%
TOT	1.167.918	
Domestic	1.002.118	85,80%
Industrial	50.646	4,34%
Pellet	0	0,00%
Sludge	68.905	5,90%
Hospital	0	0,00%
Biomass	7.566	0,65%
Other	38.683	3,31%

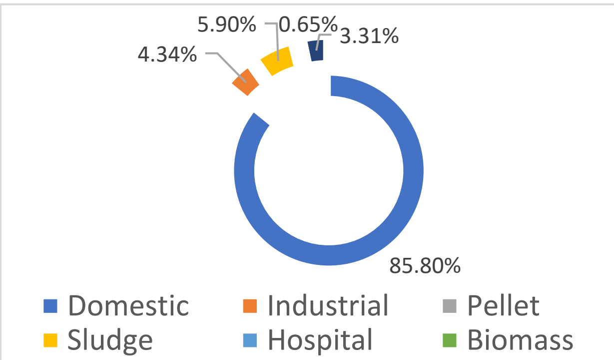

Figure 41: Processed waste composition breakdown in Rozenburg [ISWA Report].

AVR Afvalverwerking Rozenburg (Figure 40) processes more than 1.1 Mt/y of waste (cfr. Table 14 and Figure 41), mainly including household and industrial material. 7 incineration lines compose the Rozenbourg facility, and they are all endowed with movable grates: lines 1-6 dates back to 1973 (Babcock Dürr supplier) and line 7 to 1994 (from Babcock). The majority of the processed waste is converted into electrical energy by means of four steam turbines with a total installed capacity of 100 MW [https://www.pdm-group.com/nl-nl/cases/avr-rozenburg]. Electricity production is equal to 558.000 MWh/y, with 16.525.000 tons of steam produced every year (average). The Rozenburg site also supplies steam as a heat source to the neighboring company Kerr McGee Pigments, achieving a total heat production of 526.945 MWh/y.

With an estimated CO_2 production of 1.153.319 t_{CO2}/y (fossil+biogenic), AVR is planning to capture 800.000 t_{CO2}/y (~69%) in its facility in Rozenburg. [https://www.letsrecycle.com/news/latest-news/avr-to-capture-co2-in-holland/]

The targeted CCU application is greenhouse horticulture, together with production of building materials such as concrete, basic chemistry for plastics and biofuels. Assessment on the Rozenburg capture facility is based on the previous experience from AVR in Duiven. A FEED study for a 250 kt/y of captured CO_2 is ongoing [AVR private communication].

NOTE: The information reported for the AVR Rozenburg Plant have been partially provided by the owner.

6.5 Twence - Hengelo

Table 15: Processed waste composition (ISWA, 2013).

Twence Hengelo - Waste Composition	
	%mass
Domestic	96.9%
Industrial	0.0%
Pellet	0.0%
Sludge	0.0%
Hospital	0.0%
Biomass	0.9%
Other	2.1%

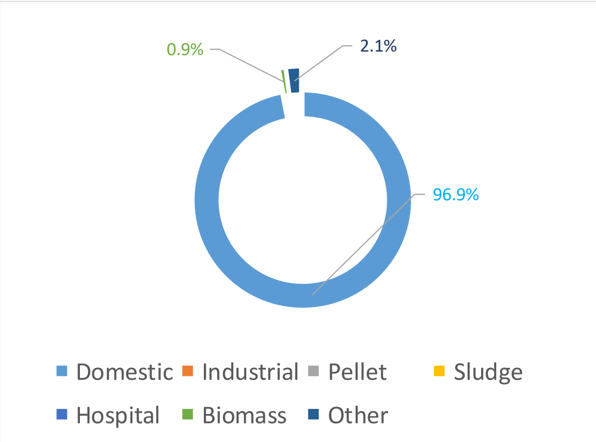

Figure 42: Processed waste composition breakdown in Hengelo

The WtE plant in Hengelo is owned and operated by the Twence company (established by fourteen municipalities in Twente) and it is composed of 3 parallel incineration lines (2 dating back to 1997 and one added in 2009), with reverse acting grate supplied by Martin (ISWA, 2013, and Twence, 2016). The amount of waste processed in 2018 was 608 kt of non-recyclable Refuse Derived Fuel (Twence, 2019). The waste composition reported by ISWA (ISWA, 2013), and summarized in Table 15 and Figure 42, highlights that the large majority of waste was of the domestic type. In 2018 (Twence, 2019), the electricity production was equal to 343,000 MWh/y, meanwhile useful heat production accounted for 364,000 MWh/y (the same quantities were 254,000 MWh_{el}/y and 635,000 MWh_{th}/y in 2015). The useful heat is partly supplied as steam to an industrial user, the remainder being hot water delivered to the Enschede district heating network.

The estimated amount of CO_2 produced by the Hengelo WtE was around ~600 kt_{CO2}/y (fossil + biogenic) over the three lines. Flue gases have a concentration of CO_2 between 10 and 11% (mol dry basis).

The Hengelo WtE has been considered for two CO_2 Capture projects developed according to the timeline of Figure 43:

1) A Pilot plant (CO2SBC) based on aqueous sodium carbonate scrubbing of a slip stream of flue gases to produce sodium-bicarbonate (first test carried out in 2011)
2) A Full-scale plant, aimed at capturing 100,000 t_{CO2}/y from line 3 of the WtE plant since 2021, is under engineering study.

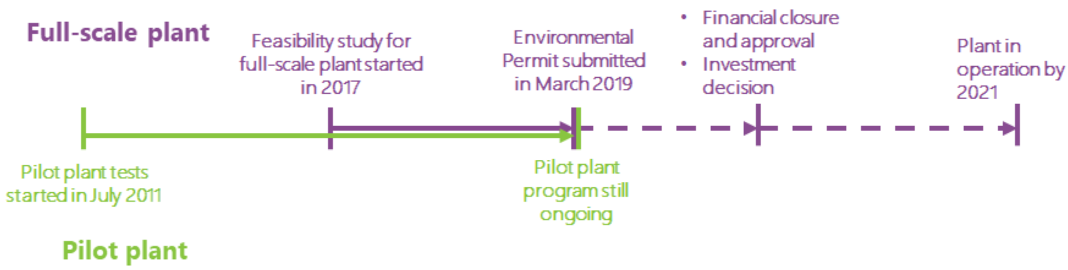

Figure 43: Time evolution of Twence Hengelo CO_2 capture projects. Sources: Twence, 2018 and Twence annual report, 2016.

The CO_2 capture pilot plant separates CO_2 from a slipstream of the WtE facility and converts it into sodium bicarbonate ($NaHCO_3$), which is then re-used (i.e. injected) inside the WtE flue gas treatment line for the removal of acid components. The main sections of the pilot plant are: Soda (Na_2CO_3) dissolving system; CO_2 capture unit; Sodium bicarbonate production plant. When operating, the pilot plant can produce up to 8,000 t of sodium bicarbonate per year, while capturing between 2,000 and 3,000 t of CO_2 per year with a thermal energy consumption lower than 2 MJ/kg of CO_2 captured (www.co2sbc.eu).
Since 2018, Twence has partnered with Coval Energy (www.covalenergy.com) in order to develop and build a new pilot plant (meant to be in operation since 2020) to produce formic acid starting via electrochemical conversion of the CO_2 captured by the CO2SBC pilot.
The concept for the full-scale CCU project under assessment by Twence is depicted in Figure 44. The CCU plant will treat the flue gases leaving the dry cleaning line of line 3 of the WtE plant with an amine absorption technology provided by Aker solutions (Aker, 2019), targeting a CO_2 removal capacity of 100 kton per year. Three alternative utilization options have been considered for the captured and liquefied CO_2: sustainable fertilizer for greenhouses to increase yields of plants and vegetables; production of formic acid and e-fuels partnering with Coval Energy; using it as an additive in the production (i.e. mineralization) of construction materials.
The main challenges reported for the development of the full-scale CCU project are (Twence, 2018):

- The lead time (years) required for project development
- Uncertainties in upscaling the first commercial (First-Of-A-Kind) plant poses technical and economic risks (from the point of view of process configuration, solvent type, operational performance and costs, large capital expenditure (CAPEX) required) and may cause a delay in project development
- Policy, subsidies and financial instruments for CCU still need to be defined.

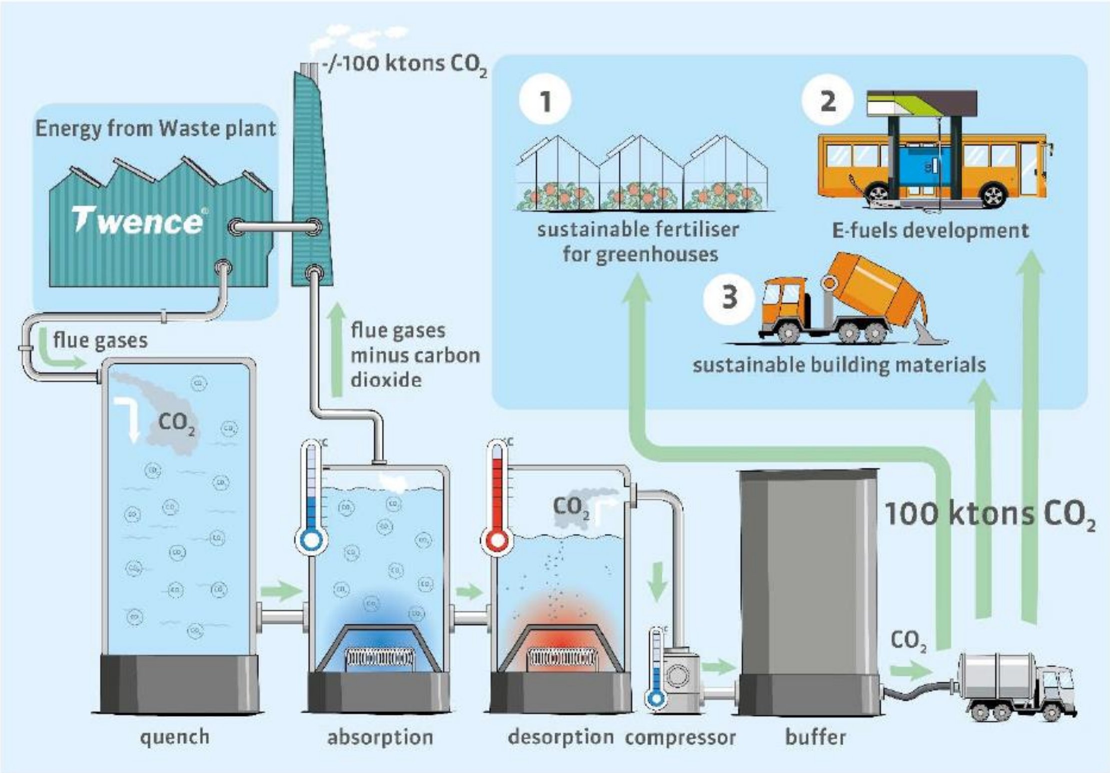

Figure 44: Full-scale CCU concept under engineering study for the Twence Hengelo plant (figure from www.co2sbc.eu).

6.6 Fortum-Klemetsrud

The WtE plant in Klemetsrud (Oslo) is owned and operated by Fortum Oslo Varme (a joint venture established by the Fortum company and the Oslo municipality) and it is composed of 3 parallel combustion and flue gas treatment lines (K1-2-3) with separate stacks. K1 and K2 are twin horizontal grate lines by Martin (in operation since 1985), each with a current capacity of 12 t of waste per hour. K3 has been added in 2011 by Hitachi Zosen Inova and it is a horizontal grate able to treat 23 t of waste per hour. The plant processes between 375 and 400 kt of waste per year, mostly of household origin as shown in Figure 45 and Table 16. The plant imports around 25% of total waste input from UK and features a biogenic fraction of 50%. The total amount of CO_2 emitted (fossil+biogenic) is around 1.14 t_{CO2}/t_{waste}, which corresponds to annual emissions ranging between 430 and 460 kt of CO_2 per year. The reported average number of operational hours was between 8,000 and 8,100 h/y over the last years. The plant features a net electric power export at design conditions of 24 MW and in 2017 generated 130 GWh of electricity plus 650 GWh of thermal energy exported for district heating purposes (heat production has the priority during Winter). The district heating system is operated by Fortum Oslo Varme with a 60-miles long distribution network which is going to be expanded in capacity (Fortum, 2018).

Table 16: Processed waste composition (ISWA, 2013).

Klemetsrud - Waste Composition	
Data from ISWA,2013	%mass
Domestic	64.6%
Industrial	33.5%
Pellet	0.0%
Sludge	0.0%
Hospital	1.0%
Biomass	0.0%
Other	0.9%

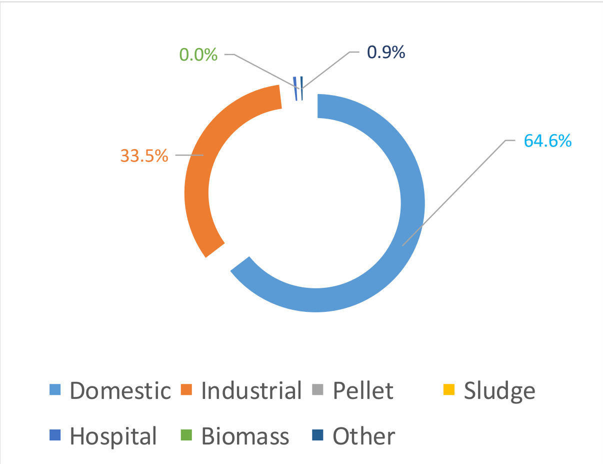

Figure 45: Processed waste composition breakdown

The Klemetsrud CCS project is part of a wider Norwegian full-scale CCS plan (Gassnova, 2016 and CCSNorway, 2019), involving other CO_2 emitters, as well as the development of large-scale transportation and storage infrastructure.
The timeline reported in Figure 46 shows the steps envisaged by Fortum Oslo in order to move from the Conceptual study results published in 2018 towards the plant detailed design and installation which is expected to be completed (in case of approval of the investment decision) by 2023-24.

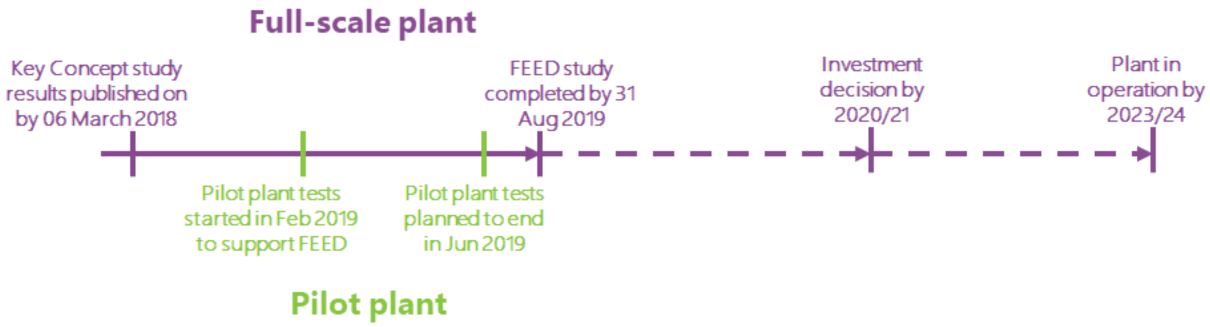

Figure 46: Time evolution of Klemetsrud CCS project. Sources: Fortum, 2018.

Since February 2019, Fortum has operated a provisional Pilot Plant (depicted in Figure 47), designed by Shell Cansolv and engineered by Kanfa (https://www.kanfagroup.com/2019/03/11/carbon-capture-test-pilot/), aimed at demonstrating the functionality of the capture technology and supporting the FEED study. Tests have been focused on the emissions and solvent degradation issues. The Pilot processes a slipstream of around 1500 Nm^3/h (corresponding to 0.5% of the overall flue gas flowrate), containing 10 – 12% of CO_2 (mol dry basis) and targets a CO_2 capture rate higher than 90%. The thermal energy for solvent regeneration is supplied by a dedicated boiler.
The unit has collected approximately 3500 operational hours (and it was still running in September 2019).

Figure 47: Fortum Oslo Pilot Plant for CO_2 Capture from WtE. Source: adapted from Bjerkas, 2019.

The Full-scale CCS project is currently under Front-End Engineering Design which aims at advancing and detailing the engineering to a ±20% CAPEX and OPEX uncertainty. The technology selected for CO_2 capture is Shell Cansolv (Fortum, 2018) and the engineering company Technip FMC will engineer and build the plant (Stuen, 2019). The full-scale will be a Retrofit plant, integrated with the existing WtE lines (K1-2-3) and is designed to capture 414 kt/year of CO_2, targeting a removal rate of 90% of the overall amount of CO_2 released by the plant. Fortum also plans to add a possible fourth line (K4) to treat additional waste (i.e. 169 kt/y) by 2025.

Given the average biogenic fraction of the waste (i.e. 50%), negative CO_2 emissions may be achieved in case the CO_2 is permanently stored. The main goal of the project is to decarbonize waste treatment, without impacting the CO_2 intensity of the electric grid (which is already decarbonized in Norway).

The key technical peculiarities of the full-scale CO_2 capture facility are (Fortum, 2018):

- An induced draft blower which extracts the flue gases from the three WtE lines (and overcomes the pressure drops across the CO_2 capture plant)
- There is no additional flue gas treatment, except for
    1. A gas-gas heat exchanger which cools down flue gases to 70 °C (while pre-heating the CO_2-lean gases leaving the CO_2 absorber to 75 °C to ensure buoyancy and dispersion at stack)
    2. A Direct Contact Cooler which chills the flue to 40 °C ahead of the CO_2 absorber
- The absorber is a packed column with water wash on top (both large single-column and 3 parallel absorber trains have been assessed)
- A thermal reclaimer is envisaged for nitrosamines and heavy metals removal from the solvent
- A new steam turbine, of the extraction and condensation type, is envisaged for lines K1-2 to allow steam extraction for the solvent reboiler

According to Fortum (2018) and Stuen (2019), the captured CO_2 will be compressed to 40 bar(g) and then dehydrated before being transported via truck (which should be emission free) to Oslo harbor where a dedicated CO_2 liquefaction (at -27 °C, 16 bar) and intermittent storage plant (with 2 to 4 days storage capacity by means of two Horton Spheres of 15 to 18 m in diameter). Then, CO_2 will be transported by ship to the final geological storage site. The CO_2 storage site will be in the North Sea. The engineering design and logistic of final storage are under definition within the Northern Lights project (Sandberg, 2019).

The major challenges to be tackled for the upscaling from pilot experience to full-scale plant in Klemetsrud are (Fortum, 2018, and Stuen, 2019):

- The CO_2 capture plant footprint which shall be reduced compared to the first envisaged configurations
- The need to develop and demonstrate the viability the complete value chain (especially final transportation and storage)
- The overall capital cost required to build a First-Of-A-Kind plant

- The design of reasonable (i.e. being robust to preserve the plant availability but avoiding overdesign) retrofitting solutions for integration with the existing WtE plant (e.g. some components such as new K1-2 extraction steam turbine and condenser shall be replaced with new ones).
- The definition of suitable heat integration solutions aimed at satisfying at the same time the heat demand from District heating (especially during Winter) and the thermal consumption for CO_2 capture operation (i.e. solvent regeneration).

With reference to the last point, the conflict between solvent regeneration and district heating will be managed with the installation of new heat pumps.
Currently, in the existing WtE plant, the thermal power output (at design conditions) for district heating is (Fortum, 2018):

- 112 MW_T in Winter (when an already existing heat pump preheats the district heating return, providing 13 MW_T)
- 26 MW_T in Summer

Concerning the new full-scale WtE+CCS plant, as described by Fortum in the Concept study (2018), two clearly distinct operational modes are defined for the WtE+CCS plant, one for Winter and one for Summer. The energy balance for the Winter case is represented in Figure 48 (Fortum, 2018). In this configuration, to keep the district heating output unaffected, a new heat pump (36 MW_T, which will use part of the heat removed by the Direct Contact Cooler) is required, in order to replace the heat removed by the steam extracted from the steam cycle (taken from the new extraction turbine in K1-2) and used for solvent regeneration purposes in the CO_2 capture plant. The outcome is a reduction in the net power output of the WtE+CCS plant, since the gross power output of the steam turbine is almost offset by the power consumption of the new heat pump. In the overall balance, also the power consumption for CO_2 conditioning, storage and loading at the harbor have to be considered. Therefore, in Winter it is expected that there will not be net electric output produced by the WtE+CCS plant, but only useful thermal power for district heating purposes, which is by the way decarbonized due to CCS. This will allow the CCS plant to operate during the whole year, without requiring long stops or intermittent operations to satisfy the district heating thermal demand.

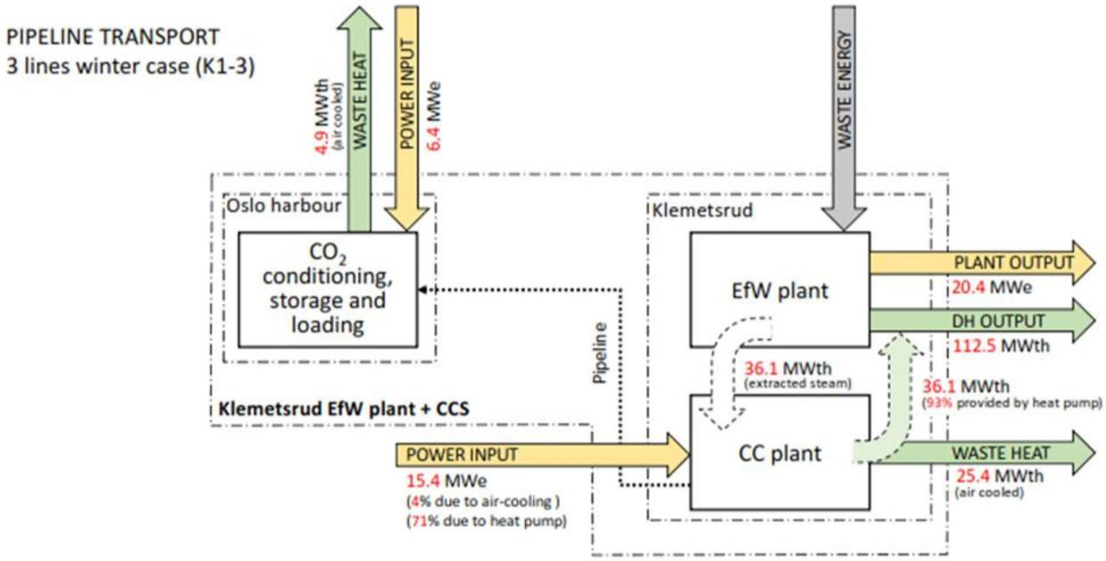

Figure 48: Power balance of the full-scale Klemetsrud WtE+CCS plant in Winter mode (thermal power flows are in green, while electric power flows are in yellow). Source: Fortum, 2018.

NOTE: The information reported for the Klemetsrud WtE+CCS project has been partially provided by the owner.

6.7 Saga City - Japan

The Saga City WtE plant is owned and operated by the Saga Municipality and it consists of 3 parallel Moving Type Grate Boilers and flue gas treatment lines with separate stacks, in operation since 2003. The plant is designed to process up to 300 t of waste per day (100 t/d per line) and in 2017 it treated 74,000 t. The average fraction of biogenic waste is around 50%, but the actual value varies considerably on a monthly basis (usually between 35% and 60%). In 2017, the net electricity production was 32,847 MWh (average net electric efficiency close to 20% on LHV basis). The gross electric power of the steam cycle powered by waste combustion is 4.5 MW_E. No district heating is carried out, essentially as a result of a lack of demand due to the mild climate of Saga City, but hot water is used to heat a pool nearby and heat supply to an adjacent farm is under planning. The WtE plant emits ~54 kt_{CO2}/y (220 t/day reported), including both fossil and biogenic emissions over the three lines. Flue gas has a concentration of CO_2 ranging between 8 and 18% (mol dry basis).

The CCU plant has been designed by Toshiba, and built upon the company's previous experience with one "pilot" plant (10 t_{CO2}/day, Mikawa thermal power plant, www.toshiba.co.jp/about/press/2009_09/pr2902.htm) and one "test" plant (20 kg_{CO2}/day, operated in Saga City WtE for 8,000 h since 2013).

The Saga city CCU plant is a commercial scale plant in continuous operation (maintenance is conducted on the occasion of WtE maintenance stops) since August 2016 (www.toshiba.co.jp/about/press/2016_08/pr1001.htm). The whole CCU project costed around 1.5 billion ¥ (Japanese Yen), equivalent to 13 M€ circa.

The CCU plant treats approximately 5% of total WtE flue gas (i.e. it processes around 3000 Nm^3/h), with a CO_2 removal target between 80% and 90%, corresponding to about 10 t of CO_2 captured per day. The CO_2 Capture technology supplied by Toshiba is chemical absorption based on a proprietary amine solvent. The thermal energy required for solvent regeneration is provided by steam extracted from the Saga City WtE section. The captured CO_2 is stored in a 100 m^3 buffer tank (up to 10 bar) and supplied in gaseous state at a pressure of 2 bar to an algae cultivation facility located a few hundred meters away from the WtE plant. Figure 49 shows an aerial view of the WtE, CO_2 capture and Algae cultivation facility.

The main technical challenges tackled during the CO_2 capture unit design have been the large variation of CO_2 concentration in flue gases and the HCl content of flue gases which poses corrosion issues on the plant components.

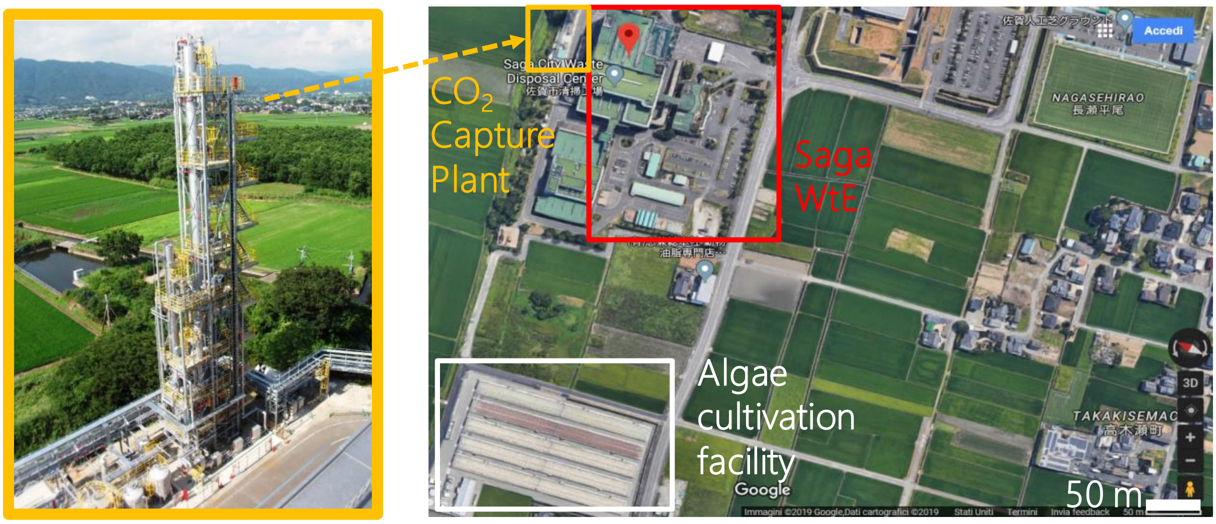

Figure 49: Aerial view of the Saga City WtE + CCU plant, with a particular image of the CO_2 capture plant (figure adapted from Google® maps aerial view and CO_2 capture picture from Kitamura, 2019).

NOTE: The information reported for the Saga City WtE+CCU plant has been partially provided by the technology provider.

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APPROVED BY	:	Vincenzo Tota

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TABLE OF CONTENT

1. Introduction to CCS/WtE Global Regulations

Waste to Energy (WtE) incineration technology combined with carbon dioxide capture storage (CCS) could form an essential part of the circular economy. Such technology is able to recuperate energy from waste[1] as well as fulfil the requirements of the following global regulations:

- The UNFCCC's Paris Agreement (2016), COP 24;
- The Kyoto Protocol (1992) and the Doha Amendment to the Kyoto Protocol (1997);
- The Energy Charter Protocol on Energy Efficiency and related Environmental Aspects (1991); and,
- The Convention and following Protocol (1979) on Long-Range Transboundary Air Pollution.

The present Task n° 2 covers regulations related to WtE/CCS in ten selected countries (Italy, Germany, the Netherlands, Norway, the UK, USA -California, Australia -Western Australia, South Africa, Japan and India) with a focus on WtE/CCS that takes in municipal solid waste (MSW).

The following thematic issues are air emission, waste water discharges, potential feedstock, incentives, solid residues, relevant laws and potential changes to the current regulatory standards and are discussed through following key questions listed in the next section.

2. WtE/CCS Regional and National Regulations

2.1 What is the limit on air emissions level/value defined by the competent Authority on air pollutants at chimney stack for WtE plants in your country/region?

Limits on air emission at the WtE stacks are provided in Table 1 for the selected Countries.

In **Europe**, air emission level values (ELVs) at the stack are regulated under the Directive on Industrial Emissions (IED, 2010/75/EU).

At the national level, the following regulation applies:

- In Germany, *the 17th BImSchV*, Article 8 specifies ELVs for waste incineration;
- In the Netherlands, *the Activities Decree* with dedicated *Activities Regulations* sets out ELVs as well as environmental regulations for industrial facilities, including waste incineration plants, providing the means for compliance, such as the techniques to be used, and imposing other requirements, such as ways to measure emissions[2];
- In Italy, the adoption of the *Legislative Decree 152/2006* on Environment Standard, Titolo III-bis, applies to the WtE industry;
- In Norway, the *Waste Regulation No. 930 adopted in 2004* set out provisions on pollution control relevant to WtE;
- The UK have autonomously implemented the Industrial Emissions Directive (2010/75/EU) (IED) with the *Environmental Permitting Regulations (2016)* rilevant to England and Wales. Schedule 13 of above-mentioned Regulation specifies that "the regulator must exercise its relevant functions so as to ensure compliance with the […] provisions of the IED".

In **Australia** air emissions limits are slightly higher at the national level and vary from one State to another. Table 1 shows the limit on air emissions in Western Australia (W.Australia) as defined by *Environmental Protection Act 1986, Part V, License.*

In **South Africa** the *Waste Act (2008)* sets out air emissions standards for waste incineration.

For **USA (California),** it has been observed through the ELVs[3] set for the Placer county (CA).

In **Japan**, the Ministry of Environment (MoE) is responsible for setting standards under the *Air Pollution Control Act (1968)*, Chapter 2 that describes the Technical Standards (*Regulatory*

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[2] *Rijkswaterstaat*, Ministry of Infrastructure and Water Management, "Activities Decree," accessed on 13 June, 2019, URL: https://rwsenvironment.eu/subjects/environmental-0/activities-decree/

[3] RULE 206 INCINERATOR BURNING, URL: https://www.placerair.org/DocumentCenter/View/2182/Rule-206-PDF

Measures against Air Pollutants Emitted from Factories and Business Sites and the Outline of Regulation, 1998) covering Regulation of Soot and Smoke Emission (outlined in Table 1), and managed by the Ordinance of the Ministry of the Environment. [4, 5]

In **India** the Central Pollution Control Board (CPCB) sets out ELVs under *Annexure-I* as shown in the table below.

[4] MoE, Japan: Air Quality Standards, accessed on 7 June 2019, URL: https://www.transportpolicy.net/standard/japan-air-quality-standards/

[5] *Regulatory Measures against Air Pollutants Emitted from Factories and Business Sites and the Outline of Regulation (1998)*

Table 1 ELVs across ten selected countries applicable to new WtE

Regulated Substances	Europe					Australasia	Africa	N. America	Asia	
	Italy	**Germany**	**The Netherlands**	**Norway**	**UK**	**Western Australia**[6]	**South Africa**[7]	**CA, USA**[8]	**Japan**[9,10]	**India**[11]
	Expressed as mg/Nm3*****, Daily emissions values [half hourly average], Flue gas conditions: EU/Australia: Dry gas, 11% O2; South Africa: Dry gas 10% O2							Expressed as mg/sm3, Daily emissions values, Flue gas Conditions Dry gas, 7 % O2	Expressed as mg/Nm3*****, Flue gas Conditions Dry gas 11% O2	Expressed as mg/Nm3 Flue gas Conditions Dry gas 11% O2
Total Dust	10 [30]	5 mg/m³ *	5 [20]	10	10	10	10	24 (mg/dscm)	17	50
TOC	10 [20]	10	10 [20]	10	10	10	10	N/A	N/A	20
HCL	10 [60]	10	8 [60]	10	10	10	10	25 (or 95% reduction obtained by the abatement system)	29	50
HF	1[4]	1	1 [4]	1	1	1	1	N/A	1 mg/m3	4
SO_2	50 [200]	50	40 [200]	50	50	50	50	30 (or 80% reduction obtained by the abatement system)	60	200
NO + NO_2	200 [400] (WtE treating >6 ton/hours) 400 (WtE treating ≤ 6 ton/ hours)	150 mg/m³ (200 mg/m³ for plants <50MW thermal input)	180 [400] 70 monthly average	200 (WtE treating >6 ton/hours) 400 (WtE treating ≤ 6 ton/ hours)	200 (WtE treating >6 ton/hours) 400 (WtE treating ≤ 6 ton/ hours)	200 (WtE treating >6 ton/hours) 400 (WtE treating ≤ 6 ton/ hours)	200	150	217	400
NH_3	30 [60]	10	[15]	30	N/A	N/A	10	N/A	N/A	N/A
CO	50 [100]	50	30 [100]	50	100	50	50	50-150	10	100
Cd	0.05 total for Cd+Tl***	0.03 mg/m³	0.05 total for Cd+Tl	0.05 total for Cd+Tl	0.05 total for Cd+Tl	0.05 total for Cd+Tl	N/A	0.020	0.01 mg/Nm3	0.05 total for Cd+Tl
Tl		0.05 total for Cd+Tl *******					N/A	N/A	10 mg/Nm3	
Hg	0.05***	0.05*******	0.05	0.05	0.05	0.05	0.05	0.08 (or 85% reduction obtained by the abatement system)	0.06	0.05
Sb, As, Pb, Cr, Co, Cu, Mn, Ni, V	0.5 as total sum***	0.5 as total sum*******	0.5 as total sum	0.5 as total sum	0.5 as total sum	0.5 as total sum	0.5 as total sum	0.20 (Pb only)	10 mg/Nm3	0.5
PCDD + PCDF I-TEQ	0.1 ng/Nm3 ***	0.1 ng/Nm3*******	0.1 ng/Nm3 ***	0.1 ng/Nm3*******	0.1 ng/Nm3***	0.1	0.1	13****** ng/dscm	9.3****** ng/Nmc	0.1 ng/Nm3***

*(10 mg/m³ for plants <50MW thermal)
** parts per million dry volume (hourly average)
*** Average ELVs over a sampling period of a minimum of 6 hours and a maximum of 8 hours applies to the total concentration of dioxins and furans calculated in accordance with Part 2 of Annex VI of the IED.
**** For dioxins/furans, you must meet either the Total Mass Basis limit or the toxic equivalency basis limit.
***** If not otherwise specified
****** Total mass basis
******* Value not identified and assumed equal to the one provided by EU WID

6 For Western Australia ELVs assumed are aligned with EU WID indications according to the advice of the Environmental Protection Authority to the Minister for Environment under Section 16(e) of the Environmental Protection Act 1986, Report 1468, April 2013

7 Waste Act, 2008, Schedule 1

8 NCBI, "Waste Incineration & Public Health", accessed on 13 June, 2019, URL: https://www.ncbi.nlm.nih.gov/books/NBK233621/table/ttt00027/?report=objectonly

9 ELVs defined according to JEGS 2010, to be verified for possible changes according to 2018 version

10 ELVs for new Municipal Waste Combustion Plant with a capacity over 250 tons per day

11 CPCB, 2019, Annexure-I, accessed on 10 June, 2019, URL: http://cpcb.nic.in/common-hw-incinerators-annexure/ also available at: http://cpcb.nic.in/uploads/MSW/SWM_2016.pdf

2.2 What is the limit on waste water discharge defined by the competent Authority in your country/region?

Based on the research carried out, only the selected European countries have specific ELVs dedicated to waste water discharge from incinerators. However, all the countries follow their respective general waste water standards for industrial plants not specified hereinafter since not specifically associated to WtE units.

In **Europe**, the Directive on Industrial Emissions (IED, 2010/75/EU) applies to WtE industries and includes ELVs for waste water discharged from incinerators after the cleaning of waste gases.

In Italy, waste discharge after purification of gaseous effluents released from incineration plant is specified under *Leg. D. 152*, *Titolo III-bis* with the following ELVs as shown in the Table 2 below.

In Germany the Ordinance on waste water discharge into water bodies (*AbwV*)[12] Appendix 33 specifies that waste water from waste gas treatment of municipal waste incineration plants shall not be discharged into water bodies, except for existing discharges which were legally in service before 1 August 2002 or which were legally started to be constructed at that time. For existing discharges, however, the Table 2 indicates all the relevant ELVs.

In the Netherlands, ELVs for discharges of waste water from the cleaning of waste gases in waste co-incineration plants are set out in Article 5.27 of the Activity Decree[13] and hereinafter presented.

Similarly, in the **UK**, emission standards are set as determined in the IED for incineration waste gases cleaning. As discussed above, the Environmental Permitting (England and Wales) *Regulations 2016* requires the provisions of the IED to be applied in England and Wales.

[12] "*Verordnung über Anforderungen an das Einleiten von Abwasser in Gewässer (Abwasserverordnung)*", accessed on 13 June, 2019, URL: https://www.gesetze-im-internet.de/abwv/

[13] Wetten, Artikel 5.27, accessed on 13 June, 2019, URL: https://wetten.overheid.nl/jci1.3:c:BWBR0022762&hoofdstuk=5&afdeling=5.1&paragraaf=5.1.2&artikel=5.27&z=2019-05-02&g=2019-05-02

Table 2 Water discharge ELVs across selected countries after the cleaning of waste gases

	Europe				
	ITALY	GERMANY *	THE NETHERLANDS	NORWAY	UK
	Unit in mg/L otherwise stated				
Total Suspended solids	45	45	45	45	45
Mercury and its compounds expressed as mercury (HG)	0.03	0.03 9 mg/ton of incinerated waste	0.03	0.03	0.03
Cadmium and its compounds, expressed as cadmium (Cd)	0.05	0.05 15 mg/ton of waste	0.05	0.05	0.05
Thallium and its compounds, expressed as thallium (Tl)	0.05	0.05	0.05	0.05	0.05
Arsenic and its compounds expressed as arsenic As	0.15	0.15	0.15	0.15	0.15
Lead and its compounds, expressed as lead (PB)	0.2	0.1 30 mg/ton of waste	0.1	0.2	0.2
Chromium and its compounds, expressed as chromium (CR)	0.5	0.5 150 mg/ton of waste	0.5	0.5	0.5
Copper and its compounds, expressed as copper (Cu)	0.5	0.5	0.5	0.5	0.5
Nickel and its comosti, expressed as nickel (Ni)	0.5	0.5 150 mg/ton of waste	0.5	0.5	0.5
Zinc and its compounds, expressed as zinc (Zn)	0.5	1.0 300 mg/ton of waste	1.0	1.5	1.5
Dioxins and furans (PCDD + PCDF) as TEQs	0.3	0.3	0.1 ng/l	0.3	0.3

* ELVs expressed in mg/l as 24-hour mixed sample

2.3 Are there any relevant prohibitions/limitations defined by the competent Authority on potential feedstock for the WtE plants operation in your country/region? If so, please explain in detail.

The potential feedstock[14] for WtE incineration plants refers to the incoming waste used for burning to produce electricity or heat energy. More generally in **Europe**, the EU countries have developed their respective country regulation according to the EU directives on wastes and executed through the national laws (examples are provided, hereinafter).

In Italy, "operator of incinerators must adopt all the necessary measures to safeguard the feedstock in order to eliminate and limit any negative effects on the environment, in particular air pollution, soil and surface and groundwater source, as well as the environment, smell and noise, and direct risk on human health."[15] As such, these measures must meet the minimum requirement of the legislative *decree 152/2006* under the guidance of the EU directive on waste.

In Germany, the *Kreislaufwirtschaftsgesetz* (KrWG)[16] implements a waste hierarchy. As a result, only wastes that cannot be utilised or treated in another environmentally friendly way (i.e. alternative treatment higher up the waste hierarchy) can be incinerated.

The 17. *BImSchV* does not set specific prohibitions or limitations on the potential feedstocks for WtE plants. However, according to the Interest Group of Thermal Waste Treatment Plants Germany[17], permits for waste incineration plants typically include limits on the concentration of certain pollutants in the waste accepted for incineration, as well as other parameters such as temperature, flash point, melting point and pH value of the waste.

In Norway feedstock at incineration plant should be weighed and registered and the right measures must be put in place to deal with hazardous or infectious waste.[18]

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[14] According to the BAT, waste should be recorded with specific description, EWC classification, annual disposal rate and a statement on whether or not such waste are hazardous (additional information needed for hazardous waste) or non-hazardous.

[15] Legislative Decree 152, Article 237-septies, Paragraph 1

[16] Bundesministerium der Justiz und für Verbracherschutz, accessed on 13 June 2019, URL: https://www.gesetze-im-internet.de/krwg/

[17] ITAD, Anforderung an Abfälle zur Verbrennung, accessed on 13 June 2019, URL: https://www.itad.de/information/wiefunktionierteinemva/338..html

[18] Waste Regulations, Chapter 10, Section 10 (5)

In the **UK**, according to the Environmental Permitting (England & Wales) Regulations 2016, Treatment of Incinerator Bottom Ash (IBA), hazardous wastes and wastes that are in a form which is either sludge or liquid shall not be accepted.

For **Australia (W.Australia)**, the present research does not highlight any specific prohibition/limitation on potential feedstock for the WtE plants.

In **South Africa** there are specific requirements that exist for waste storage, that must be designed and operated in such a way so as to prevent the unauthorised or accidental release of any polluting substances (gaseous, liquid or solid) into the air, soil, surface water and groundwater

In **USA (California)**, similarly to EU-BAT regulation, the maximum available control technology (MACT) approach applies for managing wastes fed to the incineration plant.

In **Japan**, Under Chapter II, Section 1, Article 6 of the law, the Municipal Solid Waste Management Plan comes into effect, giving power to the municipalities to set the regulation, including those on WtE feedstock, under Paragraph 4 of Article 2 of the Municipalities Law (Law No. 67 of 1947).

In **India**, Solid Waste Management policy requires that wet and dry wastes should not be mixed so that only non-compostable and non-recyclable wastes with at least 1,500 kcal/kg should reach WtE plants.[19]

2.4 Are there any relevant incentive defined by the competent Authority for the WtE plants operation regarding energy production and/or CO_2 reduction scheme for CCS adoption in your country/region? If so, please explain in detail.

WtE adoption diverts waste from landfill sites and, moreover, CCS technology application results in abating/reducing carbon emission into the atmosphere. Accordingly, especially for Europe, incentives defined by the competent Authority may be reached in the selected countries selling credits from emission savings and having the possibility to access funding solutions.

In **Europe,** the EU emissions trading system (EU ETS) is a cornerstone of the EU's policy to combat climate change and serves as a key tool for reducing GHG emissions in a cost-effective way, but waste incineration plants processing MSW are excluded[20] from such scheme.

[19] KSPCB, SWM-Rules-2016, accessed on 12 June 2019, URL: https://www.kspcb.gov.in/SWM-Rules-2016.pdf

[20] Annex 1 of the EU ETS Directive states: "*Combustion of fuels in installations with a total rated thermal input exceeding 20 MW (except in installations for the incineration of hazardous or municipal waste)*"

However, there are national incentives for CCS application in WtE incinerators as detailed below.

In Germany, the Federal Ministry of Education and Research (BMBF) is funding innovative R & D projects in the area of CCU (carbon storage and utilisation) as part of the measure "CO_2 Plus - Substantive use of CO_2 to broaden the raw material base".

In addition, the BMBF funding initiative "r + Impuls - Innovative Technologies for Resource Efficiency - Stimulating Industrial Resource Efficiency" supports implementation-oriented industrial projects in the field of CCU. The Federal Ministry for the Environment, Conservation, Construction and Nuclear Safety (BMUB) Environmental Innovation Program (UIP) can sponsor demonstration projects that are the first to implement an innovative technology that mitigates the burden on the environment.[21]

In The Netherlands, the plan outlining the policies of the Dutch government for the period of 2017-2021[22] includes an ambitious acceleration in national climate policy and a strive to take responsibility for reaching the goals of the Paris Climate Agreement. The main target is a 49% reduction in CO_2 emissions from 1990 levels by 2030, equating to an annual reduction of 56 Mt CO_2. The emission reduction targets will be formalised in a new climate law.

Noteworthy is the contribution of CO_2 capture and storage (CCS) towards the overall target, with an 18 Mt reduction from the industrial sector, and a 2 Mt reduction from the waste incineration sector foreseen. To achieve these measures, a host of supporting policies have been listed, with a total government expenditure expected of 4 billion euros per year to support emissions reduction and the energy transition.

The long-standing feed-in tariff system, the SDE+ (stimulation of sustainable energy production), will be expanded to include new emission reduction technologies (SDE++), where CCS is highlighted explicitly. Furthermore, the government will engage with the Port of Rotterdam Authority, to support the accelerated uptake of CCS, presumably within the harbour's considerable petrochemical industry (CATO, 2017)[23].

The Norwegian Emission Trading System (ETS) was amended in June 2007 and February 2009 to bring its program's features in line with Directive 2003/87/EC and thereby facilitate

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[21] *Bundesministerium für Umwelt, Nuturschutz und nukeare sicherheit, « Klimaschutzplan 2050 Klimaschutzpolitische Grundsätze und Ziele der Bundesregierun »* accessed on 13 June, 2019, url : https://www.bmu.de/fileadmin/Daten_BMU/Download_PDF/Klimaschutz/klimaschutzplan_2050_bf.pdf

[22] Government coalition agreement (2017): https://www.kabinetsformatie2017.nl/kabinetsformaties/k/kabinetsformatie-2017/documenten/publicaties/2017/10/10/regeerakkoord-vertrouwen-in-de-toekomst

[23] CATO, CO_2 Capture, Transport and Storage in The Netherlands: https://www.co2-cato.org/news/news/new-dutch-government-coalition-commits-to-ccs

compatibility with the EU ETS during the Kyoto commitment period (Phase II, 2008-12). The two programs are now fully harmonized.

The **UK** has a legally-binding target of achieving 15% of its total energy (electricity, heat and transport fuel) from renewables by 2020. A range of incentive schemes are in place to achieve this target. WtE/CCS are eligible for the following:

- The Green investment bank invests debt or equity in green infrastructure projects including WtE, across all stages of the project lifecycle (development, construction and operations).[24]
- The 2017 Clean Growth Strategy incentives/funding where the UK Government's ambition is to become a leader in Carbon Capture, Utilisation and Storage (CCUS) technology.[25] It aims "to have the option of deploying CCUS at scale during the 2030s, subject to costs coming down sufficiently" (p.70). To support this, the Government committed to spend up to £100 million from the BEIS Energy Innovation Programme to support industry and CCUS innovation to improve business and industry efficiency and to further reduce the cost of deploying CCUS. In August 2018 the Government announced a £15m call for CCUS innovation projects to encourage cost reduction.[26]

Australia's emissions reduction fund replaced the abolished carbon price scheme in 2014. The Government allocated resources.[27] to provide for purchasing in the Emissions Reduction Fund. Activities supported through the Emissions Reduction Fund shall provide important environmental, economic, social and cultural benefits. On 25 February 2019 the Australian Government announced the Climate Solutions Fund bringing the total investment in the Emissions Reduction Fund to $4.55 billion and deliver around another 100 million tonnes of emissions reductions by 2030.

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24 Green Investment Group, Macquarie, "A market leader in green finance," accessed on 13 June, 2019, URL: http://greeninvestmentgroup.com/what-we-do/

25 HM Government, The Clean Growth Strategy: Leading the way to a low carbon future," accessed on 13 June 2019, URLhttps://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/700496/clean-growth-strategy-correction-april-2018.pdf

26 Innovate UK, "£15 million call launched for Carbon Capture, Utilisation and Storage innovation," accessed on 13 June, 2019, URL: https://ktn-uk.co.uk/news/15-million-call-launched-for-carbon-capture-utilisation-and-storage-innovation

27 Australian Government Department of the Environment and Energy, "About the Climate Solutions Fund – Emissions Reduction Fund," accessed on 13 June, 2019, URL: https://www.environment.gov.au/climate-change/government/emissions-reduction-fund/about

In February 2019, a carbon tax of 120 rand (8.48 USD) per tonne of carbon dioxide equivalent has been introduced in **South Africa** (effective from the 1st of June 2019) foreseeing also tax-free allowances during the first phase of the mechanism until around 2022[28].

Public Sector Funding solutions for WtE in South Africa are listed as followed:

- Western Cape Government: Cape Capital Fund
- Eskom: Integrated Demand Management Rebate[29]
- Industrial Development Corporation: Green Energy Efficiency Fund
- Development Bank of South Africa: Green Fund
- Critical Infrastructure Programme (CIP)
- MCEP - industrial financing
- MCEP - production incentive
- Manufacturing Investment Programme (MIP)

In **California (USA)**, the California cap-and-trade program[30] came into force in 2013 and regulated by the California Air Reduction Board (CARB). Since then, the program has involved more than 450 businesses responsible for 85% of California's total GHG emissions. The cap-and-trade rules first applied to electric power plants and industrial plants that emit 25,000 tons of carbon dioxide equivalent per year or more.

In **Japan**, following the enactment of the Act on the Promotion of Global Warming Countermeasures (1998), the Kyoto Protocol (2002) and the Action Program to Arrest Global Warming to stabilize the level of CO_2 emissions (per capita) to 1990 levels by 2020, the establishment of the Japan voluntary emission Trading Scheme (JVETS) was realized through two schemes: the experimental domestic ETS (JVETS); and, the two offset crediting systems (J-CREDIT SCHEME). At the global level, Japan has established the Joint Credit Mechanism (JCM)[31] through the development and exportation of low carbon technology, products and services outside of Japan.

In **India** the Ministry of New and Renewable Energy (MNRE) offers financial incentives to a proponent who plans to set up a waste-to-energy project as per the prevailing policies of the

[28] Reuters, "South African parliament approves long-delayed carbon tax bill" accessed on 13 June, 2019, URL: https://www.reuters.com/article/us-safrica-carbontax/south-african-parliament-approves-long-delayed-carbon-tax-bill-idUSKCN1Q81U8

[29] Eskom,, "Powering your world," accessed on 13 June, 2019, URL: www.eskom.co.za/sites/idm/Pages/Home.aspx

[30] C2ES, California Cap and Trade, accessed on 13 June, 2019, URL: https://www.c2es.org/content/california-cap-and-trade/

[31] Mongolia, Indonesia, Bangladesh, Cambodia, Costa Rica, Ethiopia, Indonesia, Kenya, the Lao People's Democratic Republic, Maldives, Mexico, Palau and Vietnam are all signatories to this bilateral treaty.

ministry. The incentives are given to both private as well as public sector entrepreneurs and investors having technical and managerial capabilities. Financial assistance is provided by way of interest subsidy in order to reduce the rate of interest to 7.5%, capitalized with an annual discount rate of 12 %; and, demonstration projects comprising innovative projects for generation of power from municipal solid wastes and selected industrial wastes.:[32]

The central financial grant for these projects would be released after successful commissioning of the project, which implies operation of the project for three months, including continuous operation for at least 72 hours at minimum of 80% rated capacity.

The electric energy distribution from waste to energy plants is ensured through procurement companies in the respective state. The same development of intrastate transmission projects through a competitive bidding route for WtE projects can be made available according to the requirements//decision defined/provided by the State Electricity Regulatory Commissions (SERCs). [33]

2.5 Are there any significant barriers (e.g relevant authorization procedures, taxations) to WtE plant construction and operation defined by the competent Authority in your country/region?

Barriers to WtE plant construction and operation can be associated with their environmental control, the waste management policy and/or the lack of waste supply.

For **Europe**, Directives 2011/92/EU (Environmental Impact Assessment) and 2010/75/EU (Industrial Emission Directive) should be taken in account for the development of a WtE/CCS initiative. As such, the EU countries have developed their respective permitting procedure and regulations in accordance to the above-mentioned Directives and executed through national laws (some examples are provided, hereinafter).

Italy adopted a BAT approach. Therefore, in order to operate a waste incineration plant, the following points should be clarified with a dedicated request of application:

- The amount of heat generated;
- The amount of waste generated;
- The amount of waste disposal; and,

[32] EAI, Indian Government Support for Urban Waste to Energy Projects" accessed on 13 June, 2019, URL: http://www.eai.in/ref/ae/wte/pol/urban_waste_govt_support.html

[33]The Law Reviews, "India," The Energy Regulation and Markets Review, accessed on 13 June, 2019, UR https://thelawreviews.co.uk/edition/the-energy-regulation-and-markets-review-edition-6/1144320/india

- The techniques adopted and the related monitoring measures.[34]

Therefore, permits are issued based on the types of waste that can be treated in the plant under the EU code on waste treatment, meeting the authorized nominal capacity, nominal heat load and ELVs set out by the local authority taking in account existing site condition.

In Germany, WtE plants are subject to environmental permitting procedures under the Federal Immission Control Act (*BImSchG*)[35], in particular Articles 4-6. The permit conditions are affected by ordinances complementing the *BiMschG*, in particular the 17. BImSchV.

In Norway, an operator of an incineration plant must have a permit under the terms of section 29 of the Pollution Control Act, cf. subchapter III. An application for a permit shall be sent to the competent authority. An emissions permit for an incineration plant shall at minimum contain the provisions described in appendix VIII to Chapter 10 of the Waste Regulation. A permit shall not be granted unless the plant can meet all relevant requirements in said chapter with associated appendices. The contents of the application and of the emissions permit shall otherwise follow the requirements set down in chapter 36 of Regulations no. 931 of 1 June 2004 relating to the restriction of pollution (Pollution Regulations) on the processing of applications pursuant to the Pollution Control Act. The competent authority may set additional requirements or stricter requirements than those listed in this chapter, depending on local conditions and characteristics of the incineration plant in question.

In The Netherlands a WtE proponent will need an all-in-one permit for physical aspects (*Omgevingsloket* Online, OLO) through municipal or provincial authority.

Moreover. the **UK** developed their permitting procedures regulation according to above mentioned EU directives. Presently the Government's legislative program seeks to move the focus of planning decision making to local communities. Only very large WtE projects (above 50MW power output) remain outside local planning control. These large projects deal with by the Major Infrastructure Panel.

In **Australia (Western Australia**) obstacle to WtE adoption is the fact that there is no levy on waste disposed to landfill. The same waste supply conditions should be checked carefully since few local government authorities would generate an amount of residual waste post-recycling achieving required economy of scale.

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[34] Legislative decree 152/2006, Article 237-quinquies

[35] "*Gesetz zum Schutz vor schädlichen Umwelteinwirkungen durch Luftverunreinigungen, Geräusche, Erschütterungen und ähnliche Vorgänge (Bundes-Immissionsschutzgesetz - BImSchG)"*, available at: https://www.gesetze-im-internet.de/bimschg/

Furthermore, it is noted that a proponent of a WtE project may apply to have it declared a 'coordinated project'[36] under the State Development and Public Works Organisation Act 1971 (SDPWO Act) involving an Environmental Impact Assessment process.

In **South Africa** significant barriers are related to limited availability and accuracy of waste generation data and waste compositions.

The challenges deterring proponents from adopting WtE include:

- Restrictions on independent power producers (IPPs) of electricity to directly supply power to municipalities;
- Synchronization of policies to be improved (energy and waste policies do not provide a solid platform for establishing WtE industries);
- Better integration of WtE into waste management planning could be foreseen;
- Knowledge of technologies by decision makers and institutional support;
- Low landfill tariffs.

In **USA (California)** a WtE plant, burning solid wastes, is a solid waste transformation facility that needs a full permit procedure according to Public Resources Code (PRC), Sections 44001 and 44002. The authorization shall be consistent with the county waste management plan, with the sector standards and including the air district quality authorization and the green light about the California Environmental Quality Act (CEQA) on the acceptability of the Initiative environmental impacts.

In **Japan**, the main barrier to WtE construction consists in a decrease in the volumes of residual waste due to the substantial increase in recycling levels. With reference to environmental control the national emissions limits are a baseline minimum in the absence of more specific limits that may be set at a regional level. Prefectural governments are free to set their own, more stringent limits specific to their jurisdiction. This results in significant differences across the country, with more heavily urbanized areas typically setting stricter limits than more rural prefectures.

In **India** it is worthwhile mention that the lack of waste separation prior to incinerating and the high cost of bringing in WtE technology discourage the development of this technology.

Non-compostable and non-recyclable wastes with at least 1,500 kcal/kg to be fed to WtE plants comprises only 10 to 15 per cent of the total waste.

36 Queensland Government, „Coordinated projects“ accessed on 13 June, 2019, URL: https://www.dsdmip.qld.gov.au/assessments-and-approvals/coordinated-projects.html

Even if India's Solid Waste Management policy requires that wet and dry wastes should not be mixed municipal governments use compacters to reduce the transport cost of the waste. Compacting compresses the waste and makes even gross segregation at the plant site impossible. In the absence of adequate feedstock of non-compostable and non-recyclable waste, it may become necessary to use auxiliary fuel, switching to co-incineration technology and increasing the cost of operating the plants
Moreover, the concept of waste to energy (WtE) is still in the nascent stage in India, as such many initiatives were not successful and faced severe opposition from public in locating WtE plant in their neighborhood due to pollution concerns.

2.6 Are there any relevant prohibitions/limitations defined by the competent Authority on solid residues from WtE plants operation in your country/region? If so, please explain details.

As far as more relevant to solid residues acceptance from WtE operation it is worthwhile to highlight the requirements defined by each country, where applicable, to ensure the appropriate combustion of the treated wastes and to avoid the production of not desired ashes. The same classification of the solid residues produced, its final destination (possible reuse to be considered), and related possible need of pre-treatment, have to be taken in consideration for developing a WtE initiative in the selected countries.

In **Europe**, including the UK, the EU Waste Incineration Directive WID specified the following operating conditions: "all plants to keep the incineration […] at a temperature of at least 850°C for at least two seconds. If hazardous waste with a content of more than 1 % of halogenated organic substances, expressed as chlorine, is incinerated, the temperature has to be raised to 1,100 C for at least two seconds.[37] Generally, the slag and heavy ashes produced by incineration plants should not present the same total unburnt content as the total organic carbon (TOC) exceeding 3% of weight, or a loss through ignition exceeding 5% in dry weight (DW).[38] Similar procedure is translated Italy, Germany (17. BImSchV Article 12), the Netherlands, Norway. More generally the EU Countries developed their regulation according to EU waste policy and executed through national laws also for the management of solid waste produced by incineration (German example is hereinafter provided).

In Germany, "prior to the determination of the processes for the recovery or disposal of waste resulting from the incineration or co-incineration of waste, in particular slag, bottom ash and filter and boiler dusts, their potential for contamination, in particular their physical and chemical properties and their content of harmful substances shall be determined using appropriate tests.

[37] WID, 2000/76/EC
[38] Italy: *Legislative Decree 152*, Article 237-octies (1-3)

The tests are to be carried out for the entire soluble fraction and the heavy metals in the soluble and insoluble part.”[39]

In **Australia (Western Australia)** no specific requirements on solid residues have been identified, however the environmental compatibility of the initiative shall be obtained also for the management of the solid residues produced in the WtE operation foreseeing, where required, a post treatment[40] for their reuse or disposal in landfill.

In **South Africa**, the standard operating procedure[41] includes the following criteria aimed at ensuring the proper combustion of the treated wastes:

- Incinerator should be preheated to working temperature before charging any waste;
- Overloading of waste should be avoided at all cost;

For the proper management of solid wastes coming from incineration its category shall be recorded and have known composition.

For **USA (California)**, at the county level (Placer County), the general operating requirement should follow the method provided by the Air Pollution Control Officer. Therefore, “ […] only multiple-chamber starved-air incinerators may be used. The primary combustion chamber shall be maintained at no less than 1400 degrees Fahrenheit, and the secondary chamber shall be maintained at no less than 1600 degrees Fahrenheit; and for pathological waste, the incinerator shall distribute direct flame to pathological waste on a solid grate, the furnace design shall provide for a residence time in the secondary chamber for combustion gas of at least one second.[42]

WtE classifying solid wastes produced involves determining whether a waste is a federally regulated (RCRA) or a California regulated (non-RCRA) waste.

In **Japan** according to regulation[43] of waste management municipal solid waste shall be incinerated maintaining the surface temperature of the combustion gas generated in the

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[39] 17. *BImSchV* Article 12

[40] Waste Authority (Western Australia), “Waste Technologies : Waste to Energy Facilities” accessed on URL : http://www.wasteauthority.wa.gov.au/media/files/documents/SWIP_Waste_to_Energy_Review.pdf

[41] Department Water and Sanitation Republic of South Africa, “Process 39 Waste Incineration Process” accessed on 13 June, 2019, URL: http://www.dwa.gov.za/Documents/Policies/WDD/Waste_Incineration_Processs39.pdf

[42] Rule 206 Incinerator Burning, accessed on 13 June, 2019, URL: https://www.placerair.org/DocumentCenter/View/2182/Rule-206-PDF

[43] MoE, “Regulations of Waste Management and Public Cleansing Law,” accessed on 13 June, 2019, URL: https://www.env.go.jp/en/laws/recycle/03.pdf

combustion chamber at 800 degrees centigrade or more, the facility shall be equipped with a device to measure the temperature of the combustion gas in the combustion chamber and with an auxiliary combustion device necessary to keep the temperature.

India's operating procedure is similar the European version: "Incineration plants shall be operated (combustion chambers) with such temperature, retention time and turbulence, as to achieve total Organic Carbon (TOC) content in the slag and bottom ash less than 3%, or the loss on ignition is less than 5% of the dry weight."[44]

[44] CPVB, 2016, The Gazette of India, Extraordinary Part II, Section 3 (ii), accessed on 10 June, 2019, URL: http://cpcb.nic.in/uploads/MSW/SWM_2016.pdf

2.7 What are the relevant laws currently in force for WtE plant and CCS/CCU industry in your country/region?

The relevant laws currently in force for WtE (waste sector regulation and environmental protection acts) and CCS related regulations are shown in the hereinafter reported table.

Table 3 Comparative WtE/CCS Legal Framework for Selected Countries[45]

Region	Country	Country regulations		Region regulations	
		WtE	CCS	WtE	CCS
Europe	Italy	Leg.D. 152/2006, Title III -bis	Not available	WID 2000/76/EC WFD 2008/98/EC IED 2010/75/EC EIA Directive 2011/92/EU	Directive 2003/87/EC Directive 2009/31/EU CCS Act as of 2016
	Germany	The 17th BImSchV, Article 8			
	The Netherlands	Activities Decree			
	Norway	Waste Regulation No. 930/2004			
	UK	Environmental Permitting (England and Wales) Regulations (2016)			
Australasia	W. Australia	Environmental Protection Act 1986, Part V, License	Not available	Environment Protection and Biodiversity Conservation Act1999 Environment Protection and Biodiversity Conservation Regulations 2000	Not available

[45] Where it is written "Not available" means that no relevant regulations has been encountered.

Region	Country	Country regulations		Region regulations	
		WtE	CCS	WtE	CCS
Africa	South Africa	Waste Act (2008) National Environmental Management Act (NEMA) (Act 107 of 1998) Atmospheric Pollution Prevention Act (Act 45 of 1965)	Not available	Not available	Not available
N. America (USA)	California	California Air Resources Board 22 California Code of Regulations (CCR)	Not available	National Environmental Policy Act (1969) Resource Conservation and Recovery Act (1984) Clean Air Act (1970)	Not available
Asia	Japan	Basic Environmental Act (1993) & Basic Framework Act (2000) Waste Management and Public Cleansing Act (Waste Management Act), 1970	Not available	Not available	Not available

Region	Country	Country regulations		Region regulations	
		WtE	CCS	WtE	CCS
		Uniform National Effluent Standards Air Pollution Control Act (1995) Japan Environmental Governing Standards (JEGS) 2010			
	India	Waste to Energy (2014) Air (Prevention and Control of Pollution) Act (1981) Environment (Protection) Act of 1986 2001 Energy Conservation Act	Not available	Not available	Not available

2.8 What changes in regulations could we expect in the near future regarding compliance and support for the WtE sector and CCS/CCU industry?

The expected changes in regulation that can support WtE or CCS technologies for selected countries are mentioned as followed.

In **Europe**, the revised version of the Waste Framework Directive calls for EU member states to take more stringent measures to "ensure that waste that has been separately collected for preparing for re-use and recycling pursuant to Article 11(1) and Article 22 is not incinerated, with the exception of waste resulting from subsequent treatment operations of the separately collected waste for which incineration delivers the best environmental outcome in accordance with Article 4."[46 47 48]

The European Commission noted, however, that its member states have been too dependent on the incineration of urban waste and identified the best alternative route forward would be to replace old incinerators with newer plants that have the capacity to generate low or zero emissions with 20 to 30 years life span.[49]

Accordingly, the European Commission has published a final draft of the BAT Reference Document (BREF) on Waste Incineration[50,] calling for EU countries (including Italy, Germany, the Netherlands, Norway and UK) to align the permits in line with the BAT conclusions and their emission limit values and their regulations with more stringent prescriptions.

In parallel, regarding CO_2 emissions reduction, EU countries are committing to pursue the target taken under the Paris Agreement and to be executed through national laws (Dutch example is hereinafter provided).

The plan outlining the policies of the Dutch government for the period of 2017-2021[51] includes an ambitious acceleration in national climate policy and a strive to take responsibility for reaching the goals.

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[46] Waste Framework Directive, Article 10 (4)

[47] EC, "Circular Economy" accessed on 13 June 2019, URL: http://ec.europa.eu/environment/circular-economy/index_en.htm

[48] *Fraunhofer Umsicht, "Zur Rolle dur Termischen Arbfall – Behandung in der Circular Economy*" URL: https://www.umsicht.fraunhofer.de/content/dam/umsicht/de/dokumente/publikationen/2017/thermische-verwertung-circular-economy-studie.pdf

[49] ISPRA, 2019, "Rapporto sul recupero energetico da rifiuti in Italia," p. 10

[50] WI BREF (Final Draft, 2018), accessed on 13 June 2019, URL: http://eippcb.jrc.ec.europa.eu/reference/wi.html

[51] Government coalition agreement (2017), URL: https://www.kabinetsformatie2017.nl/kabinetsformaties/k/kabinetsformatie-2017/documenten/publicaties/2017/10/10/regeerakkoord-vertrouwen-in-de-toekomst

The main target is a 49% reduction in CO_2 emissions from 1990 levels by 2030, equating to an annual reduction of 56 Mt CO_2. The emission reduction targets will be formalized in a new climate law. Several measures have been identified and include an increased stimulation towards a more sustainable energy production (SDE++), focusing on emission reduction technologies, including in the waste incineration sector[52].

Regarding the existing CCS Roadmap outcomes, the future **UK** direction could confirm that support for CCUS is justified as innovative technology playing critical role in tackling climate change.

For **USA (California), Australia (Western Australia)** and **Japan** no changes in regulations that can support/discourage Wte/CCS have been identified.

In **South Africa**, even if the South African Centre for Carbon Capture and Storage (SACCCS) is aiming to develop and build capacity – both human and technical for this technology, at the present time there is not certain signals about the future definition of a regulatory framework dedicated to CCS and it seems like this has been placed on hold for a number of years.

In **India** the government is trying to promote schemes to encourage cities and municipalities to take up waste-to-energy projects in public-private partnership (PPP) mode.[53]

3. Conclusion

Based on the research carried out on WtE/CCS, the following points were notable:

1. ELVs at the WtE stack are more stringent compared to the USA (California) and Japan. Western Australia (Australia) and South Africa demonstrated similar ELVs to the EU countries in terms of ELVs thresholds, however India ELVs are slightly higher compared with EU countries
2. Regarding waste water discharge, only selected European countries (Italy, Germany, The Netherlands, Norway and the UK) have specific ELVs dedicated to waste water discharge from incinerators (requirements applied to waste water from the cleaning of flue gas) while other countries follow their respective general waste water standards for industrial plants.
3. Selected European countries have developed their respective country regulation for the WtE feedstock control according to the EU Directives on waste and executed through

[52]*Rijksoverheid, Klimaat en energie*, accessed on 12 June 2019, URL: https://www.rijksoverheid.nl/regering/regeerakkoord-vertrouwen-in-de-toekomst/3.-nederland-wordt-duurzaam/3.1-klimaat-en-energie

[53] https://thelawreviews.co.uk/edition/the-energy-regulation-and-markets-review-edition-6/1144320/india

the national laws. USA (California) adopt a BAT approach implementing the MACT criteria for managing wastes fed to the incineration plant. Decentralization in Japan has given more power to municipalities to manage their feedstocks accordingly. In India, the Solid Waste Management policy required that wet and dry wastes should not be mixed. In South Africa, however, specific requirements include having sound design and operating procedure to minimize the release of polluting substances into the environment.

4. There are many different incentives and CO_2 reduction schemes identified for WtE/CCS units. In Europe, the incentives can be mainly associated with the existing EU ETS. The UK are drumming up various different green funding through schemes such as the 2017 Clean Growth Strategy incentives/funding supported by the Government. Australia are working to adopt a new ETS that would replace the current funding system. South Africa are anticipating various different tax-free allowances and public sector funding solutions for WtE. The California cap and trade rules have already involved more than 400 businesses responsible for 85% of California's total GHG emissions. The Japanese JVETS has focused on establishing the J-Credit Scheme and the JCM that aimed to develop and export low carbon technology, products and services outside of Japan. In the meantime, India's Ministry of New and Renewable Energy (MNRE) is working to offer financial incentives applicable to WtE technology.

5. Barriers to WtE plant construction and operation can be associated with their environmental control (Mainly in Europe, but also in California and Western Australian), the waste management policy (e.g in Western Australia there is no levy on waste disposed to landfill) and/or, the lack of waste supply that can occur in the following scenarios:

   - Limited availability and accuracy of waste generation data and waste compositions (South Africa and India);

   - Decrease in the volumes of residual waste due to the substantial increase in recycling levels (EU countries and Japan)

6. As far as more relevant to solid residues acceptance from WtE operation it is worthwhile to highlight that each selected country has defined standards requirement to ensure the appropriate combustion of the treated wastes and to avoid the production of not desired ashes.

7. Based on the research, all country regulations in the selected countries include provisions related to WtE. However, only European countries have specific provisions on CCS regulations.

8. To round up going forward, the revised version of the WID calls for more stringent measures on reuse and recycling of materials involving a possible decrease of the residual waste to be incinerated. It is likely that other countries outside the EU will continue to align their ELVs and regulatory frameworks with the standards set by the European Community though starting at different stage of progression. However, a stricter regulation on landfilling could counterbalance the amount of MSW recovered and not convertible to energy through incineration.

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17. *BImSchV* Article 12

Australian Government Department of the Environment and Energy, "About the Climate Solutions Fund – Emissions Reduction Fund," accessed on 13 June, 2019, URL: https://www.environment.gov.au/climate-change/government/emissions-reduction-fund/about

Bundesministerium der Justiz und für Verbracherschutz, accessed on 13 June 2019, URL: https://www.gesetze-im-internet.de/krwg/

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WI BREF (Final Draft, 2018), accessed on 13 June 2019, URL: http://eippcb.jrc.ec.europa.eu/reference/wi.html

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CHECKED BY : FEDERICO VIGANÒ, VINCENZO TOTA
APPROVED BY : VINCENZO TOTA

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TABLE OF CONTENT

1. Review trends and tools in WTE plants in reducing CO_2 emission

WtE plants can play a significant role in both the energy and the CO2 markets. By recovering the energy content of waste, they can contribute in fulfilling the energy needs of society, mainly with the production of electricity and/or heat, and in replacing fossil fuels use (with associated CO_2 emissions) for the same duty. Moreover, a significant share of the energy content of Municipal Solid Waste (MSW) is biogenic and, therefore, carbon neutral.

The municipal Waste-to-Energy plants are also associated with a reduction of landfill disposal, which is of primary importance in terms of GHG emissions. In fact, the burned municipal waste would have been sent to a landfill and would have contributed to CH4 emissions. The CH4 has a significant global warming potential, compared to CO_2.

The WtE plants represents a social and economic alternative to face the environmental tasks imposed by Tokyo and Paris agreements.

The reduction of GHG emissions in the atmosphere can be therefore an important driver to maximize the efficiency of a WtE facility by improving the energy production as electricity, heat or both.

The aim to improve the existing WtE or to build new facilities is widely spread during the last decade also because of the international efforts to hinder global warming, pushing the countries with a high percentage of landfill to change their trends and action plans. The graph in Figure 1 shows as the waste management in Europe in 2017 is strongly different among the countries.

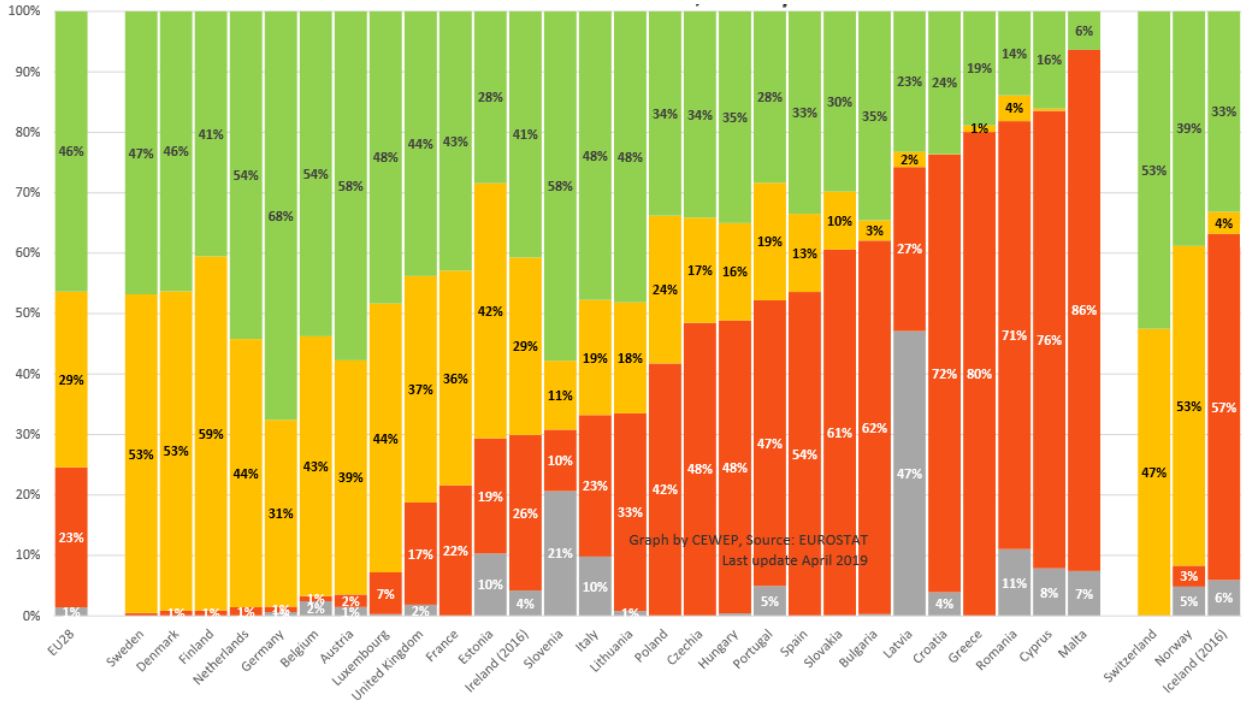

Figure 1- Waste management in EU28, Switzerland, Ireland and Norway in 2017-Last update April 2019. Red: Landfill, Yellow: Waste-to-Energy; Green: Recycling and composting; Grey: Missing data [1]

The bar graph indicates the percentages of landfill, recycling and Waste-to-Energy for the European Union members, Switzerland, Norway and Iceland.

The most virtuous states in terms of waste management are the one in Western Europe, while Greece, Romania et al. countries of Est-Europe are really stacked in landfill because of i) lack of investments or subsidies; ii) weak social acceptance and awareness of waste problem. Moreover, six EU countries (AT, BE, DE, DK, NL, SE) have introduced landfill bans encouraging the society towards the recovery and re-use of recyclable materials and by turning the waste into energy [1] in the perspective of a circular economy. The northern Europe tends to retrofit the existing facilities, not only on performances but by a beauty point of view to increase the social acceptance of a Waste-to-Energy in urban area.

1.1 Definition of the impact of each tool on WTE efficiency

The effort for reducing the CO_2 emissions imposed by Tokyo and Paris agreements and the subsidies offered by EU and EPA in Waste-to-Energy plants have contributed to push the users to improve the well-known technology. The tools that could be used to increase the energetic efficiency of a Waste-to-Energy, contributing to reduce CO_2 emissions as well, have been identified and analysed in this task:

-decrease of the combustion air excess

-use of the flue gas recirculation

-increase of the steam cycle parameters (e.g. temperature and pressure)

After describing the effect of each tool, the comparison between the several measures is done in terms of boiler efficiency and gross electrical efficiency.

1.2 Description of the tools

The tools hereinafter described optimize the energy production from waste incineration. Their indirect beneficial effect on CO_2 emission is actually related to the avoided CO_2 that would have been produced if the energy recovered by waste was obtained by fossil source.

1.2.1 Combustion Air excess

This is a trade-off in setting the combustion air excess: on one hand a minimum air excess ensures complete combustion with minimization of unburnt fuel in flue gas, on the other hand the efficiency is favoured by low air excess to minimize the thermal loss at the stack and reduce the parasitic load of the plant associated with air and flue gas blowers.

Combustion air excess also strongly influences the generation of thermal NOx in the combustion. In a WtE boiler, the air excess is used to improve the mixing of the waste with combustion air and to minimize the amount of unburnt fuel in the flue gas. Until few years ago, the minimum oxygen content (or equivalently air to fuel ratio) was imposed by an EU directive at 6% to control the gas emissions and the bottom ashes formation [2]. Recently, the constrain to respect the 6% in vol of oxygen was removed, but still most of WtE plants operates with an oxygen content ranging from 8-11% (total air to fuel ratio between 4 and 6). Lower oxygen level has benefits and drawbacks on a Waste-to-energy process. In fact, the benefits of lower oxygen levels are related to the potential for reducing thermal NOx formation, which, at the same combustion temperature, is promoted by the amount of fresh nitrogen supplied to the combustion with the combustion air. However, it has to be remarked that the reduction of air excess itself would also lead to higher combustion temperature, which would be in favor of thermal NOx generation. Hence, the reduction of the combustion air excess could be effective only when it is combined to other techniques helping in controlling the combustion temperature, namely the Flue Gas Recirculation (FGR) that is described in the following.

On the other hand, the air excess can be lowered until a certain limit, related to the need of minimizing the fraction of unburned waste with consequent too much CO emitted.

1.2.2 *Flue Gas Recirculation*

The Flue Gas Recirculation (FGR), used to control the combustion temperature to reduce thermal NOx generation, reduces the thermal losses by sensible heat at the boiler exit because the recycled Flue Gas partially substitute the secondary air injection necessary to improve the mixing and the homogeneity of glue gas [2]. The total amount of secondary air reduced is in the range of 10-15% [3].

Figure 2 is a general process diagram of an incinerator with flue gas recirculation.

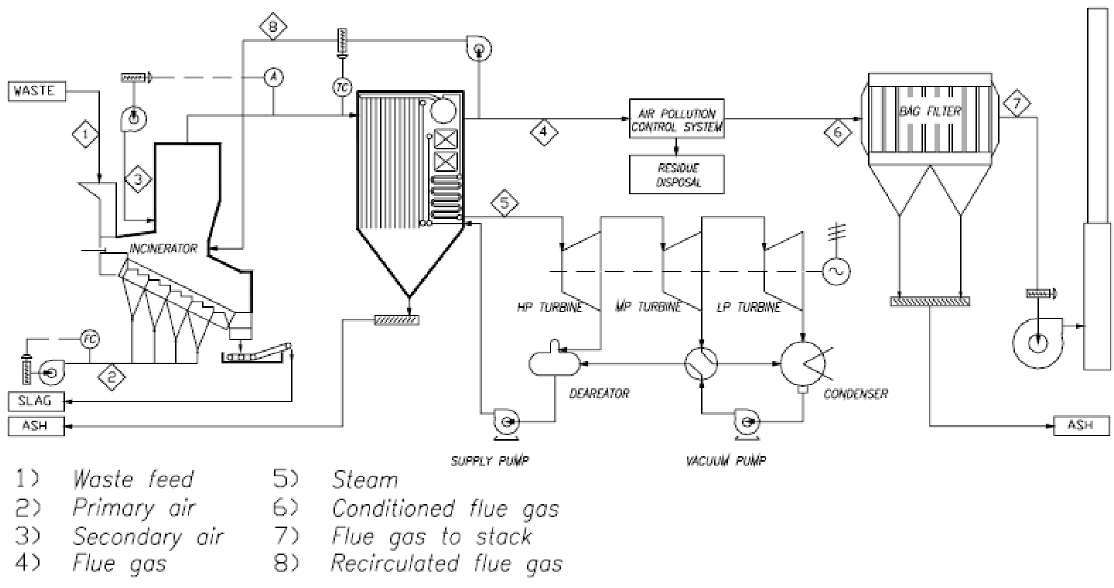

Figure 2-Incineration plant with flue gas recirculation [3]

In general, the FGR extraction point can be downstream the Flue Gas Treatment to limit the corrosion in the duct but causing some thermal losses. Otherwise, the flue gas is recirculated upstream the treatment train and the corrosion risk can be overcome by the elimination of joints and avoiding the condensation of flue gas by temperature control [3], as shown in Figure 2. With this approach, the additional costs of flue gas recirculation due to additional ducts, fans and control equipment are balanced by other beneficial effects of this technique, i.e. reducing the volume of exhaust gas to be purified in the Flue Gas Treatment has a benefit associated with the capital costs [4].

1.2.3 *Steam cycle*

The heat surfaces of a boiler in a Waste-to-Energy facility are exposed to temperature higher than 850°C. At this condition, the walls are subjected to a strong corrosion caused by meta chlorides in the ashes and the HCl present in the flue gas [4]. The steam cycle conditions at 40 bar and 400°C are an economic compromise between power generation and corrosion rate [5] [6] [2] with the flue gas temperature at boiler outlet of about 190°C [7]. As shown in Figure 3, the Waste-to-Energy plants in Europe have steam cycle operating conditions in accordance with those above mentioned.

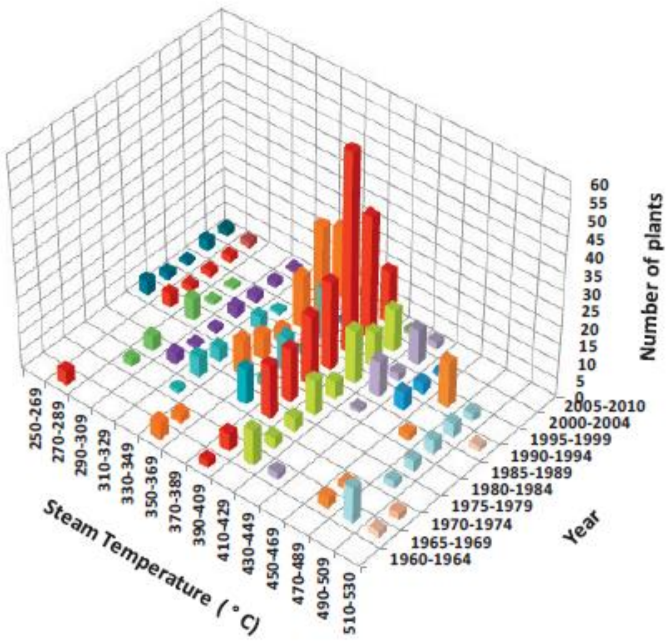

Figure 3- Steam cycle parameters in WtE plants in Europe in the last 50 years [6]

In the last ten years, the number of plants with higher steam temperature and pressure have increased to improve the energy recovery. Several measures are used to this scope. One of the most effective method to improve the efficiency and sustain increased corrosion rates is to rise the steam generation temperature and protect the coils in the boiler from corrosion by using Inconel 65 as cladding, while the boiler walls are protected with SiC plates.

Figure 4 defines the range of operative conditions in which the heaters tube walls are or not in corrosion area for different flue gas temperatures.

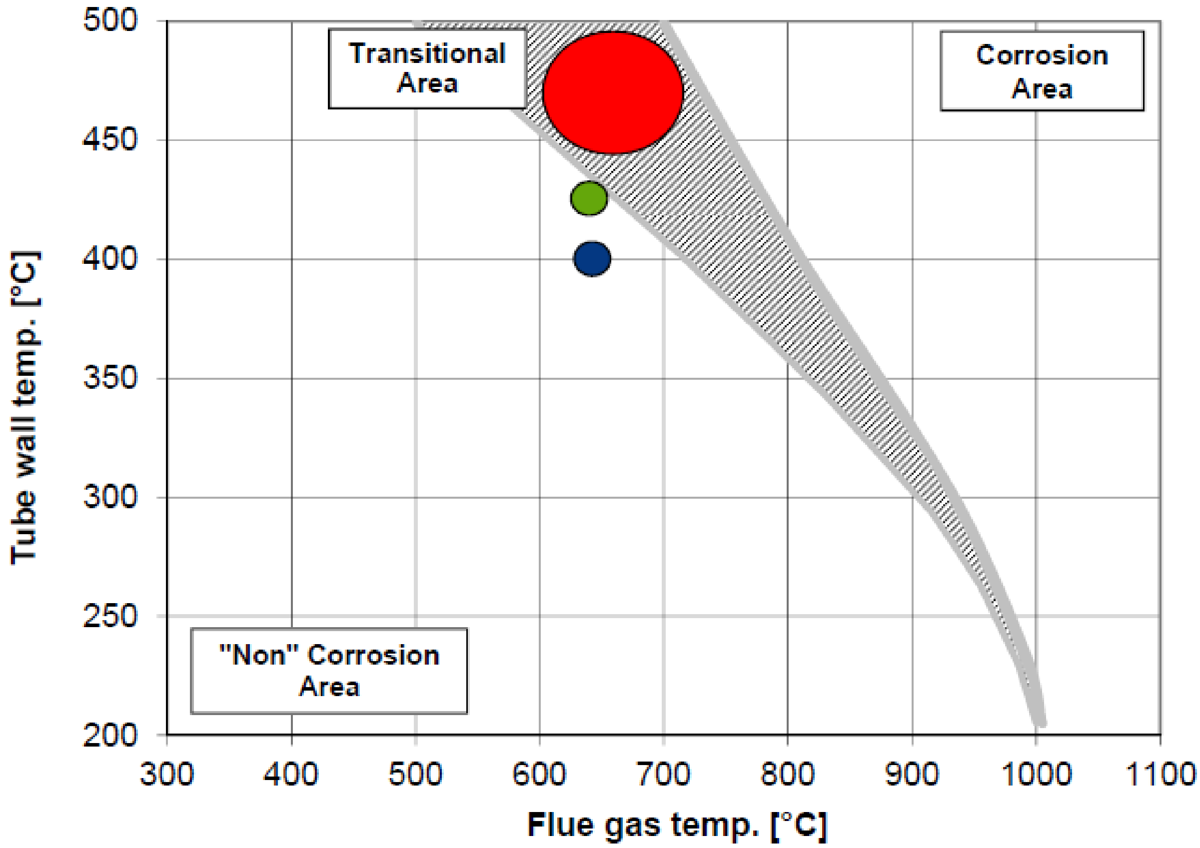

Figure 4- Corrosion diagram for a conventional boiler in an incinerator [8]. Blue circle: steam T= 400°C and P=40 bar; green circle steam T= 430°C and 70bar; red circle steam T and P much higher.

Considering that the tube walls are exposed to an average flue gas temperature of 650-800 °C, three points are indicated. The blue point refers to steam generated at 400°C and 40 bar as a conventional benchmark boiler, the green point is steam at 430°C and 70 bar. Similar conditions are reached in Riverside plant (UK) where the steam is generated at 427°C and 72 bar and after 5 years of operation no corrosion maintenance was necessary thanks to a cladding placed only at finale superheater. The red zone covers the plants where both the steam pressure and temperature are much higher than conventional conditions. Examples of different approaches to face to higher corrosion risk are described below.

Another possibility to effectively enhance steam temperature and pressure considering corrosion risk constrains is related to the use of CFB boilers instead of grate boilers. In fact, some CFB technologies (e.g. Foster Wheeler, as adopted in Lomellina plant in Italy) has a final superheater in the fluidized bed itself, which is subject to erosion but at lower corrosion rates than those associated to the heat recovery at the same temperature and from the flue gas. In practical terms, a +20°c SH temperature increase is achievable with no incremental corrosion risk as the temperature profile of the heat recovery from the flue gas in unchanged.

Pressure and temperature around 500°C and 90 bars can also be reached by placing a final superheating stage in the boiler [7]. The superheaters meet the flue gas in the boiler zone at temperature above 800°C. For a longer lifetime, the final superheaters are protected with SiC monolithic concrete, because the Inconel 625 cladding requires a greater effort in maintenance. There are several WtE examples in Europe that have applied this method and they have demonstrated that the SiC protection have guaranteed 10 years of lifetime [7]. In the Naples WtE plant (Figure 5), the steam is produced at 500°C and 90 bar. Figure 5 shows the corrosion diagram of superheaters in the plant.

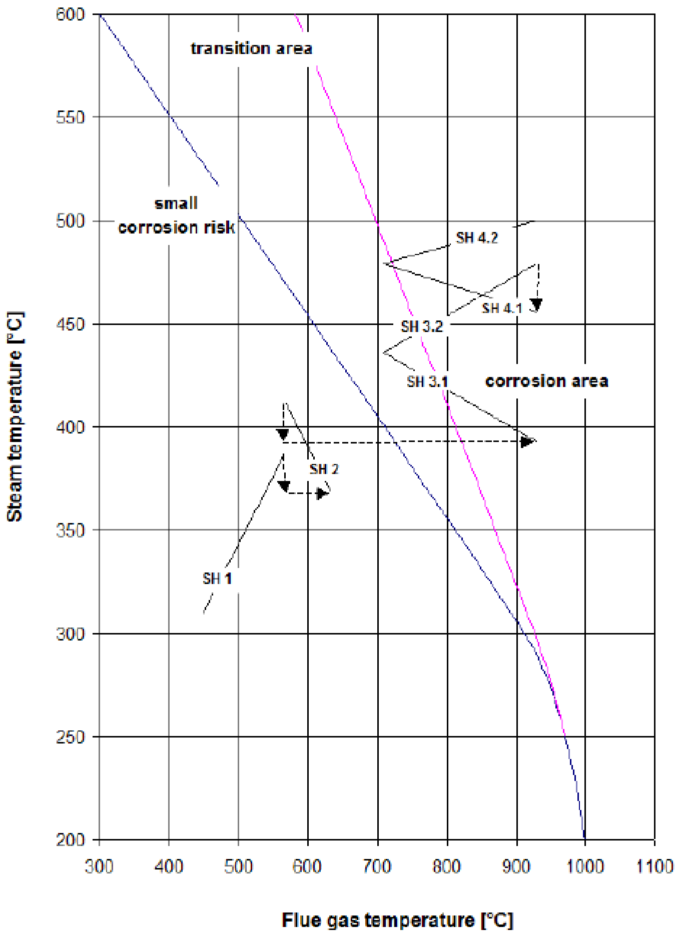

Figure 5- Corrosion diagram for Naples WtE [7]

From the figure above, it is evident that increasing the steam temperature at the same flue gas temperature (at 800°C) causes a shift into the corrosion area. At that point, it is mandatory to change the tube materials.

The increase of steam temperature allows a net increase of generator output of 15.4% [8] with a different heat recovery balance than the benchmark case.

A different method is to adopt an intermediate reheating of the steam coming out of the high-pressure turbine from 195°C to 320°C. Its main advantage is the high electric power produced. A functioning WtE plant with the steam reheater is the AEB facility in Amsterdam. The steam released from the drum has a pressure of 130 bar and reheats the steam from the HP stage of the turbine until 440°C. The furnace walls are protected with Inconel cladding. The AEB facility is actually an example of enhanced efficiency (>30% increased with respect to benchmark), result of the combination of improved steam cycle with other tools [9] like:

- air to fuel ratio was decreased from 1.9 to 1.4

-flue gas recirculation to the boiler (better combustion)

-the flue gas further cooled from 180°C to 130°C

At last, the amount of heat recovered from the combustion can be further increased by cooling the flue gas before the Flue Gas Treatment train and using as cold side the boiler feed water of the steam cycle. The heat-recovery from the flue gas by reducing its temperature, from roughly 190 °C to 130°C,to pre-heat the condensate increases both the boiler efficiency and the electrical efficiency [9].

Another method is to achieve higher steam temperatures through external superheating of steam, from 400°C to 520°C, firing oil or gas. This variant is implemented in the Heringen WtE plant in Germany. The external superheaters consist in bottom fired natural gas with natural draft. The external superheater has the same corrosion risk of the boiler in the standard case (excess air of 60%, steam produced at 40bar and 400°C), because the superheater is not exposed to the flue gas from waste combustion. It improves the power production, but it is not the best action to take for the improvement of the WtE efficiency, especially if this is aimed at reducing the carbon footprint. In fact, the increase of efficiency is achieved with fossil fuels combustion, and additional GHG emissions are produced [7]. Also, from the economic point of view, both the additional operating costs of additional fuel as source of energy (natural gas, coal or others) and the extra CAPEX associated with the external super heater are significant.

1.3 Waste-to-energy plants examples

In this section, the different measures previously described are compared in terms of boiler efficiency and gross electrical efficiency. According to literature assumptions, it was considered an average Low Heat Value (LHV) for the waste of 10.4 MJ/Kg and an average biogenic fraction of 40% [5] [2], where the biogenic fraction is the percentage of waste of biological origin.

The comparison between the different methods to improve the performances of a Waste-to-Energy is showed in Table 1 in terms of theoretically achievable final electrical efficiency and boiler efficiency compared with a defined benchmark by changing the air excess and the steam parameters. In the last column, it is reported the effect of each tool on CO_2 emissions, expressed as delta tons of CO_2 per kWh produced. The ratio is estimated by calculating the increment of kWh/tons of waste burned produced in WtE by applying the discussed tools and considering that, for 1 ton of MSW burned, 0.7 ton of CO_2 are produced [2]. The quantity ΔtCO2/kWh is calculated for each case compared with benchmark one.

Table 1- Comparison between tools to improve the Waste-to-Energy plant [7]

	Primary Air/fuel ratio (kg/kg)	Steam T, °C	Steam P, bar	Boiler Efficiency	Gross Electrical Efficiency	ΔkWh/t waste	ΔtCO2/kWh
Benchmark	1.9	400	40	86.5	26.4	/	/
Reduced Air Excess	1.39	400	40	87.7	26.6	5.55	0.126
External Superheating	1.9	520	90	87	29.7	91.6	0.007
High Steam Parameters	1.9	500	90	86.5	30.2	105.5	0.006
Steam Reheating	1.9	420	90	86.5	29.9	97.2	0.007

As seen in Table 1, the biggest gross electrical efficiency improvement is given by acting on steam cycle conditions, which results on an increase of gross electrical efficiency of 3.8% compared with the benchmark case [7] [2] . The recently-built WtE facilities, in fact, operate with higher temperature whose benefits are combined with lower air excess , achievable thanks to flue gas recirculation.

Table 2 lists the examples of Waste-to-Energy plants worldwide in which the improvements described above were implemented. Table 2 underlines the effect of those tools on the CO_2 emissions. The emission offset was calculated considering that the emission factor of a Combined Cycle Gas Turbine (CCGT) is 0.38 tCO2/MWh, as average of the values given in the literature [10] [11] [12] [13] [14].

Table 2- Waste-to-Energy plants with integration of improvement tools *Data are referred to a single treatment line (data from [10] [11] [12] [14] [15])

	Brescia (IT)	AEB (NL)	Mainz (GE)	RIVERSIKE (UK)	RENO-NORD (DK)	OSLO (NW)
Type of furnace	**grate**	**grate**	**grate**	**grate**	**grate**	**grate**
Waste treated, t/h	100	100	33*	32*	20*	20
LHV, MJ/kg	6.3-13.8	10	9.8	7-13	12	12
Primary air to fuel ratio, kg/kg	-	1.4	-	-	1.5	-
Steam produced, t/h	-	44	100	54	81	77.2
Steam cycle, bar/°C	60/450	130/440	42/550	72/427	50/425	41.5/402
Biogenic Waste, %	27	53	-	54	-	50-60
CO_2 avoided for electricity, tCO2/MJ	0.02	0.33	-	0.54	0.23	0.08
CO_2 avoided for heating, tCO2/MJ	0.30	0.03	0.12		0.59	0.71
Electricity produced, GWh	60	888	-	462	18 (MW)	53
Heat produced, GWh	796	70	48 (MW)	-	47 (MW)	449
Electrical Efficiency, %	27	30	25.8	27	27	-

The selection of WtE plants to analyze figures of electrical efficiency, optimization tools and energy produced was based on the availability of public information in the literature.

The avoided CO_2 emissions represent the CO_2 avoided, compared to the base case, where the energy (electrical and heating) is produced by natural gas fired plants. Based on Table 2, it can be seen that the avoided CO_2/MJ of waste figure for type of energy produced are comparable for centre Europe, while there is a net difference in the northern Europe countries, where the potentiality of a waste to energy is mostly used for district heatingfor local needs . The possibility to thermally integrate the WtE plant into the local context by district heating certainly improves the exploitation of the Waste-to-Energy technologies. According to three associations active in the energy field [16], the potential of WtE is not fully used in the EU. In fact, less than half of the potential energy from more than 400 WtE incinerating plants is effectively used. As an example, in The Netherlands, only the 4% of local heating is generated by WtE due to the change in regulations by a Dutch Heat Act[1] in terms of district heating [17]. Considering that on average 30 million tons of fossil fuels are avoided to produce that energy, which would emit 21-41 million tons of CO_2, the economic and environmental advantages of DH are indisputable.

2. Contribution of WTE plants to the local energy production and CO_2 emission

The major contribution of WTE plants to the energy production is released through the national grid and/or district heating. Additionally, in general, the energy produced by the WtE plants meant the reduction of indirect CO_2 emissions from fossil sources.

Figure 6 compares the contributions on CO_2 emissions of the main productive sectors within the EU28.

[1] The Heat Act regulates the supply of heat to users with a connection off less than 100 kW. Heat suppliers are required, under the Act, to secure a reliable and affordable heat supply against reasonable conditions and good quality service. To facilitate this, the Act introduced a license obligation for the supply of heat, as well as price regulation.

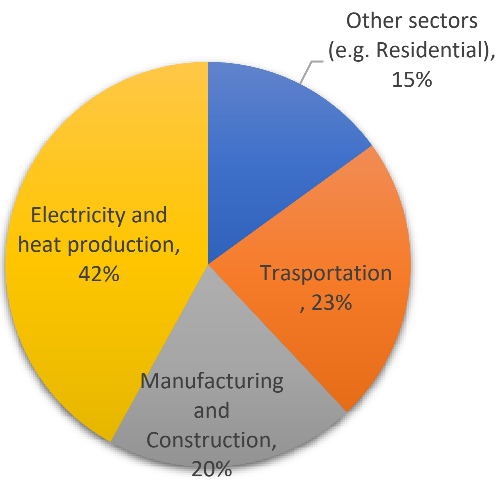

Figure 6- Fraction of CO_2 emission for main productive sectors in Europe [18]

As seen in Figure 6, the electricity and heat production sector represents the major source of CO_2 emissions, while the other sectors appears in the same percentages.

To quantify the effective contribution of a WtE plant to the local energy, a comparison between the CO_2 emissions from fossil sources and from a WtE was done. Figure 7 shows the million tons of CO_2 emitted in 2017 by the counties analyzed in Task 1 of this study. In this graph, only the CO_2 emissions from power generation plants were included.

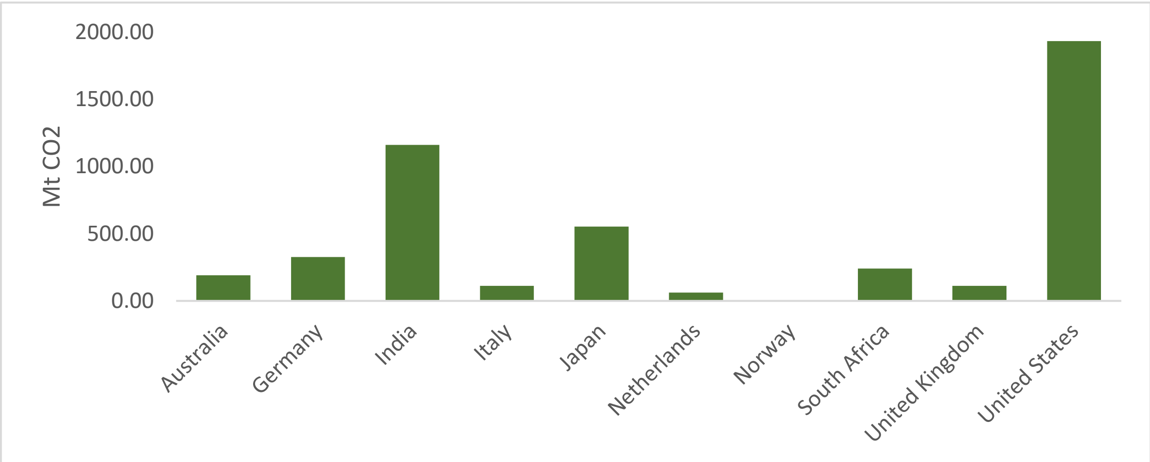

Figure 7- Emission of CO_2 from fossil fuel for power generation in 2017 [19]

Looking at Europe, Norway and Netherlands show the less amount of CO_2 emitted by fossil fuels, because the huge investment in green energy has reduced significantly the exploit of coal and fossil sources for energy production, differently from Germany, Italy and UK, which are trying to keep the trend but still demonstrate a not negligible use of fossil fuels. The green policy of northern-Europe countries is strongly related to lots of subsidies to invest and develop green industries. Australia and South Africa have started recently to focus on environment protection and to invest in green energy. The maximums onCO2 emission from fossil sources, shown in Figure 7, are found in India, USA, and in Japan. In Japan, the incinerators have always been the major waste treatment strategy due to the lack of space for landfilling. However, the waste treatment plants are at small-scale and the energy that could be recovered is used for in-plant consumptions, as is not enough for national grid distribution. It means that the major source of energy in Japan is still the fossil fuels. USA uses roughly 641 GT of coal in a year, comparable with the consumption of the whole Europe (~ 800 GT in a year). The challenge of USA is, in fact, its huge demand of energy that should be sustained with green energy. India consumes 1000GT coal per year. The challenge of India is to handle the million tons of waste generated and the growing of population with consequently decrease of space for landfilling. India Renewable Energy Department Agency (IREDA) has estimated that only the 2% of waste-to-energy potential is used in the country, and among all the projects proposed to government or industries for funding, only 4 are at the moment on-going. [20] [21].

In Task 1, a figure for each country summarizing the tons of MSW burned by country was presented. It represents most of the WtE plants and considering the amount of electricity and heat produced. The data summarized in Table 3 indicate the number of Waste-to-Energy plants in each country, the total energy produced (as electricity and as heating), the total waste treated, the total CO_2 emitted by WtE stacks, and the total waste treated and burned.

Table 3- Recall of results of Task 1 on energy production of Waste-to-Energy plants

	Electricity, GWh/yr	Heating, GWh/yr	N. WtE plants, -	Total CO_2 emitted from WtE, Mt/yr	Total Waste, Mt/y
The Netherlands	1997	962	13	6.92	7
Norway	430	3800	17	1.51	1.53
Italy	1750	1150	39	6.05	6.1
Germany	5768	11800	81	22.3	22.6
UK	7146	865	42	10.8	10.9
USA	20850	n.a.	78	27.5	27.8

Japan	821	n.a.	1020	n.a.	52.5
India	444	n.a.	8	n.a.	1.3
Australia	n.a.	n.a.	0	n.a.	n.a.
South Africa	n.a.	n.a.	n.a.	n.a.	n.a.

In South-Africa and Australia, there are no WtE plants in operation. For USA, Japan and India no data are available on heat generation.
In Table 4, the total energy, electrical and heating, that is used by each country is reported. The contribution of Waste-to-Energy on energy production is calculated as ratio between the energy produced by MSW plants (listed in Table 3) and the total energy consumed. The CO_2 emissions refers to the tons/year emitted in 2017 by the energy sector. It includes thermal power stations, combustion installations and oil and gas refineries [22].

Table 4- Contribution of the energy produced by WtE on the local energy production [24]

	Energy consumed, Twh	Contribution of WtE on energy consumtpion, %
The Netherlands	109	2.71
Norway	122	3.47
Italy	293	0.99
Germany	537	3.27
UK	309	2.59
USA	3902	0.6
Japan	944	-
India	1137	-
Australia	229	-
South Africa	207	-

The contribution of Waste-to-Energy is the percentage of the total energy produced by WtE plants (listed in Table 3) over the total energy consumed. It represents the energy that potentially can be produced from non-fossil source.

Table 5 compares the emissions of CO_2 from the energy sector and from WtE plants for each country. The total CO_2 emitted byenergy production is fossil sourced, while the CO_2 coming out from the municipal waste can be divided in biogenic and fossil fractions. The percentage of biogenic fraction is set at 51% for all countries [25] [23].The last column reports the contribution of fossil CO_2 from WtE on total CO_2 emission (as sum of carbon dioxide from WtE and energy production).

Table 5- Contribution of WtE on total fossil CO_2 emission for each country. WtE= Waste to Energy; MSW= Municipal Solid Waste

	Total fossil CO_2 emission from energy sector, Mt/y	Total CO_2 emitted from WtE, Mt/yr	% Biogenic of total MSW	% Fossil of total MSW	% Fossil CO_2_WtE/ total fossil CO_2
The Netherlands	71.6	6.92	3.53	3.39	4.5
Norway	4.8	1.51	0.77	0.74	13.4
Italy	100.9	6.05	3.08	2.96	2.9
Germany	304.5	22.3	11.37	10.93	3.5
UK	110.3	10.8	5.51	5.29	4.6
USA	1932	27.5	14.02	13.48	0.7
Japan	552	1.76	0.90	0.86	n.a.
India	1160	-	-	-	-
Australia	190.5	-	-	-	-
South Africa	241	-	-	-	-

The most of countries in Table 5 has an average value of fossil CO_2 from WtE plants over the fossil CO_2 from total industrial activities in the country ranging from 3%and 4%. The out-of-trend states are Norway and USA.

In USA, the ratio smaller than 1 represents the few waste-to-energy factories operating , compared to the amount of energy necessary to sustain the population and supplied by fossil sources.

In Norway, the total CO_2 emitted from both the energy sector and WtE plants, are comparable, which results in a contribution much higher than others (13.4%). It is due to the very low exploitation of fossil sources for energy production. In fact, in Norway, the electricity is mainly of renewable origin, while the most of waste-to-energy plants are used for district heating.

In Japan,the data about CO_2 emissions from WtE plants are not enough reliable, so no considerations can be drawn on the specific subject.

3. Identification of CO_2 savings

As stated by the European Waste Framework Directive (WFD, Dir. 98/2008/EC), the evaluation of the environmental sustainability of waste management in general, and of various treatment options, must be based on its Life Cycle Assessment (LCA). This technique, which is defined by the international set of norms ISO 14040, quantifies the environmental impacts associated with the production/treatment of a reference unit of product/material/etc. by considering not only the direct emissions associated with such an activity, but also the indirect emissions, as well as the emissions avoided/substituted.

In the case of WtE, a simple representation of this approach is depicted in Figure 8.

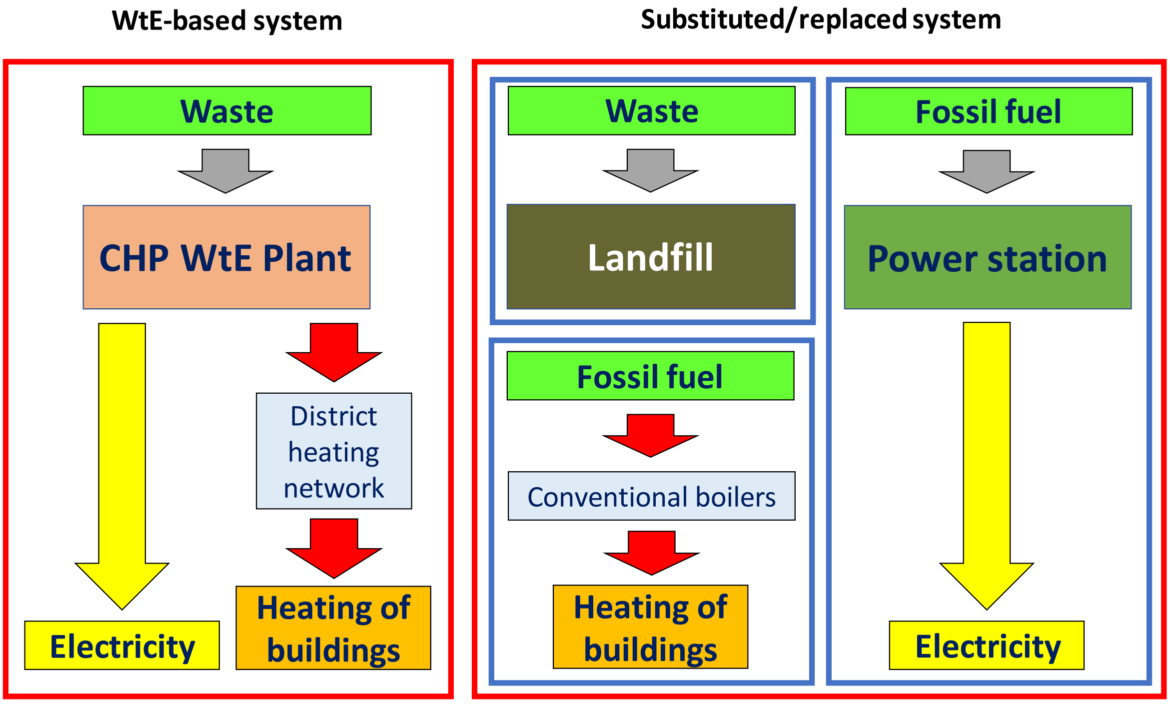

Figure 8: Simple representation of the systems to be considered when applying LCA to a CHP WtE plant.

WtE plants emit directly into the atmosphere mainly the CO_2 contained in the flue gas. Part of it is fossil and, hence, must be considered as a greenhouse gas emission, and part is biogenic, i.e. carbon neutral. Other emissions (indirect) are those associated with the handling / treatment / possible recovery or disposal of solid residues, as well as those associated with the construction materials used to build the plant, those associated with the energy consumed to build the plants and imported by the plant from the grid, those associated with the production of reactants for flue gas cleaning, etc.

However, WtE plants produce useful forms of energy, typically electricity and/or heat that would be produced in alternative ways. These replaced/substituted productions are associated to CO_2 emissions that are avoided thanks to the WtE plant.

Similarly, the management/treatment of the waste would be carried out in an alternative way without the WtE plant. In the example depicted in Figure 8, WtE replaces landfilling and avoids the associated emissions.

The net CO_2 emission of a WtE plant is the algebraic sum of all the direct/indirect and avoided contributions. The direct (fossil) emissions increase the overall emission figure, whereas avoided emissions reduce such value. When the result is positive, the WtE plant emits more fossil CO_2 than the alternative systems. When, instead, the result is negative, the WtE plant is less CO_2-intensive than the alternative systems.

The LCA is an evaluation approach that requires significant amount of detailed data. However, the result is typically determined by the main contributions that, for WtE plants, are:

- direct emissions associated with the discharge of flue gas into the atmosphere;
- avoided emissions associated with the production of useful effects;
- avoided emissions associated with the alternative management/treatment of the waste;
- potential avoided emissions associated with the possible recovery of solid residues.

The following paragraphs describe these four main contributions, how they can be quantified, and which are the key parameters that have strong influence on such contributions.

3.1 CO_2 emissions of a WtE plant

The net CO_2 emission of a WtE plant can be estimated as the sum of four components:

1. the direct fossil CO_2 emissions at plant stack due to the combustion of waste and other fuels;
2. the avoided fossil CO_2 emissions due to electricity/heat/CHP production;
3. the avoided CO_2 emissions associated with the alternative treatment/disposal route of waste, typically landfilling;

4. the avoided CO_2 emissions due to the recovery of materials (metals and inert materials) from bottom ash.

3.1.1 Direct CO_2 emissions at stack

The CO_2 emissions at a WtE plant stack are mainly related to the oxidation of the carbon content of the incinerated waste. In addition, some CO_2 emissions are due to the combustion of fossil fuels in auxiliary burners[2].
These emissions have both a biogenic and a fossil component: the first one is related to the biogenic fraction of the incinerated waste, which depends on its composition. Because of the intrinsic variability of waste properties, it is very difficult to establish general rules to quantify the biogenic fraction of the CO_2 emissions. There are several methods, more or less accurate, to estimate or measure it (norms EN 15440:2011 for RDF, ISO 13833:2013 and ISO 18466:2016 for general waste).

As a rule of thumb, MSW with LHV of 10 MJ/kg has a biogenic energy content roughly equal to 51%, whereas RDF with LHV of 13 MJ/kg features roughly 44% [25] biogenic energy content[3]. Even if the breakdown of energy content and that of carbon between biogenic and fossil shares are not the same, for the sake of simplicity, such assumption can be accepted, given the overall accuracy of the evaluations carried out hereinafter.

The direct CO_2 emission factor for MSW with LHV of 10 MJ/kg can be assumed equal to 0.9875 ton CO_2/t of waste, of which 0.5036 ton CO_2/t of waste (51%) is from biogenic source, and 0.4839 ton CO_2/t of waste (49%) is fossil. For RDF with LHV of 13 MJ/kg, the direct CO_2 emission factor can be assumed equal to 1.100 ton CO_2/t of waste, of which 0.4840 ton CO_2/t of waste (44%) biogenic, and 0.6160 ton CO_2/t of waste (56%) fossil.

In addition to the CO_2 generated by the oxidation of the carbon content of waste, CO_2 emissions at the stack of WtE plants is, in a minor extent, due also to the combustion of auxiliary fuels. The share of the energy input (LHV basis) from auxiliary fossil fuels in a modern WtE plant is between 1% and 3%. Such auxiliary fuels can typically be natural gas, fuel oil, or similar fossil fuels. For all hydrocarbons, the CO_2 emission factor can be approximately 0.065 kg CO_2/MJ_{LHV}[4]. By introducing this correction, the CO_2 emission factors for the refence MSW and RDF considered can be recalculated, leading to the figures summarized in Table 6.

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[2] Typically, during startup and shut-down phases, as well as seldomly to contribute to combustion control.
[3] This is due to the upstream Mechanical Biological Treatment (MBT) needed to produce RDF, where part of the biogenic material is consumed and/or removed with the aim of increasing the LHV (by reducing moisture and ash contents).
[4] It is around 0.056 kg CO_2 / MJ_{LHV} for natural gas and 0.074 kg CO_2 / MJ_{LHV} for light fuel oil.

Table 6: Summary of the direct CO_2 emission factors for WtE plants.

	LHV	Biogenic CO_2		Fossil CO_2		Overall CO_2	
	MJ/kg	kg/kg	kg/MJ	kg/kg	kg/MJ	kg/kg	kg/MJ
MSW	10	0.5036	0.05036	0.4969	0.04969	1.0005	0.10005
RDF	13	0.4840	0.03723	0.6329	0.04868	1.1169	0.08592

Furthermore, RDF is produced from MSW, after a complex Mechanical Biological Treatment (MBT), which features energy consumptions, production of residues, recovery of materials, etc. With the “zero burden” assumption, the Global Warming Potential (GWP) associated to MSW is zero. Instead, for a fair comparison, the GWP associated with RDF cannot be zero, but must consider all greenhouse gas emissions due to the production of RDF from MSW.

From the evaluations carried out by [26] [27], it is possible to infer that the GWP associated with the production of RDF from MSW is of the order of 0.0300 kg fossil CO_2 / kg of RDF, i.e. 0.0023 kg fossil CO_2 / MJ_{LHV}. This additional indirect contribution to fossil emissions (not included in Table 6, which refers only to direct emissions) must be taken into account when comparing systems based on the direct combustion of MSW with those involving the combustion of RDF in dedicated plants.

Direct CO_2 emissions of WtE plants without CCU/CCS must consider only the fossil share of the emitted CO_2, since the biogenic share is carbon neutral. However, the biogenic share of the produced CO_2 becomes very relevant when CCU/CCS is applied. In fact, by capturing all the fossil CO_2 and part of the biogenic one, the direct CO_2 emissions become negative, i.e. the system indirectly captures CO_2 from the environment.

3.1.2 Avoided CO_2 emissions for electricity/heat production

WtE plants use waste to produce electricity and/or heat that otherwise would be generated, from country to country, with a different energy mix. This energy mix depends on the mix of generation technologies and the amounts of fossil fuels consumed. Consequently, there are three key parameters that determine the relevance of this emission contribution (that is always negative, i.e. “avoided”):

- the energy efficiency of WtE plants, which defines the amount of electricity/heat produced per unit of treated waste;
- the fuel mix for electricity/heat production in the country;
- the average efficiency for the conventional production of electricity/heat from the fuel mix in the considered country.

Taking into account the 10 selected countries of the study, the CO_2 emissions factors for electricity production (year 2017) ranges from 0.008 ton CO_2/MWh_E for Norway (energy mix mainly based on renewables) to 0.900 ton CO_2/MWh_E for South Africa (energy mix mainly based on fossil fuels) [28]. For the heat production, instead, the CO_2 emission factor can be assumed as 0.065 kg CO_2/MJ_{LHV}, given the fact that a mix of natural gas and light oil could be representative of the fuel mix for heat generation in all the selected countries.

A very preliminary estimate of the avoided CO_2 emissions due to electricity / heat production from WtE could be carried out also based on the data of the R1 energy efficiency of WtE facilities. In fact, the European Waste Framework Directive (WFD, Dir. 2008/98/EC) [29] introduced the R1 energy efficiency for WtE facilities with the aim of quantifying the potential avoidance of primary energy consumption associated with WtE operations:

$$Energy\ Efficiency = \frac{\left(E_p - \left(E_f + E_i\right)\right)}{\left(0.97 * \left(E_w + E_f\right)\right)} \cdot CCF$$

where:

- E_p = annual energy produced as heat or electricity. The electricity is multiplied by 2.6 and the heat produced for commercial use is multiplied by 1.1 (GJ/year);
- E_f = annual energy input to the system from fuels contributing to the production of steam (GJ/year);
- E_w = annual energy contained in the treated waste calculated using the net calorific value of the waste (GJ/year);
- E_i = annual energy imported excluding E_w and E_f (GJ/year);
- 0.97 is a factor accounting for energy losses due to bottom ash and radiation;
- CCF = Climate Correction Factor to equalize the evaluation of the efficiency among different Member States, with various climatic situations and, therefore, different potentials of exploiting heat production.

The 2.6 factor equals to 1/0.38, where 0.38 is an average efficiency for electricity production from fossil fuels. The 1.1 factor, instead, equals to 1/0.91, where 0.91 is an average efficiency for heat production from fossil fuels.

The European directive set also two thresholds for the R1 value:

- 0.6 for installations in operation and permitted before 1st January 2009;

- 0.65 for installations permitted after 31st December 2008.

Plants that achieve R1 energy efficiency equal to or greater than the applicable threshold are classified as "recovery facilities", meaning that their main purpose is recovering energy from waste; those plants below the threshold are classified as "disposal" facilities.

The R1 energy efficiency (without taking into account the CCF) gives an immediate, rough estimate of the saved primary energy consumption and, therefore, of the saved CO_2 emissions.

An evaluation of the status of European WtE plants carried out by the Confederation of European WtE Plants [30] shows that plants located in Northern Europe have the highest average R1 indexes (ranging from 0.5 to 1.45), because there the contribution of the heat generation is very significant compared to South Europe (results ranging from 0.21 to 1.04), where only few CHP plants are installed (Figure 9). Even the influence of the plant size is significant, with large plants (annual capacity > 250,000 ton/year) showing higher R1 values (average 0.77) than medium-sized plants (annual capacity between 100,000 and 250,000 ton/year) or small-sized plants (annual capacity < 100,000 ton/year), respectively assessing average R1 values of 0.7 and 0.63 (Figure 10).

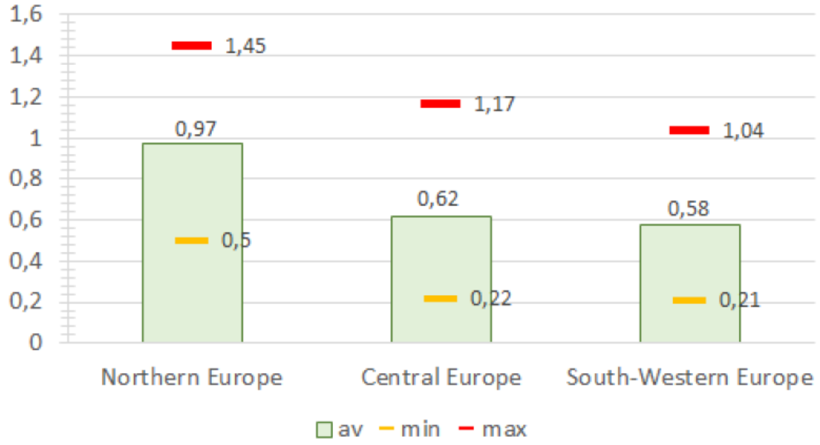


Figure 9: R1 energy efficiency (without CCF) for different European regions (LEAP evaluation from CEWEP data) [30]

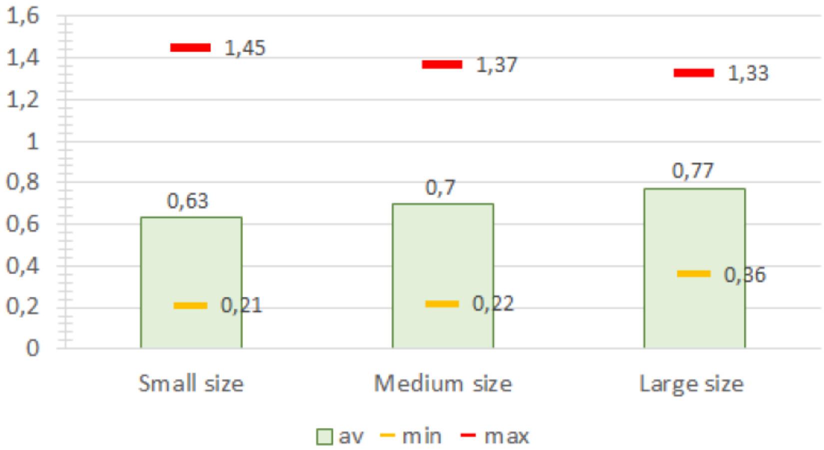


Figure 10: R1 energy efficiency (without CCF) for different WtE plant sizes (LEAP evaluation from CEWEP data) [30]

3.1.3 Avoided CO_2 emissions from waste landfilling

The waste being used as feedstock by WtE plants would otherwise have been disposed to landfill. In the large volume of waste inside a landfill, anaerobic digestion processes take place over time, with the production of a biogas rich in CH_4, CO_2 and other gases. This biogas features a high greenhouse potential if released into the environment, since the GWP_{100} of CH_4 is 28 times higher than that of CO_2. Therefore, although the produced biogas contains only biogenic carbon, whilst the emitted CO_2 is carbon neutral, the emitted CH_4 is not. It gives a net GWP_{100} contribution that is 27 times that of fossil CO_2 (i.e. the GWP_{100} of fossil CH_4 reduced by the GWP_{100} of CO_2).The decomposition of the biogenic share of the waste and the concomitant production of biogas develop through time at a diminishing rate, taking many years to be completed. A formula to assess the methane production of a landfill site is given by the First Order Decay (FOD) method (Tier 2) [31]:

$$CH_4\ gen\ in\ t - yr\ \left(\frac{Gg}{yr}\right) = \sum_0^t \left(\left(A * k * MSW_T(x) * MSW_F(x) * L_0(x)\right) e^{-k(t-x)}\right)$$

where:

- t = year of inventory;
- x = years for which input data should be added;
- $A = (1 - e^{-k}) / k$ = Normalization factor which corrects the summation;
- k = 0.03÷0.2 = Methane generation rate constant (1/yr);
- MSW_T (x) = Total municipal solid waste (MSW) generated in year x (Gg/yr);
- MSW_F (x) = Fraction of MSW disposed at SWDS in year x (Gg/yr);
- L_0 (x) = Methane generation potential.

In turn:

$$L_0(x) = MCF(x) * DOC(x) * DOC_F * F * \frac{16}{12}$$

where:

- MCF (x) = Methane correction factor in year x (fraction);
- DOC (x) = Degradable organic carbon (DOC) in year x (fraction) (Gg C/Gg waste);
- DOC_F = Fraction of DOC dissimilated;
- F = Fraction by volume of CH_4 in landfill gas;
- 16 / 12 = Conversion from C to CH_4.

The methane generation rate constant k is the time taken for the DOC in waste to decay to half its initial mass: rapid rates (k = 0.2) are associated with high moisture conditions and fast degradable material (e.g. food waste), while slower decay rates (k = 0.03) are associated with dry site conditions and slowly degradable waste (wood or paper).

Degradable Organic Carbon (DOC) is the organic carbon that is accessible to biochemical decomposition: it is dependent to the waste composition and it can be calculated from a weighted average of the carbon content waste components:

$$DOC = 0.4 * A + 0.17 * B + 0.15 * C + 0.3 * D$$

where:

A = paper and textiles fraction;
B = garden waste, park waste or other non-food organic putrescible fractions;
C = food waste fraction;
D = wood or straw fraction.

Usually the CH_4 fraction F is considered as 0.5, but it can vary between 0.4 and 0.6 depending on the waste composition and whether the landfill is still active.

Modern landfills in developed countries[5] generally collect the produced biogas and burn it in a flare (rough CH_4 oxidation to biogenic CO_2) or, even better, in a gas engine (CH_4 converted to biogenic CO_2 with the benefit of the production of electricity with an average efficiency of 30-35%).

On the other hand, the dump sites still existing in developing countries have no biogas collection so that all the produced CH_4 is emitted into the atmosphere with no treatment or energy recovery.

Different studies for the modeling of L_0 suggest a value close to 160 m^3 CH_4/ton for high biodegradable fractions like organic waste, 120 m^3 CH_4/ton for moderate biodegradable fractions like paper, wood or textiles, 20 m^3 CH_4/ton for the biogenic matter associated with inert wastes, metals and plastics [32].

An example of biogas production from a conventional landfill throughout a 100-year period is shown in Figure 11 (taken from LEAP experience):

[5] In respect to waste management.

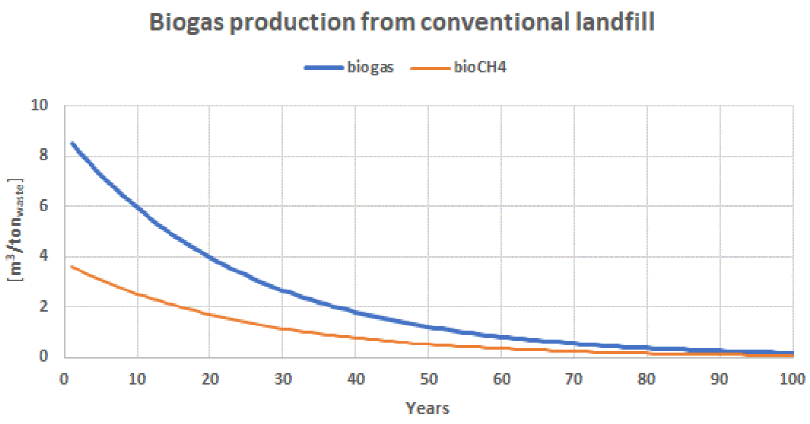


Figure 11: Example of biogas production from a conventional landfill (LEAP evaluation)

Consequently, the overall fossil CO_2 equivalent emission deriving from the landfilling of waste is the sum of the following contributions:

- direct emissions of fossil $CO_{2,eq}$ due to the methane contained in the non-collected biogas and released directly into the atmosphere as a greenhouse gas;
- avoided fossil $CO_{2,eq}$ emissions related to the electricity produced by the biogas-powered engines, which replaces the production of the same amount of electricity by the single country generation system.

Considering a modern landfill with biogas collection and energy recovery via gas engines, the net fossil CO_2 equivalent emissions has an average value of 0.6 ton $CO_{2,eq}$/ton untreated MSW disposed and 0.5 ton $CO_{2,eq}$/ton RDF or treated MSW disposed: this value could rise up to 1.7 ton $CO_{2,eq}$/ton MSW disposed for dump sites [33]. Turning the perspective upside down these values can be considered as the avoided fossil $CO_{2,eq}$ emissions due to the treatment of waste in WtE plants.

1.1.1 Avoided CO_2 emissions from bottom ash recovery

The ash content of MSW is typically in the range 15-25% by mass. In WtE plant burning directly MSW (grate-based plants), most of such ash ends up as bottom ash that can be recovered. In WtE plants burning RDF, the situation is rather complex, because a significant part of the ash content of MSW is removed during the RDF production process. There, metal scraps are sent to recovery, whereas the removed inert material is typically sent to landfill. RDF still features an ash content of 10-15% by mass. When burned in a dedicated WtE plant (normally a fluidized-bed plant), most of such ash ends up as fine boiler ash, which is currently disposed of into landfill. Only a minor part of such ash produces inert bottom ash, which can follow the same recovery route of the inert part of the bottom ash produced from the direct combustion of MSW.

Bottom ash typically undergoes metal separation (ferrous and non-ferrous, mainly aluminum), then the inert fraction can be used as road background (added to the mixture of sand, bitumen and water for the creation of the foundation layer), as landfill recovery (replacing gravel, sand or clay), as raw material to be used for the preparation of raw flour fed to cement kilns, as raw material in the concrete or ceramic production. The inert fraction can also be subjected to vitrification processes (high temperatures treatment up to 1,500 °C) followed by rapid phases of quenching in water, to obtain amorphous materials, with properties similar to glass.

On the other hand, the recovery of scrap metals (typically aluminum and iron) for secondary metal production avoids the use of a significant amount of raw materials (depending on the quality loss of which they are subjected by oxidation and corrosion).

In a state-of-the-art recovery system, relevant recovery efficiencies can be achieved, starting from 43% for heavy non-ferrous scraps and reaching 85% for ferrous and stainless-steel scraps [34]. By enhancing the grain size recovery, the recovery rates could be pushed forward (from 85% to 97% depending on the metal type).

Assuming a complete substitution scenario (i.e. 1 t of secondary material replaces 1 t of primary material) the avoided $CO_{2,eq}$ emissions can range from 0.1 ton $CO_{2,eq}$ / ton of collected bottom ash for a baseline case with only ferrous scrap recovery (85%) and landfill disposal of the mineral fraction, to 0.4 ton $CO_{2,eq}$ / ton of collected bottom ash for the case of enhanced recovery of scraps and mineral fraction sent to road construction.

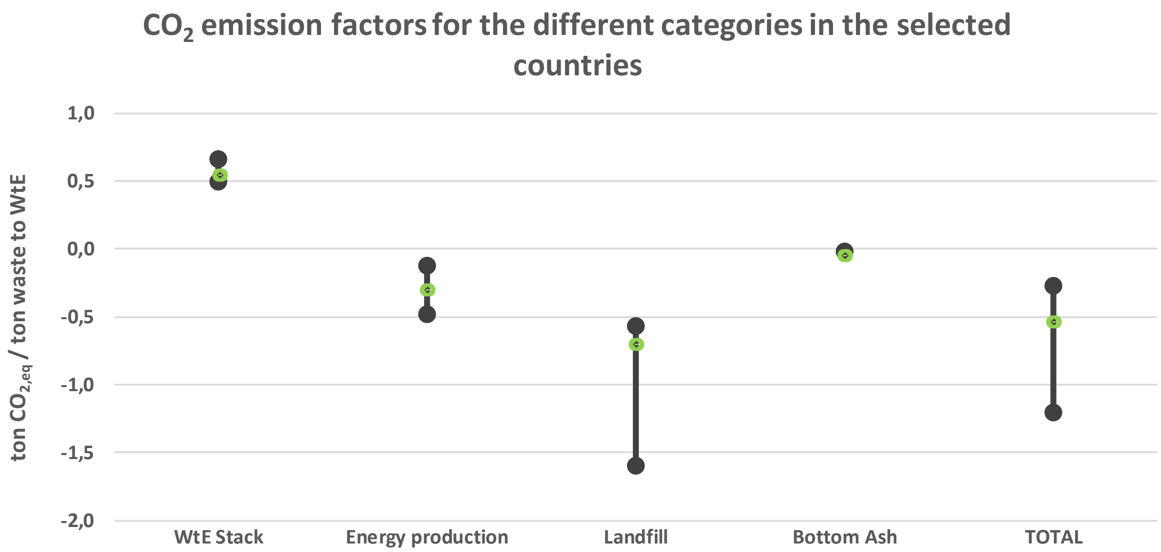
The evaluations carried out in the following consider two levels of avoided $CO_{2,eq}$ emissions due to the recovery of bottom ash, meant to represent the average situations of the different countries: 0.3 ton $CO_{2,eq}$ / ton of collected bottom ash for all European countries and the USA; 0.1 ton $CO_{2,eq}$ / ton of collected bottom ash for all the other countries.

3.2 Assessment of CO_2 emissions from WtE plants in the selected countries

Following the methodology previously described, an assessment of the CO_2 emission factors for each of the main contributions and the calculation of the total amount of the fossil CO_2 equivalent emissions associated to WtE operations have been carried out for the countries selected in Task 1. Furthermore, the potential for capturing CO_2 from the flue gas of WtE plants (including both fossil and biogenic CO_2) has been reported.

For each country, some CO_2 emission factors (ton CO_2/ton waste) have been evaluated, based on the data available for all, or only part, of the WtE plants in operation. Data on waste treatment capacity or electricity/heat productions were often missing or not consistent (different sources): only the most significant plants have been considered to carry out the calculation. Once the average emission factors have been determined, they have been applied to the total amount of treated waste (most recent available datum) to estimate the total $CO_{2,eq}$ emissions at country level. All the reported results depend on the hypothesis introduced in the methodology.

Figure 12 shows the ranges of variability (min, max and average) considering the different categories (emission contributions due to WtE stack, energy production, landfilling avoidance, bottom ash management) by considering all the selected countries.



	WtE Stack	Energy production	Landfill	Bottom Ash	TOTAL
min	0,497	-0,478	-1,600	-0,060	-1,209
max	0,663	-0,125	-0,565	-0,020	-0,268
average	0,536	-0,311	-0,714	-0,055	-0,544

Figure 12: $CO_{2,eq}$ emission factors for the different contributions in the selected countries (min, max and average values).

The most significant variations can be ascribed to the avoided CO_2 emissions for landfilling, due to the fact that in most of the selected countries landfills have biogas collection (so lower

$CO_{2,eq}$ emissions) but in some cases (like South Africa or India) dump sites are very spread (so with very high $CO_{2,eq}$ emissions).

In this analysis, only the direct fossil CO_2 emissions from the stack of WtE plants give a positive contribution, whereas all the other terms are negative (avoided emissions). The total result itself is negative, leading to the conclusion that WtE plants, where in operation, already play a beneficial role for CO_2 emission savings, especially in the countries where waste recovery options are minimal and the average emissions for the conventional production of electricity/heat from the fuel mix are significant.

Table 7 reports a summary of the $CO_{2,eq}$ emission factors associated to WtE in the selected countries (Australia and South Africa are not considered because no WtE plant burning MSW/RDF is currently in operation).

Table 7: summary of CO_2 emission factors from WtE plants for the selected countries (Australia and South Africa are not considered since no WtE plant burning MSW/RDF is currently in operation).

Country	Current fossil $CO_{2,eq}$ emissions					Additional Contribution from Potential Capture from WtE
	WtE Stack*	Energy production (electricity & heat)	Landfill	Bottom Ash	TOTAL	
The Netherlands	0.521	-0.304	-0.585	-0.060	**-0.427**	**-1.018**
Norway	0.497	-0.478	-0.600	-0.060	**-0.641**	**-1.001**
Italy	0.555	-0.292	-0.565	-0.060	**-0.363**	**-1.041**
Germany	0.521	-0.299	-0.585	-0.060	**-0.424**	**-1.017**
United Kingdom	0.509	-0.125	-0.593	-0.060	**-0.268**	**-1.009**
USA	0.524	-0.340	-0.584	-0.060	**-0.460**	**-1.019**
Japan	0.497	-0.399	-0.600	-0.060	**-0.562**	**-1.001**
India	0.663	-0.252	-1.600	-0.020	**-1.209**	**-1.117**
Australia	NA	NA	NA	NA	**NA**	**NA**
South Africa	NA	NA	NA	NA	**NA**	**NA**

** includes RDF production*

The total fossil-equivalent CO_2 emission factors show that WtE is always associated to significant CO_2 emission savings in all the considered countries, even without considering CO_2 capture. This latter option (CO_2 capture) offers the potential for a significant enhancement of the CO_2 emission saving figures, entailing the possible doubling or even more increasing of the results for such a performance indicator.

3.2.1 The Netherlands

Full sets of data (year 2013) are available for 8 out of the 13 Dutch WtE plants, entailing a total amount of 6 million tons of waste incinerated, 3,800 GWh of electricity exported to the grid and 960 GWh of heat to district heating.

Concerning the avoided emissions for electricity production, an emission factor of 0.420 ton CO_2/MWh_E has been considered **[28]** while for landfill disposal the emission factor has been taken equal to 0.5 ton $CO_{2,eq}$/ton waste disposed for RDF and 0.6 ton $CO_{2,eq}$/ton waste disposed for MSW (landfill with biogas collection and valorization).* includes RDF production

Table 8 shows the CO_2 emission factors for the different contributions, whereas Figure 13 shows the total fossil equivalent CO_2 emissions: by recovering roughly 7 million tons of waste via WtE plants in 2017, the Netherlands avoided circa three million tons of CO_2.

Table 8: CO_2 emission factors from WtE plants - The Netherlands

CO_2 emission factors (ton $CO_{2,eq}$ / ton waste)	Current fossil $CO_{2,eq}$ emissions					Additional Contribution from Potential Capture from WtE
	WtE Stack*	Energy production (electricity & heat)	Landfill	Bottom Ash	TOTAL	
The Netherlands	0.521	-0.304	-0.585	-0.060	**-0.427**	**-1.018**

** includes RDF production*

Figure 13 shows that, among the different contributions, the most significant quota of avoided emissions is given by landfill diversion. In fact, although most of the Dutch WtE plants are CHP facilities, the main contribution to avoided emissions is due to the electric production, which is accounted based on the carbon intensity of the national generation system, encompassing a significant share of renewable sources.

The potential for CO_2 capture from WtE plant stacks indicates the possibility of more than tripling the overall beneficial effect of WtE.

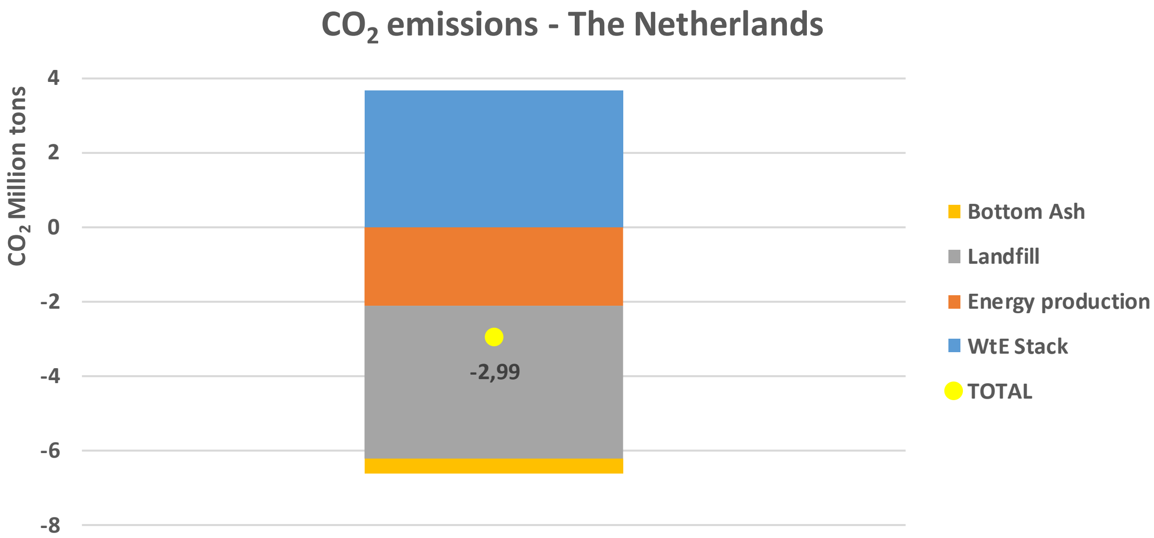


Figure 13: CO_2 emissions from WtE plants - The Netherlands

3.2.2 Norway

Full sets of data (year 2013) are available for 9 out of the 17 Norwegian WtE plants, entailing a total amount of 0.64 million tons of waste incinerated, 228 GWh of electricity exported to the grid and 1,226 GWh of heat to district heating. All the selected plants treat MSW, therefore there is no information on the Oslo RDF-based WtE plant.

Concerning the avoided emissions for electricity production, an emission factor of 0.008 ton CO_2/MWh_e has been considered [28], whereas for landfill disposal the emission factor has been taken equal to 0.6 ton $CO_{2,eq}$/ton MSW disposed (landfill with biogas collection and valorization).

Table 9 shows the CO_2 emission factors for the different contributions, whereas Figure 14 shows the total fossil equivalent CO_2 emissions: by recovering roughly 1.53 million tons of waste via WtE plants in 2018, Norway avoided almost one million tons of CO_2.

Table 9: CO_2 emission factors from WtE plants - Norway

CO_2 emission factors (ton $CO_{2,eq}$ / ton waste)	Current fossil $CO_{2,eq}$ emissions					Additional Contribution from Potential Capture from WtE
	WtE Stack	Energy production (electricity & heat)	Landfill	Bottom Ash	TOTAL	
Norway	0.497	-0.487	-0.600	-0.060	**-0.641**	**-1.001**

Figure 14 shows that, similarly to the Netherlands, the contribution of landfill diversion is determinant for the overall result. However, in this case the contribution of the recovered energy is larger, thanks to the intensive use of heat for district heating. In fact, the avoided CO_2 emissions related to electricity generation are negligible, because of the very low emission factor of electricity from the grid, mostly of renewable origin.

The potential for CO_2 capture from WtE plant stacks indicates the possibility of more than doubling the overall beneficial effect of WtE for Norway also.

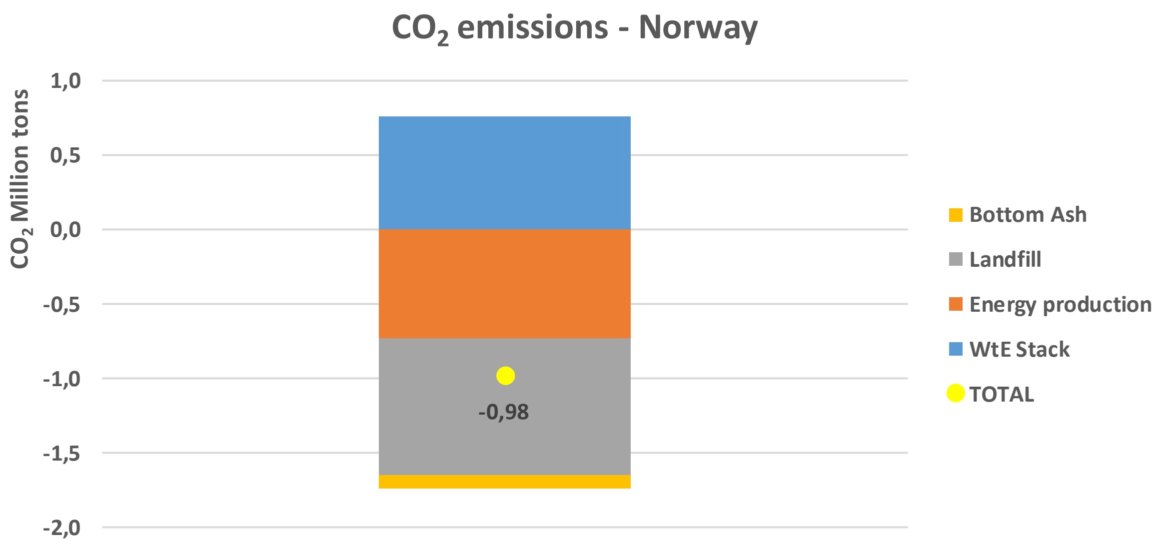


Figure 14: CO_2 emissions from WtE plants - Norway

3.2.3 Italy

Full sets of data (year 2017) are available for all 37 Italian WtE plants, entailing a total amount of 6 million tons of waste incinerated, 4,440 GWh of electricity exported to the grid and 1,820 GWh of heat to district heating.

Concerning the avoided emissions for electricity production, an emission factor of 0.302 ton CO_2/MWh_E has been considered [28], whereas for landfill disposal the emission factor has been taken equal to 0.5 ton $CO_{2,eq}$/ton waste disposed for RDF and 0.6 ton $CO_{2,eq}$/ton waste disposed for MSW (landfill with biogas collection and valorization).* *includes RDF production*
Table 10 shows the CO_2 emission factors for the different categories, whereas Figure 15 shows the total fossil equivalent CO_2 emissions: by recovering roughly 6.1 million tons of waste via WtE plants in 2017), Italy avoided more than two million tons of $CO_{2,eq}$ emissions. Such a figure could be more than doubled by sending to WtE also the almost 7 million tons of RDF/MSW currently landfilled in the country.

Table 10: CO_2 emission factors from WtE plants - Italy

CO_2 emission factors (ton $CO_{2,eq}$ / ton waste)	Current fossil $CO_{2,eq}$ emissions					Additional Contribution from Potential Capture from WtE
	WtE Stack*	Energy production (electricity & heat)	Landfill	Bottom Ash	TOTAL	
Italy	0.555	-0.292	-0.565	-0.060	**-0.363**	**-1.041**

** includes RDF production*

Figure 15 shows that also for Italy, landfill diversion is determinant. However, the contribution of the avoided emissions for energy production is significant and mostly due to electricity generation.

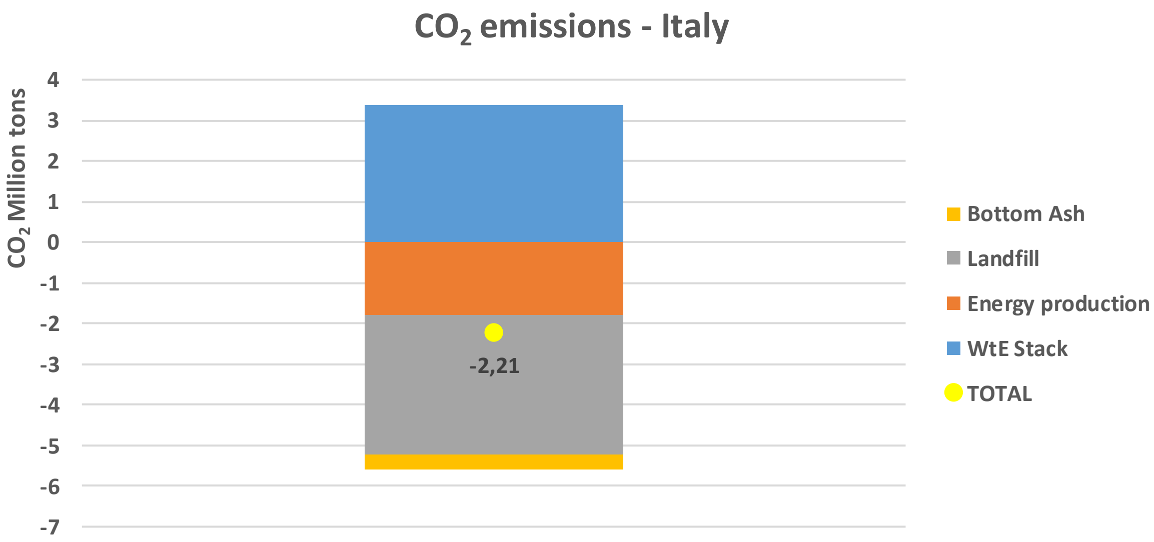


Figure 15: CO_2 emissions from WtE plants - Italy

The potential for CO_2 capture from WtE plant stacks indicates the possibility of tripling the overall beneficial effect of WtE for Italy also.

3.2.4 *Germany*

Full sets of data (year 2013) are available for 31 out of the 81 German WtE plants, entailing a total amount of 9.6 million tons of waste incinerated, 3,525 GWh of electricity exported to the grid and 6,145 GWh of heat for district heating.

Concerning the avoided emissions for electricity production, an emission factor of 0.405 ton CO_2/MWh_E has been considered [28], whereas for landfill disposal the emission factor has been taken equal to 0.5 ton $CO_{2,eq}$/ton waste disposed for RDF and 0.6 ton $CO_{2,eq}$/ton waste disposed for MSW (landfill with biogas collection and valorization).

Table 11 shows the CO_2 emission factors for the different contributions, whereas Figure 16 shows the total fossil equivalent CO_2 emissions: by recovering roughly 22.6 million tons of waste via WtE plants in 2018, Germany avoided the emission of more than nine million tons of CO_2.

Table 11: CO_2 emission factors from WtE plants - Germany

CO_2 emission factors (ton $CO_{2,eq}$ / ton waste)	Current fossil $CO_{2,eq}$ emissions					Additional Contribution from Potential Capture from WtE
	WtE Stack*	Energy production (electricity & heat)	Landfill	Bottom Ash	TOTAL	
Germany	0.521	-0.299	-0.585	-0.060	**-0.424**	**-1.017**

** includes RDF production*

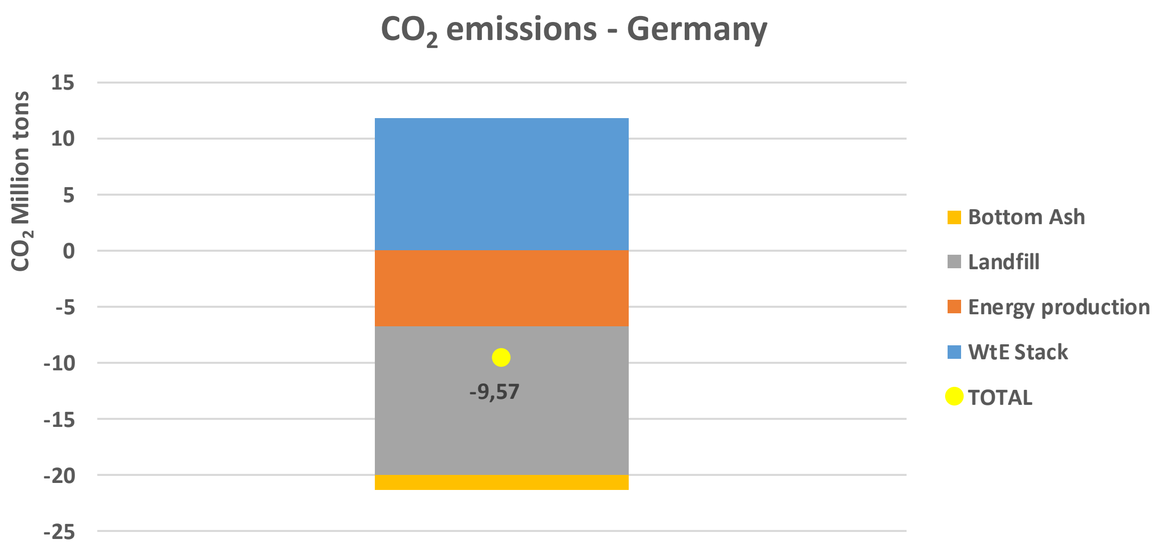


Figure 16: CO_2 emissions from WtE plants - Germany

Figure 16 shows that, similarly to the other countries, landfill diversion is determinant also for Germany. The contribution of the avoided emissions for energy production is ascribable for the same extent to both heat and electricity generation.

The potential for CO_2 capture from WtE plant stacks indicates the possibility of tripling the overall beneficial effect of WtE for Germany also.

3.2.5 UK

Data (year 2018) are available for all the 38 WtE plants in operation in UK, entailing a total amount of 11.6 million tons of waste incinerated and 6,193 GWh of electricity exported to the grid. Data on heat generation are available for only one out of the six CHP plants in operation.

Concerning the avoided emissions for electricity production, an emission factor of 0.228 ton CO_2/MWh_E has been considered [28], whereas for landfill disposal the emission factor has been taken equal to 0.5 ton $CO_{2,eq}$/ton waste disposed for RDF and 0.6 ton $CO_{2,eq}$/ton waste disposed for MSW (landfill with biogas collection and valorization).* includes RDF production
Table 12 shows the CO_2 emission factors for the different contributions, whereas Figure 17 shows the total fossil equivalent CO_2 emissions: in 2018, the UK avoided the emission of almost three million tons of CO_2.

Figure 17 shows, once again, the determinant role of landfill diversion. The contribution due to energy recovery is rather limited, on the one hand, because of the quite low carbon intensity of the electricity from the grid, on the other hand, because of the limited use of heat for district heating (which, moreover, is underestimated as a result of the missing data).

Table 12: CO_2 emission factors from WtE plants - UK

CO_2 emission factors (ton $CO_{2,eq}$ / ton waste)	Current fossil $CO_{2,eq}$ emissions					Additional Contribution from Potential Capture from WtE
	WtE Stack*	Energy production (electricity & heat)	Landfill	Bottom Ash	TOTAL	
United Kingdom	0.509	-0.125	-0.593	-0.060	**-0.268**	**-1.009**

** includes RDF production*

The potential for CO_2 capture from WtE plant stacks indicates the possibility of quintupling the overall beneficial effect of WtE for the UK.

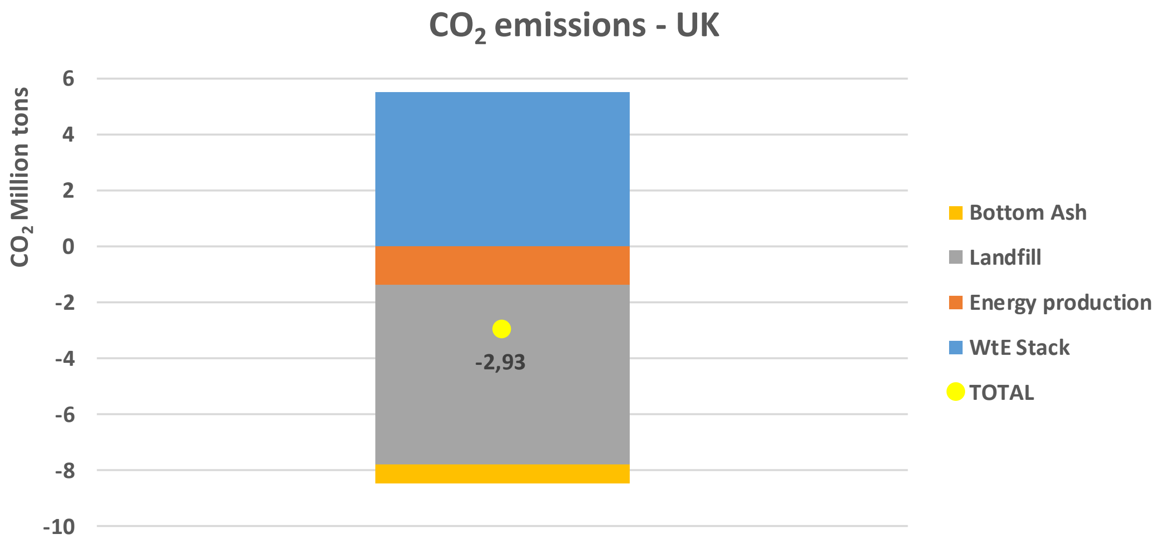


Figure 17: CO_2 emissions from WtE plants - UK

3.2.6 *USA*

Data (year 2016) are available for 72 out of the 77 US WtE plants, entailing a total amount of 25 million tons of waste incinerated and 20,820 GWh of electricity to the grid. No data on heat generation for the 16 CHP plants are available.

Concerning the avoided emissions for electricity production, an emission factor of 0.409 ton CO_2/MWh_E has been considered [28], whereas for landfill disposal the emission factor has been taken equal to 0.5 ton $CO_{2,eq}$/ton waste disposed for RDF and 0.6 ton $CO_{2,eq}$/ton waste disposed for MSW (landfill with biogas collection and valorization).* includes RDF production
Table 13 shows the CO_2 emission factors for the different contributions, whereas Figure 18 shows the total fossil equivalent CO_2 emissions: by recovering roughly 27.8 million tons of waste via WtE plants in 2016), the USA avoided the emission of almost thirteen million tons of CO_2.

Table 13: CO_2 emission factors from WtE plants - USA

CO_2 emission factors (ton $CO_{2,eq}$ / ton waste)	Current fossil $CO_{2,eq}$ emissions					Additional Contribution from Potential Capture from WtE
	WtE Stack*	Energy production (electricity & heat)	Landfill	Bottom Ash	TOTAL	
USA	0.524	-0.340	-0.584	-0.060	**-0.460**	**-1.019**

** includes RDF production*

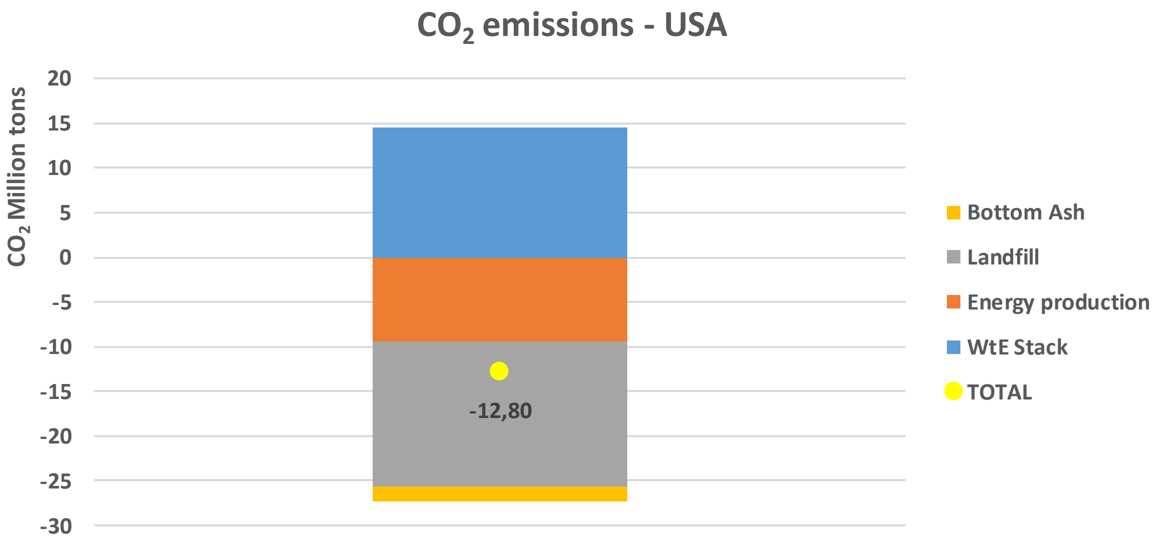


Figure 18: CO_2 emissions from WtE plants - USA

Like in the UK, no data on heat generation are available even if several WtE plants are reported to be CHP facilities. Therefore, the contribution of energy recovery in Figure 18 is somehow underestimated. Anyway, avoided emissions for landfill diversion are again the determinant contribution.

The potential for CO_2 capture from WtE plant stacks indicates, like in other countries, the possibility of more than tripling the overall beneficial effect of WtE for the USA.

3.2.7 Japan

Data (year 2017) are available for 5 out of the 1,146 Japanese WtE plants, entailing a total amount of 1 million tons of waste incinerated and 821 GWh of electricity exported to the grid[6]. No data on the type of waste treated by the selected plants (assumed to be MSW) and no data on heat generation are available. Unfortunately, the depicted situation is very poorly significant, so the assessed results could be considered just as indicative estimations.

Concerning the avoided emissions for electricity production, an emission factor of 0.485 ton CO_2/MWh_E has been considered [28], whereas for landfill disposal the emission factor has been

[6] The electricity production has been calculated considering the single plant installed capacity (MW_e) and a reasonable estimation of the average number of equivalent operating hours per year (7,000 hr/yr).

taken equal to 0.6 ton $CO_{2,eq}$/ton MSW disposed (landfill with biogas collection and valorization).

Table 14 shows the CO_2 emission factors for the different contributions, whereas Figure 19 shows the total fossil-equivalent CO_2 emissions: Japan, by recovering 0.18 million tons per day of waste via WtE plants, roughly corresponding to 52.5 million tons for year 2017[7], avoided the emission of almost thirty million tons of CO_2 equivalent.

Table 14: CO_2 emission factors from WtE plants - Japan

CO_2 emission factors (ton $CO_{2,eq}$ / ton waste)	Current fossil $CO_{2,eq}$ emissions					Additional Contribution from Potential Capture from WtE
	WtE Stack	Energy production (electricity & heat)	Landfill	Bottom Ash	TOTAL	
Japan	0.497	-0.399	-0.600	-0.060	**-0.562**	**-1.001**

The potential for CO_2 capture from WtE plant stacks indicates, like in the other countries, the possibility of almost tripling the overall beneficial effect of WtE for Japan.

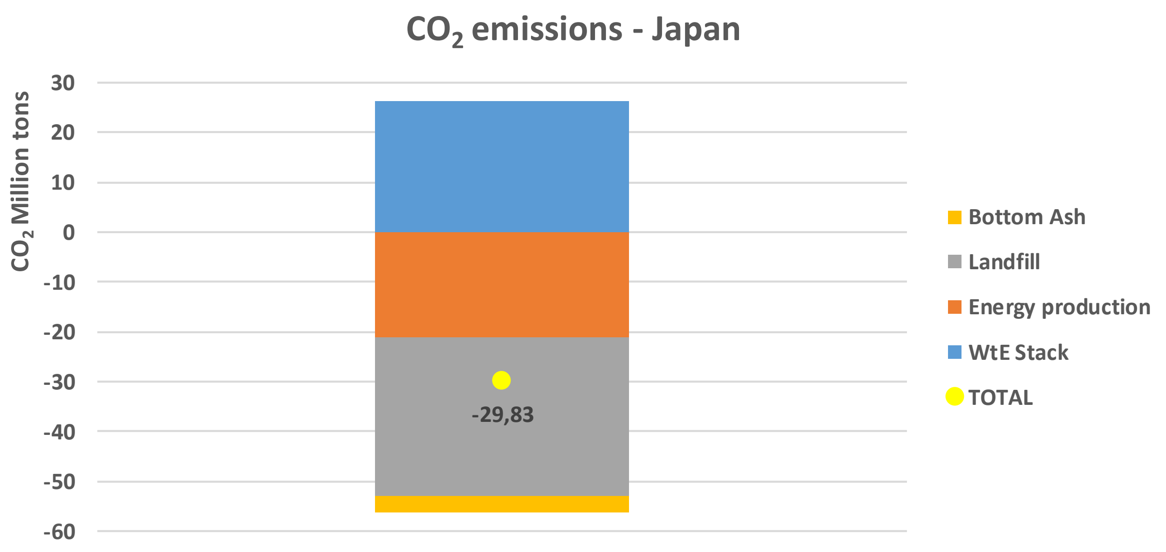


Figure 19: CO_2 emissions from WtE plants - Japan

[7] Having considered 7,000 hr/yr of operation at full capacity.

3.2.8 India

Data (year 2018) are available for 4 out of the 8 Indian WtE plants, entailing a total amount of 1.3 million tons of RDF incinerated and 444 GWh of electricity exported to the grid[8]. No data on heat generation are available. The depicted situation is relatively significant, leading to rather reliable estimations on CO_2 equivalent emissions.

Concerning the avoided emissions for electricity production, an emission factor of 0.718 ton CO_2/MWh_E has been considered [28], whereas for landfill disposal the emission factor has been taken equal to 1.6 ton $CO_{2,eq}$/ton RDF disposed (dump sites with no biogas collection).* includes RDF production

Table 15 shows the CO_2 emission factors for the different categories, whereas Figure 20 shows the total fossil-equivalent CO_2 emissions: in 2018, India avoided the emission of about one and a half million tons of $CO_{2,eq}$.

Table 15: CO_2 emission factors from WtE plants - India

CO_2 emission factors (ton $CO_{2,eq}$ / ton waste)	Current fossil $CO_{2,eq}$ emissions					Potential Capture from WtE
	WtE Stack*	Energy production (electricity & heat)	Landfill	Bottom Ash	TOTAL	
India	0.663	-0.252	-1.600	-0.020	**-1.209**	**-1.117**

** includes RDF production*

Among the selected countries, India is the one with the highest avoided CO_2 emission factor, mainly because of the waste disposal at dump sites without biogas collection is very $CO_{2,eq}$ intensive. Even without considering the contribution of energy production by WtE plants, thermal treatment in India represents a significant advancement toward sustainable waste management.

Starting from a situation of high CO_2 emission intensity, the potential for CO_2 capture from WtE plant stacks indicates the possibility of almost doubling the overall beneficial effect of WtE for India, which is already, even without CO_2 capture, very relevant.

[8] The electricity production has been calculated considering the single plant installed capacity (MW_e) and a reasonable estimation of the average number of operating hours per year (7,000 hr/yr).

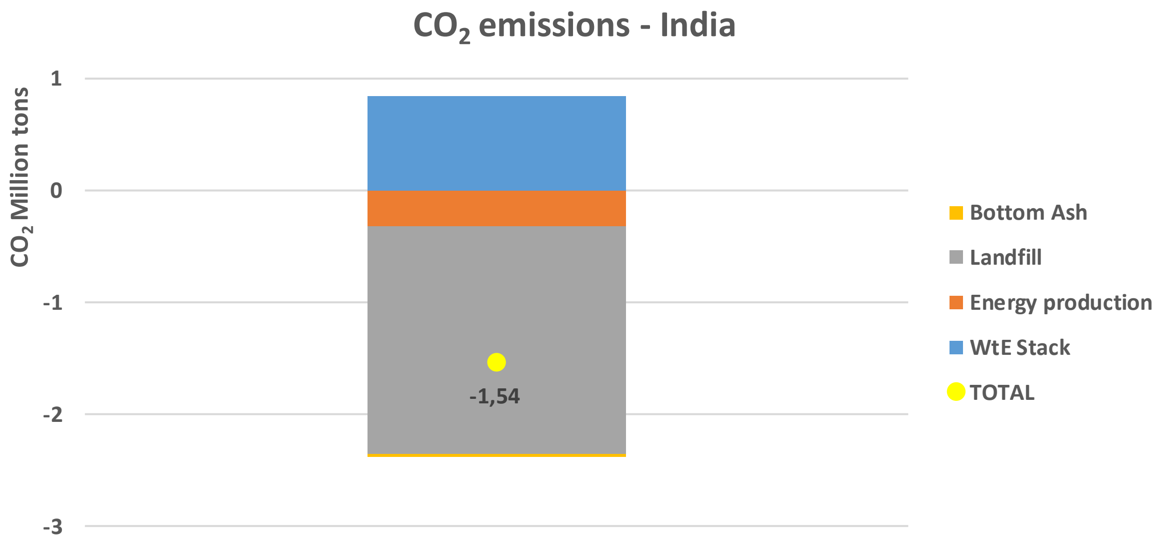


Figure 20: CO_2 emissions from WtE plants - India

3.2.9 Australia

Currently no incineration or WtE plants for MSW/RDF are in operation in the country. About 1.97 million tons of waste is disposed of into landfills, with biogas collection and energy valorization. By assuming that this amount of waste (MSW with LHV roughly 10 MJ/kg) could be diverted from landfilling to WtE plants (grate incinerators with an average electric efficiency of 23%, 7,000 hr/yr of operation at full capacity, no production of heat for district heating and basic bottom ash recovery) a total amount of 1,258 GWh of electricity exported to the grid can be achieved.

In addition, by considering an emission factor for electricity production of 0.714 ton CO_2/MWh_E [28], an emission factor for landfill disposal equal to 0.6 ton $CO_{2,eq}$/ton MSW disposed and an emission factor for bottom ash recovery equal to 0.1 ton $CO_{2,eq}$/ton BA, Australia could avoid the emission of a total amount of roughly one million tons per year of $CO_{2,eq}$.

3.2.10 South Africa

Like Australia, no incineration or WtE plants for MSW/RDF are in operation in the country. Additionally, many landfill/dump sites are operating without compliance with modern standards, resulting in poor environmental performances, associated with significant environmental impacts (due to no biogas collection). Furthermore, South Africa has the higher emission factor for electricity production among the selected countries, being 0.900 ton CO_2/MWh_E in consideration of the national fuel mix used [28]. Consequently, WtE could provide several benefits in terms of CO_2 emission savings that can be estimated as the avoided emissions guaranteed by MSW diversion from landfill/dump sites disposal to energy recovery in dedicated plants (1.7 ton $CO_{2,eq}$/ton MSW disposed).

4. Review carbon capture options for WTE plants

The high concentration of CO_2 in the air and its continuous emissions increasing due to the strong consumption of fossil sources, the energy demand and waste produced pro capita are the main reasons of the interest in CO_2 capture technologies, its utilization or storage. In light of advantages of Waste to energy plants discussed in previous section, the development of an integrated process WtE-PCC system, where PCC stands for Post-Combustion Capture. represent a promising option to reduce significantly the CO_2 emissions, with potential for overall negative life-cycle emissions

Unlike coal and gas, the composition of waste changes over time, due to changing societies and government policies. This may raise some concerns for the design of the CO_2 capture section, connected to the possible changes on flue gas composition, its flowrate and the content of pollutants. Operational data of WtE plants burning mainly MSW show great variation of the content of pollutants in the raw gas, which are, however, normally managed by the Air Pollution Control (APC) system, in a way to keep almost constant emission levels at the stack. Moreover, variation in flue gas flowrate, CO_2 concentration and CO_2 flowrate are commonly limited to +/- 10% and mainly attributable to changes in the waste contents of moisture (which changes mainly the flowrate of flue gas) and biogenic matter (which affects the content of CO_2 in flue gas). The FDBR Guideline-RL 7 [35] defines a correlation between energy content and waste composition that confirms the aforementioned range of variation for the properties of flue gas from MSW combustion. The ISO 18466:2016 norm defines a method to evaluate the biogenic share of the waste carbon content based on mass and energy balances of the combustion process and, for MSW, suggests results in line with those of the FDBR document. Variations of flue gas properties of the order of +/- 10% are similar to those due to load fluctuation during normal operational conditions, therefore they can be considered manageable for the design of the capture system.

The aim of Task 3.2 is to analyse the CO_2 capture process state of art, storage and utilization options to apply to WtE plants. Firstly, the main CO_2 capture technologies are described with their benefits and drawbacks, secondly the integration of a capture technology after a Waste-to-Energy plant is discussed and at last, the possible use and destination of captured CO_2 are discussed from a geographic perspective, as done for Task 1 and Task 3.1.

4.1 Review of CO_2 capture technological options: benefits and drawbacks

The technologies for CO_2 removal can be classified according to combustion process in post-combustion, pre-combustion and oxy-combustion, as showed in Figure 21 [36] [37]. Considering that the aim of this study is to integrate the CO_2 capture with a WtE plant, focusing on a retrofit approach, only the post-combustion technological methods will be analysed.

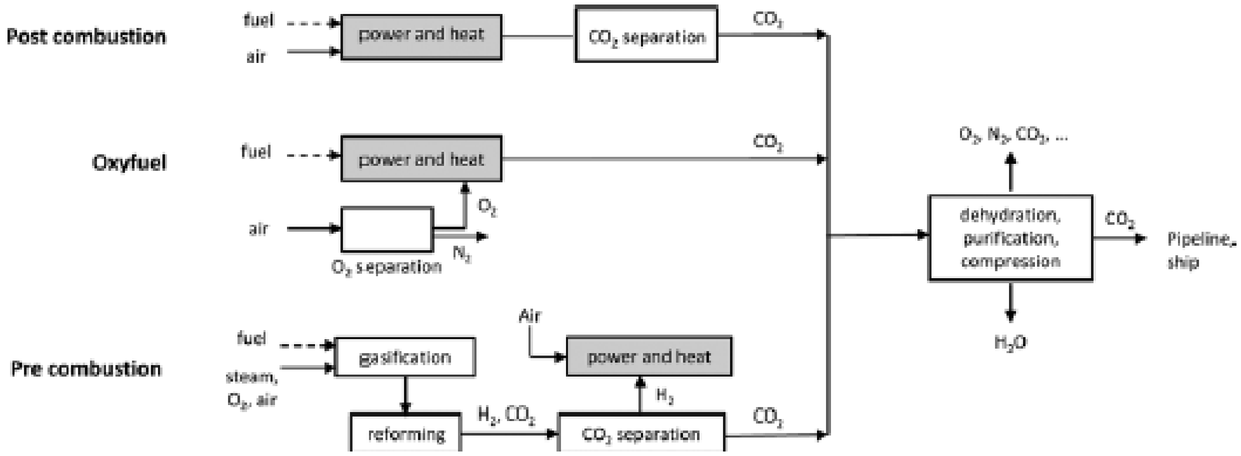


Figure 21- Main CO_2 capture systems associated with different combustion processes [37]

The separation task is to remove the CO_2 from a mixture of N2, oxygen and impurities as SOx and NOx. The capture technologies mostly investigated are listed in Figure 22.

The choice of which capture technology use differs across industries, depends on the source of CO_2, the amount of CO_2, the industrial scaling-up and the technological readiness level, the ease of retrofit to existing industrial plants, the experience in industries other than CCS. For example, microalgae and electrochemical processes (e.g. fuel cells) have a TRL of 4, which indicates that the two processes are not ready for industrial development.

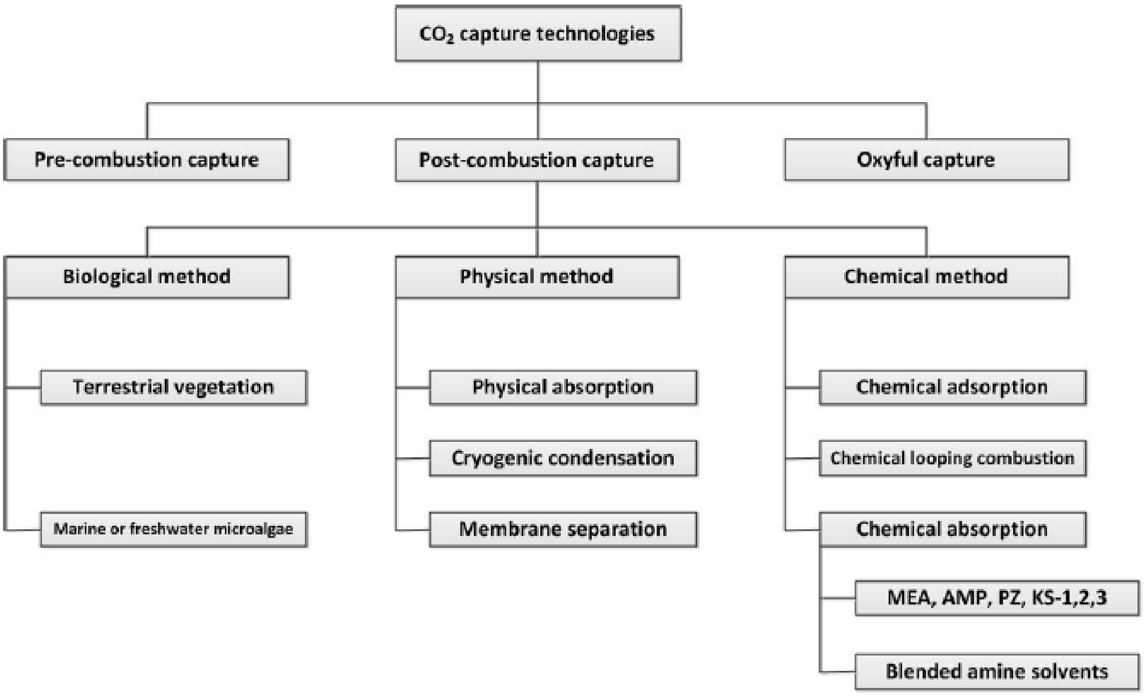


Figure 22- CO_2 capture from post-combustion application [38]

The key parameters for membrane separation are the material, shape and geometry of the membrane module, the configuration of the membrane stages (i.e. modules placed in parallel, series, with recycle, etc.), the operating conditions (i.e. volumetric flow rate, temperature, pressure, etc.). This process does not require a separation agent and the gas separation is achieved by applying a pressure difference across the membrane that drives the permeation of the gas. Generally, the membrane materials are inert to O_2 content and has a high tolerance to acid gases. Previous studies (Merkel et al., 2010), conducted on coal-fired power plants, reported CO_2 removal efficiencies with membrane separation up to 90%. Efficiencies between 85% and 90% are achievable with Polaris membranes as well, which have separation layer coated on an ultrafiltration membrane. This membrane was tested on a 0.6 MWe coal-fired boiler and the TEA analysis showed that the 90% of capture could be reached at costs lower than traditional process [39] [40] [41].

The application of membrane technology is very challenging for a post combustion CO_2 capture because of very low pressure of flue gas stream, the high selectivity required and the large membrane surface due to the low pressure, the particulate matter that needs to be removed before membrane purification. Future opportunities are focused on composite membranes that could take advantages from both polymeric and inorganic membranes, nevertheless it means an expensive cost for the membrane itself. [42].

The cryogenic process uses different points of condensation or solidification to separate the CO_2 from gas stream. It consists in either a flash (single or multiple stages) or a distillation column (or a combination of both) at very low temperature and relatively high pressure. The application limit of this method for a post combustion purification is related to the high energy required [42]. The energy investment could be re-paid only if the concentration of CO_2 were very high, much higher than a post-combustion application to air blown boilers for which this capture technology is not convenient.

The adsorption process uses solid sorbent beds with physical and chemical affinity with the CO_2. It is a cyclical process of CO_2 removal and release with the regeneration of the adsorbent bed. The sorbent materials should have a large specific area and a high regeneration ability [42]. The materials are not so expensive as membranes and have a low heat capacityin case of temperature swing adsorption, during the regeneration, the adsorbent bed does not require a large amount of heat, in comparison with the chemical absorption processes described later. The flue gas can be purified of the CO_2 content by swinging the pressure (PSA) or the temperature (TSA) as driving force to adsorb CO_2 and then release it separately from the flue gas. The main limitation of the PSA method is that the operating pressure levels necessary to make an effective swing are really high compared to the near atmospheric flue gas conditions. Also, the achievable CO_2 recovery is lower than 90%. An example of industrial application of PSA is in Finland, where a pressure swing adsorption process is placed downstream a refinery to capture the CO_2, which is then distillate to obtain a food-grade CO_2 [43].

On the contrary, the TSA method has a higher efficiency of capture, but it is applied on small-scale capture plant and is on development for industrial applications, because the capture cost is estimated to be about 80-150 USD/tonne CO_2 captured, which is still too high to be competitive [42] [44] [45] [36]. The adsorption process could be improved by modifying chemically the adsorbent bed by impregnation with amine, alkali-earth metal or lithium to improve the selectivity and consequently the capture efficiency of the CO_2, but the process is still at pilot-scale.

The most used and ready for industrial application of CO_2 capture is the chemical absorption with amine-based solutions due to the strong affinity between the amines and the Carbon dioxide [45]. The removal efficiency of CO_2 is high (>90%) and industrial large-scale plants are already on-going. Examples of projects to integrate the amine-based post combustion CO_2 capture within existing Waste to Energy are in The Netherlands, where AVR company is building the PCC systems for Duiven plant and planning a similar initiative at Rozenburg, and in Norway, where the Fortum Oslo project forecasts a WtE-PCCS plant [46] [12].

The challenges of this technology are related to the contaminants in the flue gas and the high energy demand.

Concerning the flue gas composition, the amines are easily degraded in presence of oxygen, SOx and NOx (the latter can lead to nitrosamines and nitramines formation),, which are harmful for human health and the environment [42] [37]. This issue can be avoided by controlling the oxygen in the combustion (pre- CO_2 capture) and by purifying the flue gas with Selective Catalytic Reduction (SCR) and scrubbing the flue gas for SO_2 removal. In addition, for a carbon capture plant after a Waste-to-Energy, it is necessary to control the HCl content in the flue gas. In fact, the HCl has a double effect. It reacts with the amines causing a lower carbon dioxide captured content and corrodes the stainless steel normally used as construction material. The latter problem should be avoided by using a more resistant material but increasing the overall costs. The HCl can be removed in acid gases by scrubbing the flue gas from the boiler.

Some R&D activities are ongoing at lab-scale, especially at technical Universities to develop amine based solvents that could reduce the specific energy demanded for regeneration [47] [48] [49]. The Tsinghua University, for example, has carried a lab screening of mixed amine solutions with 1,4-butanediamine and N, N-diethylethanolamine. The desorption heat for the blend solvent was estimated to be 30% lower than the heat necessary for the 30% wt of MEA process [50].

Other emerging technologies, instead, have been already tested at industrial scale. In fact, amino-acid processes as Siemens' PostCap and TNO's CASPER will simultaneously capture SO_2 and CO_2 from the flue gas. These processes have been tested on a pilot plant and a reduction of 10-20% was found in terms of FGD and CO_2 capture costs [51]

Shell Cansolv has developed a new aqueous amine process, which involves two solvents: the first purifies the flue gas from the SO_2, the second amine captures the CO_2. The regeneration of two absorbents is integrated to save energy and steam. The process is employed in Boundary Dam project and its TRL has become 6 (commercially available) [52]

The high energy demand is related to the regeneration of amines and release of captured CO_2. The energy is supplied by steam sent to the reboiler placed under the regeneration equipment. As a rule of thumb, the heat required for a standard PCC (30%wt MEA) in a Natural Gas Combined Cycle application is close to 4GJ per tonne of CO_2 [37]. The new-developed processes have optimized the reboiler heat duty as MHI and Shell licensed solvents, which have regeneration duty of 2.6 GJ/ton of CO_2 and 2.3 GJ/ton of CO_2, respectively [53] [54]

Several technologies are available from different licensors and the difference among them is mainly the capture efficiency, the type of solvent used and the plant configuration. . The solvents commercially used can be grouped into two macro categories: the already mentioned amine-based and ammonia-based. In last years, two phase liquid solvents got a foothold in CO_2 capture scenario, which minimizes the amount of absorbent sent to the regeneration and the energy requirement. The drawback is that the rich- CO_2 phase becomes more viscous, resulting in less mass transfer and higher pump costs [55].

The majority of CO_2 capture plants currently in operation at industrial scale use amine-based solvents for both fossil fuels fired plants and WtE plants, as indicated in Task 1.2.

The amine-based solvents have a strong affinity with the carbon dioxide and currently represent the most diffused technology for post-combustion capture. However, there are several amine-based solvents: primary and secondary amines have a faster kinetics but a lower loading capacity (mol of amine/mol of CO_2) compared with tertiary amines but require more energy for regeneration; secondary amines have issues with harmful emissions, because they have a greater potential to form nitrosamines after being emitted [56] [57]. Piperazine needs less heat to release the CO_2, but it has a lower capture affinity with the CO_2.

In Table 16, a semi-qualitative comparison between the different CO_2 capture technologies based on the type of solvents is taken in terms of CO_2 recovery, solvent make-up, heat duty to regenerate the solvent, investment cost, space necessary to build the unit and major equipment sizing. The used scale, ("high", "medium and "low") represents a qualitative relative ranking among the considered technologies. The comparison was based on Wood in-house database.

Table 16- Comparison between different CO_2 capture solvents. Data source Wood database

	Amine-based	Ammonia-based
CO_2 recovery, %	medium	low
Solvent Make-up (quantity)	Low-	medium-high
Regeneration Heat	medium	low
Capital Cost	Low-medium	high
Space	medium	medium
Major Equipment Sizing	Low-medium	medium

The choice among the licensors for the right solvent is a key parameter also because it influences the Flue Gas Treatment (FGT) pre- CO_2 capture and the energy demand. In fact, if the sorbent is high-resistant to flue gas impurities, specific actions to purify the gas before the CO_2 absorption column are not necessary. It happens with ammonia-based process. The drawback of this method is the removal efficiency lower than 90%. If a removal efficiency >90% is the design parameter, a solvent with high selectivity has to be used and the flue gas has to be purified of each contaminant, the extent of the purification depending on the type of solvent. The chilled ammonia process, for example, is known to have a low regeneration heat but a slower mass transfer kinetics than those based on aqueous MEA [58].

The CO_2 capture needs a not negligible amount of energy to keep high the temperature in the solvent regeneration column. The heat duty of a carbon capture plant depends on type of solvent (primary or secondary amine, chilled ammonia or others), the flue gas concentration of CO_2, on the overall process design and configuration. physical treatment of captured CO_2 and the heat integration with the WtE plant, which is further discusses in next section. For example, if the flue gas is more CO_2-concentrated, the absorption process is enhanced thanks to a higher driving force and, consequently, savings in main equipment sizing can be achievied.

After the capture, depending on its final destination, the captured CO_2 typically is compressed, dehydrated and, in some case, liquefied. These physical transformations are energy-expensive and would have significant impact on the overall energy balance of a WtE-CCS integrated system.

In last 20 years, the heat duty required for solvent regeneration is reduced from an average of 5.5 to 2.6 GJ/t CO_2. The reduction is due to improvements in chemical structure of the solvent and in capture process configuration. Figure 23 shows the trends of Heat Duty to regenerate the solvent of three different amine-based solvents over a period of 12 years, up to 2012. MEA is the commercial and well-known ethanol-amine, KS-1 is a licensed solvent of MHI and PZ is piperazine.

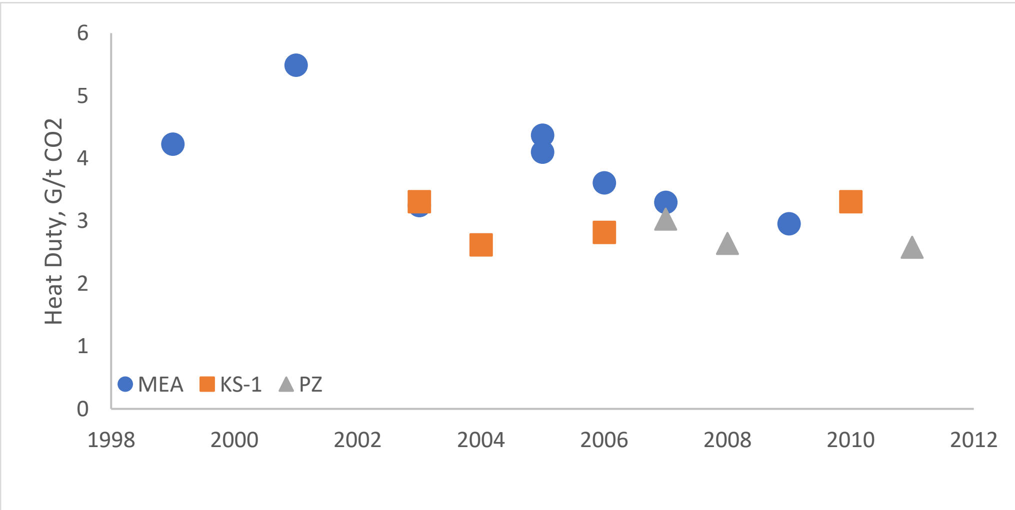


Figure 23- Heat Duty for solvent regeneration in the period 1998-2012 [58]

MEA is historically one of the first amine-solvent used for CO_2 capture and the decreasing trend of its heat duty is due to the improvements is the engineering of the process. The other two solvents (i.e. KS-1 and Piperazine), instead, have a more complicated chemical structure: the piperazine is a secondary diamine, whereas KS-1 is a proprietary mildly hindered amine.,. The drawback of using a solvent based on hindered amine that require less energy but at same time has a lower capture affinity is the need fora taller absorber and a larger amount of solvent in circulation, leading to higher investment costs. Piperazine offers higher CO_2 absorption rate, high intrinsic working capacity and lower heat of absorption [59]

In Table 17, more recent data about the commercially available licensed amine-based solvents are shown. They are the most recent developed solvent with a heat duty for regeneration lower than MEA.

Table 17- Comparison of different licensed solvent heat duty

Technology	**Licensor**	**Type of amine**	**Heat duty, GJ/tCO2**
n.a.	**Commercially available**	**MEA**	**~3**
KS-1	MHI	Sterically hindered	2.6 [54]
DC	Shell Cansolv	n.a.	2.2-2.8 [53]
Ecoamine FG	Fluor	Aqueous solution of MEA	3.2-3.6 [60]
n.a.	Aker solution	n.a.	2.8 [61]
TS-1	Toshiba	n.a.	2.6 [62]
H3	Hitachi	n.a.	2.4 [63]

Looking at the WtE facilities that have integrated / planned to integrate CCS, in Duiven (The Netherlands, where the integration of CO_2 capture and locally re-use with a WtE plant is ongoing and the amount of captured CO_2 is roughly 50 ktCO_2/y, which is around 12% of the overall CO_2 produced, including both fossil and biogenic fractions), the CO_2 will be captured by amine-based solvent (commercial MEA) supplied by SIAD group in an absorption-stripper cycle. The CO_2 will be used for horticulture with seasonal arrangement from April to September.

The solvent is regenerated by Low Pressure steam extracted from steam turbine in-plant and that is used for District Heating as well. A similar approach is followed for the FEED study in Rozenburg (NL).

The Fortum Oslo facility is a WtE plant where CO_2 capture based on Shell Cansolv technology has been tested at pilot scale and the full-scale project is at FEED stage. In the latter, The energy produced from WtE is used for district heating and to sustain the energy consumption of capture plant. The captured CO_2 is sent via pipeline first and then via shipping to a storage site in the North Sea. In June 2019, tests focused on emissions and solvent degradation were completed.

A secondary amine sterically hindered are used in PCC technology owned by Toshiba and applied in SAGA facility in Japan. The Saga project is about a WtE plant burning municipal waste. The WtE is composed by 3 parallel grate type boilers that treat on average 100 t/d for each unit. The steam produced in the burning cycle is partially furnished to local Health Center and the remaining is used for the regeneration of solvent in PCC. The 5% of total flue gas is treated in the PCC technology to capture about 80-90% of the CO_2, which is sent to farming industry nearby. In this WtE-PCC plant, the steam is not used for district heating thanks to the local warm climate.

5. Energy integration of the capture system within the WTE plant

The energy as MWh produced in a Waste-to-Energy is partially used for the in-plant consumptions. These are mainly linked to the Flue Gas Treatment train. For example, an FGT system with a SCR for NOx removal, a bag house filter for particulate matter and a wet scrubbed for acid gases as SOx and HCl has a consumption of about 80 kWh/MW of entering waste. Typically, a boiler with grate furnace produce less than 600 kWh/Mg of waste with an LHV of 10.4 MJ/kG: the 13% of produced electrical energy is used in the plant operation [4] [5].

When the Waste to energy is integrated with a CO_2 capture and storage/utilization system, , the auxiliary consumption of the overall system increases. As an example, Table 18 summarises the outcome of a study or a theoretical 100 MWe WtE palnt integrated with Post Combustion Carbon Capture [64]. The waste feedstock has an average heat content of 13 MJ/kg, the Capture system is an amine-base absorption and the CO_2 is compressed to 15 MPa for transportation to a saline aquifer for geological storage situated within max 20 km from the facility.

Table 18- Power consumption of a WtE-CC system [64]

	Power, MW	**Energy Penalty, GJ/t CO_2 captured (*)**
Amine-absorption unit	7.2	0.19
CC Steam use (electricity equivalent)	32	4.7
CO_2 compression	14.2	0.38
Auxiliaries no-CC	6.3	0.13
Other	4.6	0.12

(*) Refers to electric energy for all items except for CC Steam Use, where thermal energy is referred

The net 100 MWe available in a Waste-to-Energy becomes roughly 40 MWe, when CCS is integrated. The energy consumption in Table 18 are for a generic WtE-CCS system, it has to be considered that the same consumptions can vary based on performances of whole plant, energy recovery systems and etc.

With the purpose of deepening this kind of technical review, Wood has carried out two study cases (cases 1 and 2), starting from inhouse reference projects, to estimate of the impact of CO_2 capture system on energy production in two WtE plants. The first plant uses a CFB boiler, while the second one is based on a grate incinerator.

One of the most significant parameters is the ration between the steam required by the CO_2 Capture Unit and the steam produced in the boiler and sent to the Steam Turbine.

The CFB WtE plant of case 1 has the following characteristics:

- The plant is non-co-generative, i.e. produces electricity only, with a net electric power output of 20 MWe and a net electrical efficiency of 25.4%
- The flue gas flow rate is 155,000 Nm^3/h with a CO_2 content of approx. 10% vol. and a temperature of 150°C at the stack.

- The steam cycle throughput is 115 t/h
- The steam conditions at the boiler outlet are approx. 60 barg and 430°C

The amount of CO_2 generated is 31 t/h and, for an assumed average heat duty of regeneration of 3 GJ/tCO2, the plant would require about 150 GJ/h of energy to separate the CO_2 from the flue gas. The amount of steam necessary for a >90% removal of CO_2 would be approx. 40 t/h

Considering that the plant produces 115 t/h of steam, approx. the 38% of the Steam Turbine throughput should be extracted at a pressure of approx. 6 barg to supply energy for solvent regeneration in the Capture Unit. Assuming an equivalent electricity production factor of 150 kWh/t of steam, this would correspond an equivalent electric power of 6 MW_E.

Another major energy penalty is associated with the CO_2 compression and liquefaction (if required). Assuming that liquid should be delivered from the CO_2 capture plant @ 20 barg, the overall electricity consumption of the compression + liquefaction (chiller) would be 2.8 MW_E. Overall,the net electricity production would be almost halved due to the carbon capture energy requirement.

The same technical evaluation is made for the grate-boiler WtE plant of case 2:

- The plant is non-co-generative one; i.e. electricity production only, with a net electric power output of 20 MW_E and an electrical efficiency of 24.4 %.
- The flue has flow rate is 186,000 Nm^3/h with a CO_2 content of 8.18% vol. and a temperature of 150°C at the stack
- The steam cycle throughput is 101.5 t/h
- The steam conditions at the boiler outlet are approx. 61 barg and 420 °C.

The amount of CO_2 produced in the WtE is 35.3 t/h and, for an assumed heat duty regeneration of 3 GJ/t_ CO_2, the energy required to separate the CO_2 would be about 95 GJ/h. The amount of steam necessary for a CO_2 capture higher or equal to 90% would be approx. 45 t/h.

Considering that the plant produces 101.5 t/h of steam, about the 45% of the Steam Turbine production should be extracted at a pressure of approx. 6 barg to supply energy for solvent regeneration. Assuming an equivalent electricity production factor of 150 kWh/steam produced, the equivalent electric power of 6.8 MW_E would be necessary to sustain the capture unit.

In this case, with same assumptions as case 1, the energy penalty is associated with the CO_2 compression and liquefaction would be 3.2 MW_E.
Overall, the net electricity production would be halved with respect to the case with no carbon capture.
The two examples show how significant is the energy penalty associated with the CO_2 separation only.

Hence, it is crucial to find in the WtE plant other heat recovery sources. One potential source is surely the residual energy of the flue gas discharged at the stack.

In the considered reference cases, the flue gas is discharged to the atmosphere at approx. 150°C.

Usually, the temperature of flue gas is kept high enough to prevent the formation of corrosive deposits and acid condensates typical of municipal waste.

However, the heat of flue gas could be recovered by gas condensation, which has become a standard in WtE plants with District Heating.

In fact, in the gas condensation, the flue gas is cooled below the water dew point so that the water vapour condenses, and the thermal energy releases are recovered. The boiler heat output can be increased of 10-30% [65]. The gas condenser is placed in the final part of the gas path after the FGT so that the flue gas is already largely purified from contaminants, although some traces of SO_2, HCl and NOx are still present. The condensation of these species could enhance the corrosion risk of duct and heater coils. The risk is analysed and evaluated during the development of the plant, for example by anti-corrosion protection of chimneys and flue gas ducts.

The waste-to-energy plant in Copenhagen, connected to a District heating system, is an example of exploitation of flue gas condensation. . The plant has a two-step condensation process. In the first step, the heat is transferred directly to the district heating connection. In the second one, an absorption heat pump cools the flue gas to 30°C with an increase of heat output from the boiler line of about 20%. [66]

Figure 24 is the schematic representation of the whole WtE plant.

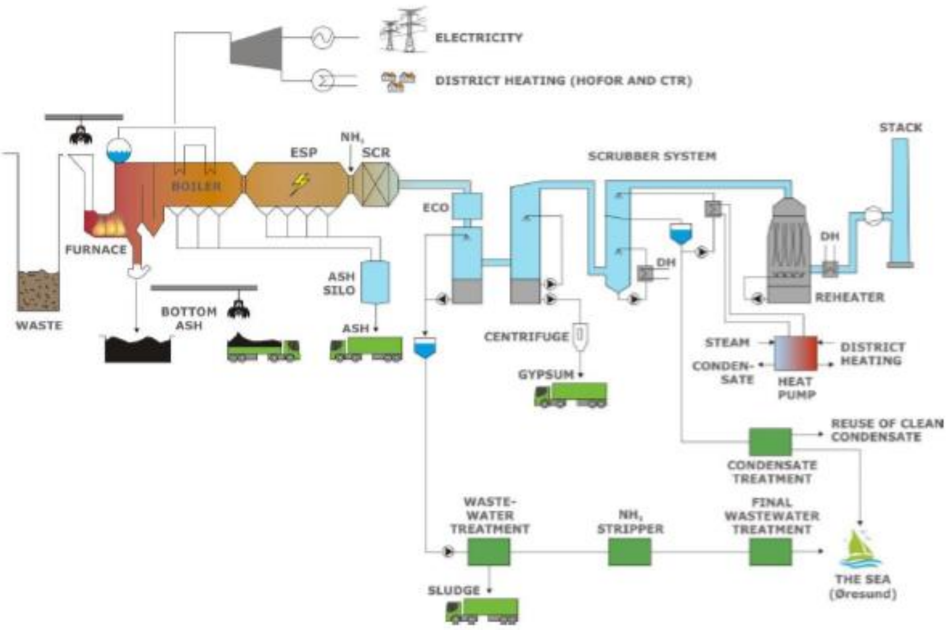


Figure 24- Copenhagen Waste to Energy plant with implantation of Glue Gas Condensation [66]

The adoption of such a system could be affective in WtE plants both with and without carbon capture. It has to be remarked that the heat recovered from a flue gas stream of 150°C cannot be effectively used in the CO_2 capture, which typically requires thermal energy for solvent regeneration at approx. 120-140°C. However, in absence of District Heating, a useful alternative would be to recover the heat of flue gas by preheating the Boiler Feed Water (BFW), avoiding the use of steam extraction from the Steam Turbine for this duty and thus contributing to reduce the overall energy penalty in terms of lost electricity production.

To hinder the energy conflict between the district heating and the CO_2 capture, an optional improvement to recover additional energy is to place a heat pump, a thermal machine composed by an evaporator, condenser, compressor and expansion valve, which is used to transfer heat from a hot source to a cold one. To this end, Wood carried out a specific evaluation through a third study case (case 3) starting form one of the two study cases described above, namely case 2, and assuming that the plant can be integrated with a District Heating (DH) network. The integration with carbon capture system and the implementation of a heat recovery system, as the heat pump, would get available energy for the district heating, reducing the adverse effect on the overall net energy production of the plant. The heat recovery for district heating in a heat pump can be partial or total. In a partial system, the DH water is partially heated at a temperature of about 50°C and it is then sent in an additional heat exchanger to be heated to a temperature suitable for DH (e.g. at least 70°C). In a total heat recovery, the DH water temperature is raised to 70°C in the heat pump itself. In this third study case, the heat pump is used for a total recovery, in order to integrate the plant with a new DH as the starting plant is non-cogenerative.. In the following, the thermal balance calculation for this additional study case is presented.

For the selected WtE plant, after the boiler, the flue gas is purified of pollutants in a treatment sequence composed by bag filter for dust removal, semi-wet reactor for soluble acid gases and SCR for deNOx. The flue gas at SCR exit has a temperature of 125°C and its temperature is lowered by heating the CO_2-free gas leaving the capture system at 35°C. The heat transfer is made in a Gas-Has Heater, which is placed downstream the FGT after the SCR.

After the GGH, the cooled flue gas at a T slightly higher than 80°C is further cooled in a quencher or Direct Contact Cooler to avoid solvent degradation in CO_2 capture absorber. The water used as refrigerant in the DCC is used as external heat source for the heat pump.

In fact, the cooling water enters the DCC at 27°C and is heated up to 57°C at its exit. The heat is released from the quencher water to a secondary closed loop, which is heated from 24 to 34°C and then used as heat source for the heat pump. The District Heating water is heated at the heat pump condenser from 35 °C to 70°C.

The full scheme is showed in Figure 25.

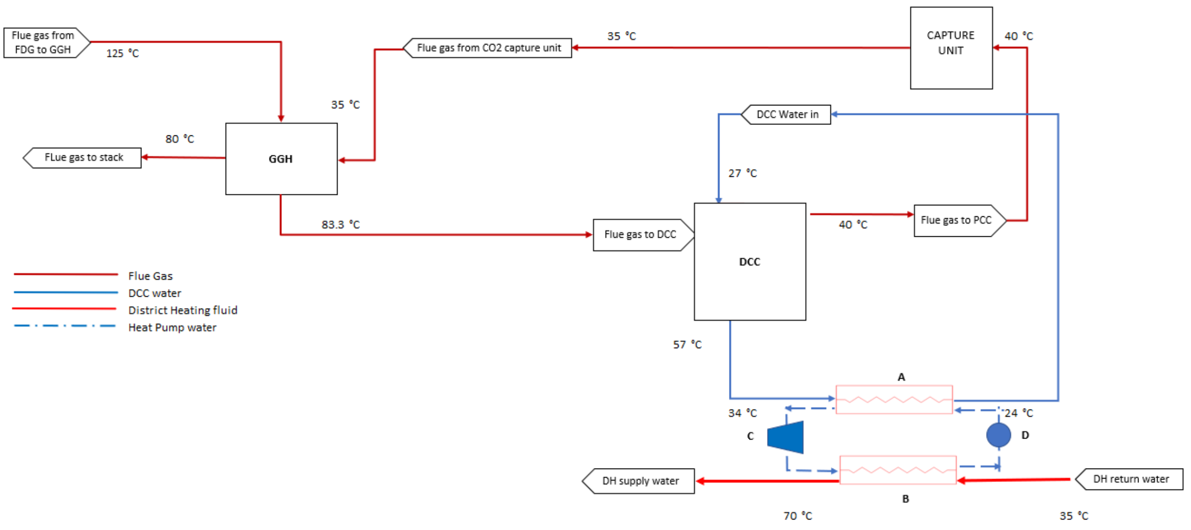


Figure 25- Gas-Gas Heater and Heat Pump integration in a WtE-CC plant. Reference Wood Database. A: Heat Pump evaporator, B= Heat Pump condenser, C= Heat Pump Compressor, D= Heat Pump expansion valve.

The heat available from the DCC is estimated to be 12.3 MW_T.

The thermal power effectively transferred to the district heating water depends on the Coefficient of Performance (COP) of the heat pump. For the analysed total heating option, Wood estimated from in-house data that the COP of such heat pump ranges between 5 and 6. This value is in line with technical datasheet of heat pump vendors [67].

The heat output from the condenser is the sum of the heat at the evaporator and the power of the heat pump compressor. The heat at evaporator can be estimated considering that there are no thermal losses and the amount of energy transferred between the flue gas and the DCC water is totally transferred to the cooling fluid circulating in the Heat Pump.

The amount of heat in the DCC is calculated to be 12.3 MW_T. For a COP of 5.5, the estimated electricity consumption of the compressor is 2.7 MW_E, resulting in an output of 15.1 MW_T at heat pump condenser for district heating.

In addition, with the previous assumption about CO_2 delivery condition (liquid @ 20 barg) the intercooling of the CO_2 offers the possibility to recover heat to the DH system. For case 3, this amount is estimated to be 2.3 $MW_{T.}$

Retrieving the energy balance calculation done for case 2, the electric energy penalty is further increased by 2.7 MW_E, leading to an overall penalty of more than 60% with respect to the original plant without carbon capture, but the plant can supply a significant amount of heat (more than 17 MW_T) to the local community, recovering an amount of heat that would be otherwise wasted.

A similar solution has been proposed and is going to be implemented is Klemestrud WtE plant (Oslo), but with a slightly different purpose. In fact, this WtE is a co-generative plant with 112 MW_T output for district heating and about 42 MW_E as available electricity. When the Carbon Capture is added to this plant, the power consumption is reduced to 20 MW_E to sustain the electric consumption of CO_2 capture and CO_2 liquefaction, while 36 MW_T are consumed for solvent regeneration. The thermal consumption is counter balance by heat recovery from the Direct Contact Cooler. The DCC cools down the flue gas entering the absorption column to 30-35°C to avoid the thermal degradation of solvent. The heat pump recovers the heat of water used in the DCC and sustains the district heating. The use of the heat pump introduces an additional electric consumption which increase the offset of electrical energy available tor Norway grid by about further 10 MW_E, however it allows fully balancing the heat requirement of the carbon capture, i.e. with no penalty on the heat output to the district heating after the integration with the Carbon Capture

6. Use and destination of CO_2

The captured CO_2 has two possible routes: carbon capture storage (CCS) and carbon capture utilization (CCU). Nevertheless, the carbon capture and storage has been mainly investigated, funded and developed at industrial scale, the gaseous carbon utilization, on the other hand, has progressively earned more visibility as renewable resource, low-cost and not-toxic alternative to GHGs emissions [44]. Figure 26 groups the main CO_2 emission sectors, the combustion options and capture technologies and, in the end, the main CO_2 destinations, which will be described in detail, reporting projects or existing plant that re-use the Captured CO_2.

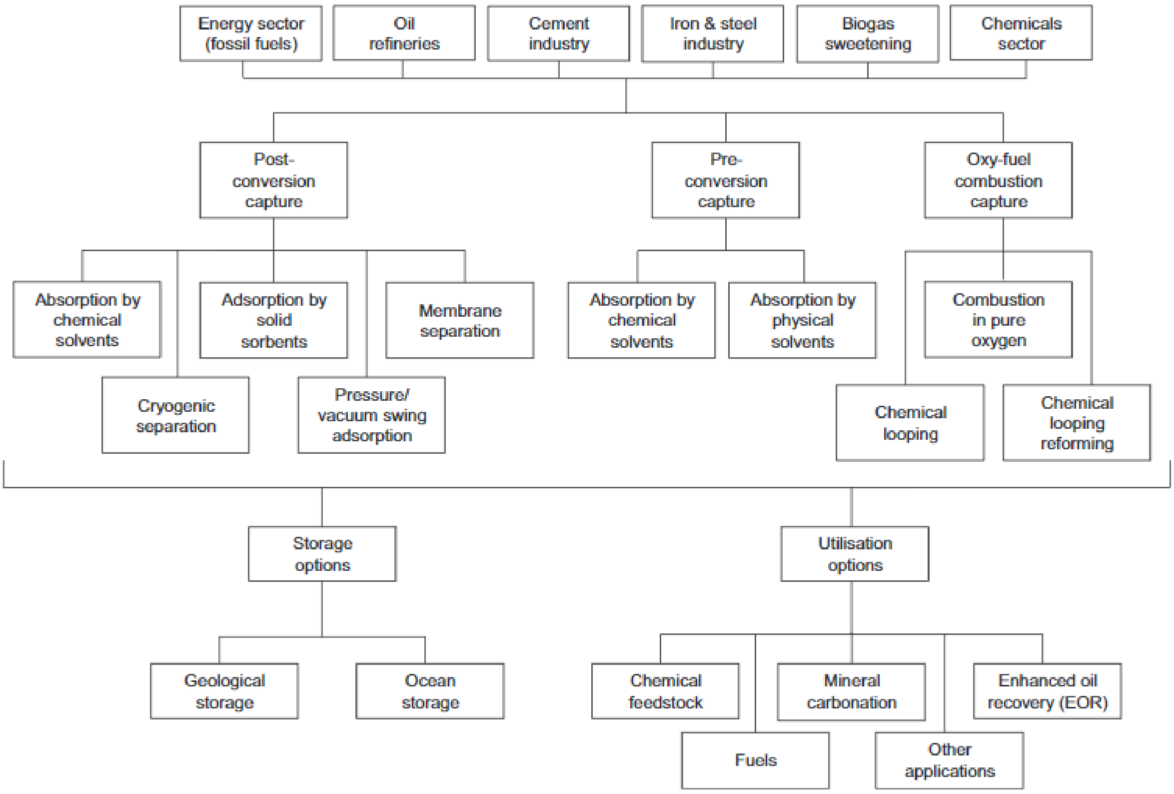


Figure 26- Different carbon capture storage and utilization options [44]

It is remarked that the environmental benefits of CO_2 storage or utilisation could be different: in case of geological storage, if the well or site is properly selected, managed and monitored, nearly all of the CO_2 stored is likely to remain sequestered and mineralized permanently. On the other hand, in case of CO_2 utilisation, a proper (and not always easy to perform) Life Cycle Assessment should be carried out to identify the direct and indirect CO_2 emissions connected to CO_2 utilisation (for instance in case of CO_2 to fuels).

Looking at national contexts of Italy, Germany, Norway, Netherlands, USA, UK, Japan, India, Australia and South Africa, Figure 13 summarizes the uses of captured CO_2 at 2018 [68].

As it is expected, the major uses of carbon dioxide are the geological storage and the EOR, while the less industrially developed is the fuel production.

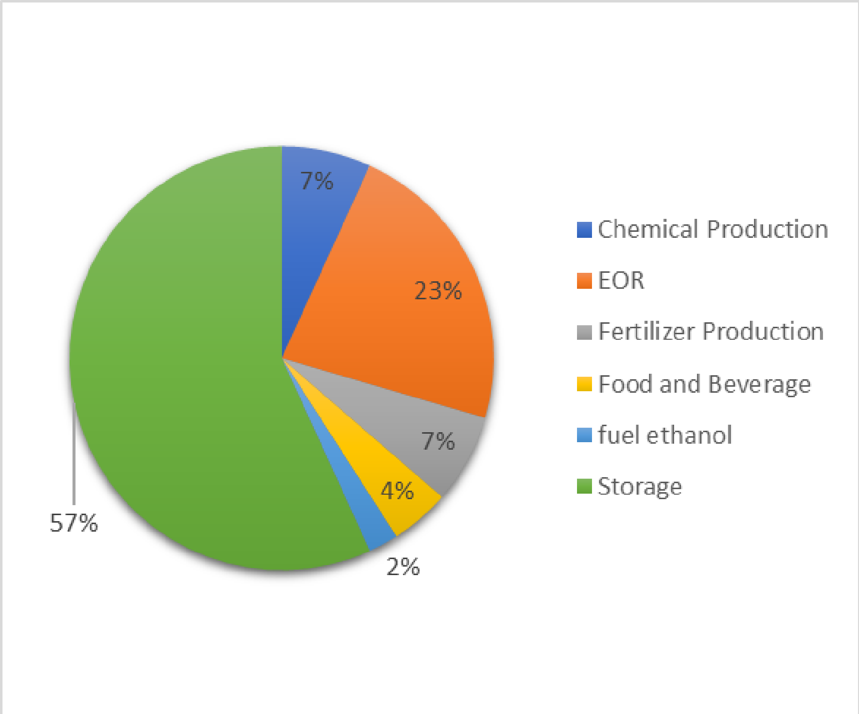


Figure 27- Overview of CO_2 destination for major world countries

The geological storage of the capture CO_2 is the injection of the liquid CO_2 into depths of 800 and 1000 m under the ground as in deep saline aquifers that have a storage capacity estimated of about 800 Gt of CO_2 or in depleted hydrocarbon fuels. Moreover, the CO_2 could react with the minerals present underground and act as a natural mineral sequestration. The liquid CO_2 is transported and sent in geological sites to counter-balance the CO_2 taken from the earth during the centuries. The main troubleshooting of geological sites is the leakage of the CO_2 in the environment, and the operative and energetic costs of compression and transportation that can be done via pipelines, trucks or ships.

The Global CCS Institute [68] has estimated the potential CO_2 storage capacity for the 80% of world countries. Figure 28 shows the Gtons of CO_2 that could be stored in geological sites for the states chosen as examples in this study.

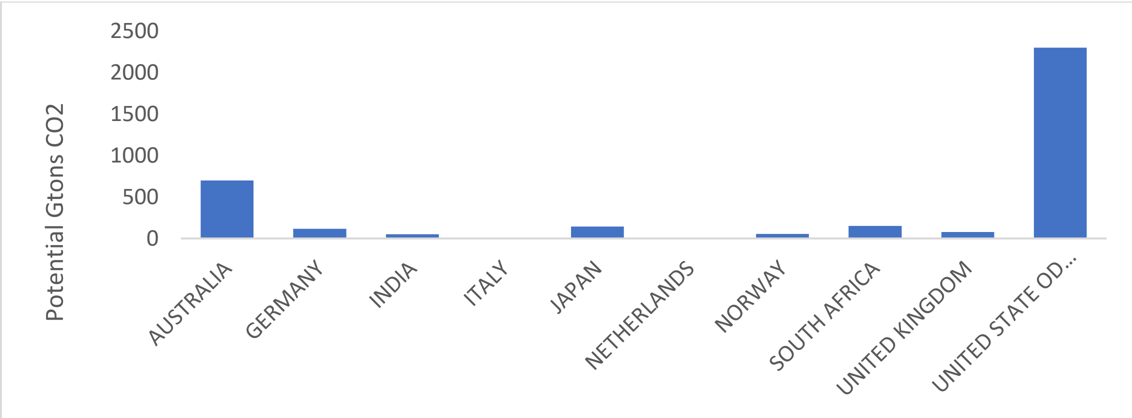


Figure 28- Estimated CO_2 storage for countries analyzed in Task 1 [68]

The USA has the major storage capacity due to the strategic position between the two oceans and its geographic extension, as well as the Australia. For the EU states, public acceptance towards CO_2 storage is much more challenging, and this limits the availability of easily accessible storage sites while increasing the investment costs related to pipelines and transportation. These challenges have stopped many EU members to not push towards the CO_2 storage. In fact, dedicated research and funding programmes have been established in four countries only: France, Norway, Germany and Netherlands.

The countries in which the CO_2 geological storage is mostly on focus are showed in Figure 29.

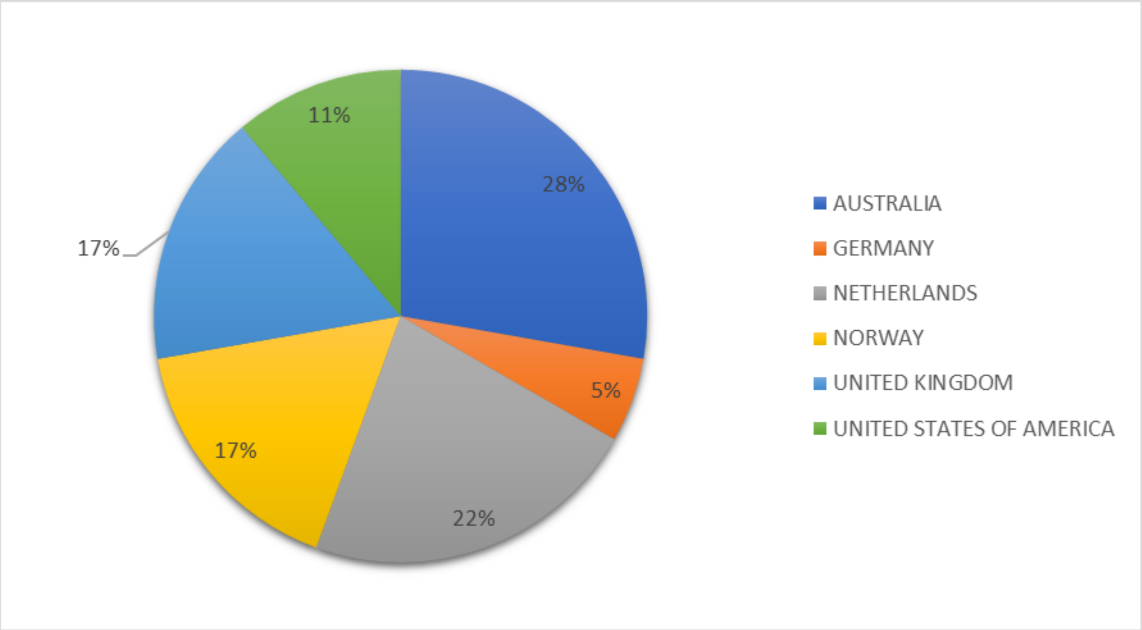


Figure 29- Geological storage use of CO_2 [68]

The percentages in Figure 29 takes in account the operating or advanced construction storage plants. In fact, Italy is not present because there are no in-operation CO_2 geological storage sites and the research projects on the subject are at early-development status. Australia and USA show the higher percentages. The former has highly invested in CO_2 storage with some sites already in operation and other in construction [68], the latter exploits its geographic location to use all possible storage sites under the sea and in exhausted natural gas reservoirs. Specifically, for the USA, the most used application of CO_2 is the Enhanced Oil Recovery and only with Texan CCS facility captures 8.4 million tons of CO_2 [68].

Norway is developing a demonstration CCS unit for the WtE plant in Klemetsrud [68], run by Waste-to-Energy Agency of Oslo (EGE) that has a capacity of 160,000 ton/year (1 out of 3 WtE lines) and produce electricity (10.5 MWe) and thermal energy (55.4 MWt). The flue gas produced by the boiler is sent to a CO_2 capture unit at Klemestrud. Final destination of the CO_2 is an offshore storage planned in Smeaheia (saline formation at 1.2-.7 km depth or Johansen formation at 3.3 km depth), both near Troll field, about 600 km from shore. Even though it is not applied downstream to a WtE, a Norwegian cement plant is designing to capture the CO_2 and send it to a storage site. The Norcen Brevik plant in fact produces approx. 1.2 Mtons of cement and 0.925 Mtons of CO_2 per year. Two different capture technologies are under technical-economic evaluation: 30%wt MEA absorption and two-stage membrane filtration.

The major risk of this project is the lack of additional incentives as public funding to deal with the investment cost [69]

In Germany, it is worth noting that the coal-fired plant in Essen, North Rhine-Westphalia, is involved in the [70] is involved in the Align CCU/CCS [71] Project, where a CCU/CCS is foreseen for the above-mentioned plant that is identified as part of the industrial cluster across five EU countries.

In 2012, some studies were done to estimate the amount of CO_2 storage in a year in the referenced national contexts. In Table 19, the amount of CO_2 , the main CO_2 source and the type of storage location are indicated.

Table 19- Operating CCS plants [37]

	CO_2-source	Type of storage location	Amount of CO_2, kT/y
Norway	Natural gas	Saline aquifer	1000
Netherlands	Natural gas	Natural gas field	100
Australia	Natural gas	Depleted gas field	50
Norway	Natural gas	Saline aquifer	0.75
USA	Industry	EOR	50000
Australia	Natural gas	Saline aquifer	129000
Germany	External delivery	Saline aquifer	60
Japan	Industrial production	Saline aquifer	10
UK	Industrial production	Saline aquifer	200

In Table 19, Italy is not shown because no data on CO_2 storage are available, and the only approach to CCS technology was a the project in Porto Tolle, where the post-combustion capture process aimed to capture about 1 million tons of CO_2 and store it in an offshore saline aquifer. In 2013 the project was interrupted for lack of authorizations and support to complete the project.

The Global CCS Institute controls the state of development of CCS and EOR projects and in the following a list of main facilities in national contests is presented, even though the major of them is not integrated with a WtE plant but reflects the local awareness towards the CCS process.

-**Norway** has a demonstration CCS unit for the WtE plant in Klemetsrud [68], run by Waste-to-Energy Agency of Oslo (EGE) that has a total capacity of 160,000 ton/year and produce electricity (10,5 MWe) and thermal energy (55,4 MWt). Final destination of the CO_2 is an offshore storage planned in *Smeaheia* (saline formation at 1.2-.7 km depth or Johansen formation at 3.3 km depth), both near Troll field, about 600 km from shore. In advanced development is the project of a post-combustion CO_2 capture e partially reutilisation in cement production in the southern Norway. The remaining CO_2 is sent to a geological storage in the Smeaheia area by pipeline and shipping transportations [68]. The CO_2 is obtained from a Waste to Energy and the full chain will be operational in 2023/2024.

-In **Germany,** it is worth noting that the WtE plant in Essen, North Rhine-Westphalia is involved in the Align CCUS[9] Project, where a CCU/CCS is foreseen for the above-mentioned plant that is identified as part of the industrial cluster across five EU countries. The waste generated by the cities of Essen and Gelsenkirchen alone takes up over 50% of the available incineration capacity at the plant. The energy generated during the thermal processing of the waste (Net electrical output equal to 38 MW) is used for district heating and electricity generation. The project will develop a unique CO_2 storage in the North Sea basin and their near and mid-term infrastructure facilities by 2025 [72].

-In **The Netherlands**, the PORTHOS project is under development. PORTOS stands for **P**ort **O**f **R**otterdam CO_2 **T**ransport **H**ub and **O**ffshore **S**torage and is a joined initiative of Port of Rotterdam, Gasunie and EBN. The aim is to Capture, Use and Store the CO_2. The CO_2 will be captured from refineries and chemical plants, a portion of CO_2 will be sent to greenhouse farming for plants' growth and the remaining portion will be compressed and stored in a depleted gas field in the North Sea at a depth of approx. 3 km [73]. Aiming at a final investment decision (FID) 2021, PORTHOS will focus on three main issues in 2020: a) Technical development of the transport and storage infrastructure; b) Environmental Impact Assessment and permits; c) Agreements with companies to supply CO_2 and with the government to enable CCU/CCS.

-In **UK**, the Caledonia Clean Energy Project (CCEP) captures the CO_2 produced by natural gas fired power plant. The CO_2 is sent by pipeline to a storage site in the Captain sandstone formation. The 95% of required pipeline is existing [74].

-In USA the PETRA NOVA plant is the first large US power plant with CCS. The plant captures 5000 tons per day of CO_2 with a post combustion technology applied to a coal.fired electricity

[9] AlignCCUS, About the Project, accessed on 18 June 2019, URL: https://www.alignccus.eu/

generation plant. The CO_2 is transported via pipeline to the Rest Ranch oil field where it is injected for EOR. [75]

- In Canada, the Boundary Dam plant captures the CO_2 produced for electricity production. The gas is transported via pipeline and stored more than 3km under the ground in a saline aquifer. [75]

-In **Australia**, the Gorgon Project is a large-scale CCS project that aims to capture the CO_2 from natural gas, compress and transport it via pipeline to one of three drill centers where the CO_2 is injected into the Dupuy formation (Barrow Islands). The injection site is continually monitored to observe wells and seismic activity of the area [76].

Based on the outcome of a very recent study carried out by Wood for IEA GHG ("Update techno-economic benchmarks for fossil fuel-fired power plants with CO_2 capture), considering also very high capture rate options (up to 98.5-99%), the process of carbon capture from power applications accounts a global cost of 50-60 €/tCO_2 for large coal plants and 70-75 €/tCO_2 for large gas-fired palnts, due to capture and compression processes), transportation and storage. The impact of CCS on electricity cost is 40-50 €/MWh for a coal-fired power plant and 20-25€/MWh for a gas-fired power plant.

To offset the costs associated with the CO_2 storage, the interest towards the Carbon Capture Utilization (CCU) is growing and the potential uses of CO_2 are showed in Figure 30.

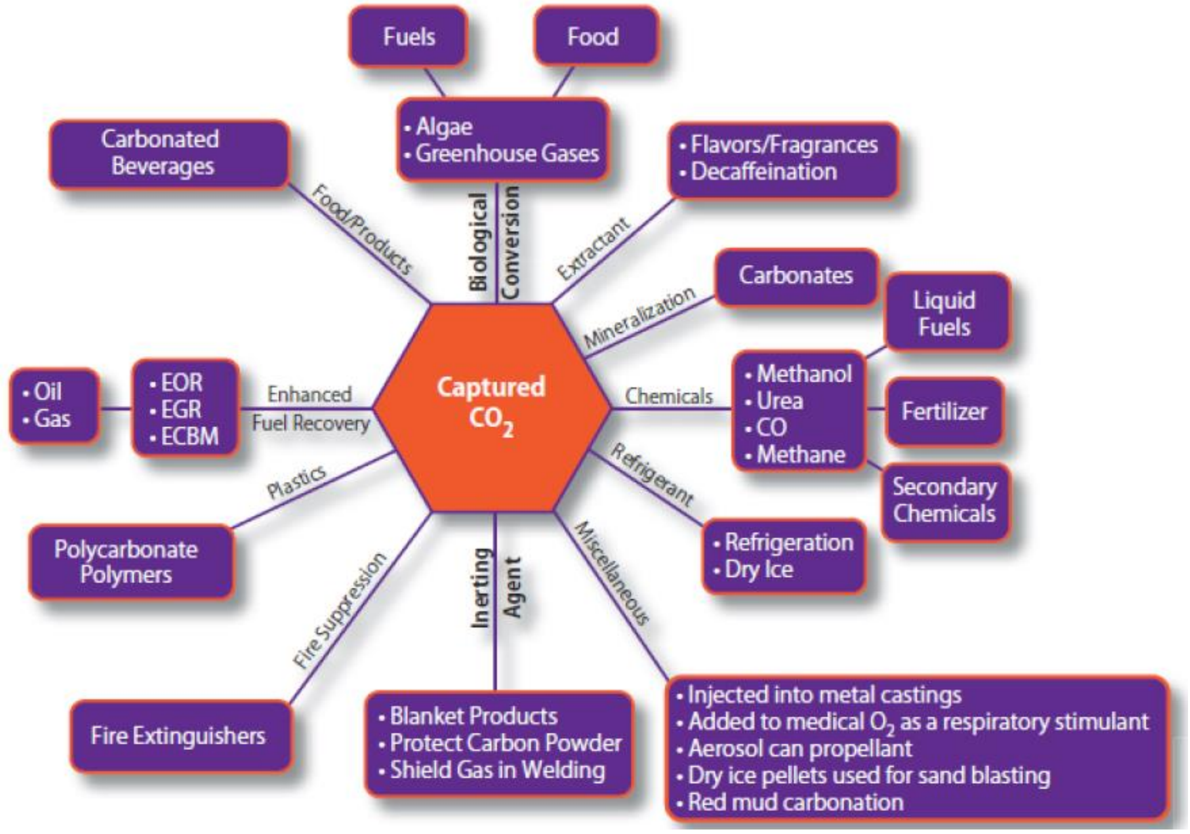


Figure 30- Classification and potential uses of Capture CO_2 [78].

The basic idea is to not treat the CO_2 as waste but as a chemical resource. Among all the applications, just few have overcome the research phase and are ready for the industrial market: the EOR, the chemicals production as urea or methanol, the sodium carbonate production, the use of CO_2 for algae and the biofuel. These processes are associated to different TRLs (Technology Readiness Levels), which ranges from 0 to 9 and indicating the development status of an innovative process and how much it is ready for large-industrial application. The methanol production is at a demonstration level corresponding to TRL 6, while chemicals production as urea synthesis or polymerisation have already entered in the market with a TRL of 8-9. The EOR and algae cultivation have a TRL of 9where values of TRLs higher than 5 indicate that the technology has achieved the prototype/pilot scale [79].

In this analysis, it has to be considered that the CCU technologies are not stand-alone but integrated with a generation process. So, an IRL (Integration Readiness Level) should be considered as well.

The use of CO_2 as Enhanced Oil Recovery (EOR) is borderline between storage and utilization. In the enhanced oil recovery, the CO2 is used to extract the oil or natural gas from rocks that otherwise would have been unrecoverable reservoirs, and with the CO2 storage, it is the main application now developed at large-scale. For example, in Louisiana, the Lake Charles Methanol proposed to capture over 4Mtpa of CO_2 from syngas used to produce methanol. The capture CO_2 is used in Denbury Resources for Enhanced Oil Recovery in Texas. The operation data of this plant is planned to be 2022 [68].

Figure 31 shows the distribution of operational installation of large CCU plants other than Storage and EOR (i.e. chemical and fertilizer production, food and beverage industry) in the selected counties, according to Global CCS Institute database.

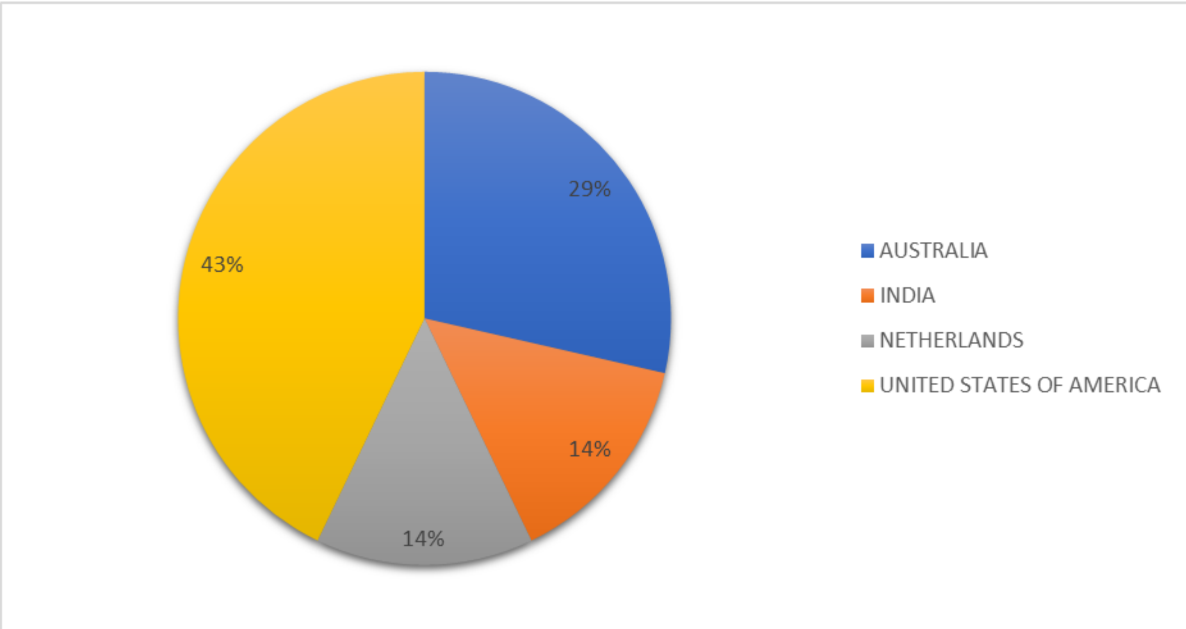


Figure 31- National contest CO_2 uses [68]

For food industry, the USA has operating plants for re-use of capture CO_2 in beverage productions, while in Finland the CO_2 captured from a refinery is sold to food industry after a purification process to reach the necessary CO_2 purity-grade [43].

About the re-use of CO_2 for fertilizers, Australia has one operating plant for fertilizer re-use and another in development, Netherlands and Japan are pointing at reuse of CO_2 for algae production at Twence and Saga city WtE-CCU plants, which are among the most advanced examples in the world [80] [81].

India has an operating plant for chemicals production. MHI signed an agreement with Indian National Fertilizers Limited (NFL) company to develop a CO_2 capture unit from natural gas, where it is used the licensed solvent KS-1. The CO_2 is recovered at 99% purity to be provided as feedstock for urea synthesis from ammonia [82] [83].

In South-Africa, the Swayana engineering firm is collaborating with LanzaTech carbon recycling company to develop a carbon capture and utilization plant in the country. The carbon monoxide (CO) gas, coming from the smelter in a ferroalloy production plant is converted in fuel ethanol in a gas-fermentation technology owned by LanzaTech. A pilot unit has been already tested for the pre-feasibility study successfully [68] [84].

Another example of CO_2 utilisation is represented by the greenhouses. In Duiven WtE (The Netherlands), a project of CO_2 capture integration is ongoing. It captures 50,000 tonnes CO_2 per annum and it has started the operation in 2020. The system uses an improved amine-based post-combustion process that can capture around 90% of the CO_2. The captured and liquefied CO_2 will then be supplied by road tankers to users such as nearby greenhouses, where it will increase the yields of plants and vegetables [80] [81]. Similarly, it is done in Japan, as described in section 2.1. In this plant, the amine used is a secondary sterically hindered solvent, and the CO_2 is transported only few hundred meters far from the WtE-CC plant, reducing significantly the costs of transportation

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CHECKED BY	:	FEDERICO VIGANÒ, VINCENZO TOTA
APPROVED BY	:	FEDERICO VIGANÒ, VINCENZO TOTA

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TABLE OF CONTENT

1. Identify the challenges in WtE plants

Modern WtE plants are mostly based on the same technologies of fossil fuel-fired power stations. However, since they are targeted to serve certain collection areas, their size, in terms of thermal input, is determined by the amount of treated waste and the corresponding energy content. The resulting thermal inputs span from tens to few hundred megawatts, which compare to the sizes of fossil fuel-fired power stations of few gigawatts (i.e. WtE are one-two order of magnitude smaller than power stations). Therefore, WtE plants are too small to generate large economies of scale, the specific costs of the adopted technologies are rather high, leading to very capital-intensive facilities. To ensure their economic sustainability, WtE plants need relevant annual revenues, which come from both the fee for the treatment of waste and the sale of electrical/thermal energy.

In the light of these considerations, the continuity of operation and, therefore, reliability, are of crucial relevance for WtE plants. Any interruption of the service means loss of revenues that can jeopardise the economic balance. Moreover, failures imply maintenance interventions, which are very expensive on these facilities. This is in part due to peculiarities of the adopted technological options (like the refractory lining of the combustion chamber and part of the boiler), and in part due to the high costs of the spare parts that are linked to the aforementioned high costs of the technologies because of the relatively small sizes of these plants.

Reliability is relevant also for the possible integration of WtE plants with CCS systems. For example, unplanned stops with complete interruption (or even significant reduction) of flue gas flow can compromise the working regime of absorption columns and require repeating start-up sequences.

1.1 Potential failures occurring in WtE plants

Although the significantly smaller size, the complexity of a modern WtE facility is greater than that of power plants. To ensure the proper working of a WtE plant, many systems must interact: feeding system, combustion system, steam generator, steam cycle, Air Pollution Control (APC) system, solid residues handling, etc.

Reliability is a crucial aspect for all the WtE plants treating unsorted waste, since they normally receive waste from the urban collection. For a short period (a few days) of unavailability of the plant, the storage capacity of the bunker is usually enough to allow the normal waste management. However, a prolonged full stop of the plant requires the activation of other waste treatment options, like waste export to other WtE plants, landfills, etc., which are very expensive and add to the costs of interrupting operation.

Therefore, WtE plants treating unsorted waste are usually designed according to multiple-line layouts, so that the unavailability of one line can only reduce the treatment capacity of the plant. In general, crucial components of the plant/line are normally redundant. The only section of the plant that, for the sake of energy efficiency, is often kept common to all the treatment lines is the power cycle. However, in the case of a unique steam turbine, it usually features a by-pass system to allow the operation of the plant even when the turbine is unavailable.

As already highlighted, reliability influences significantly the economics of a WtE plants, not only because maintenance interventions are typically very expensive on this type of facilities, but also because it determines the availability of the plant and, hence, both the annual waste throughput and energy production, with their associated revenues.

To increase plant availability, a maintenance program is adopted and continuously improved throughout the whole life of the plant. During scheduled stops, both ordinary and preventive maintenance are carried out, as well as upgrading interventions can be put in place. Ordinary maintenance is devoted to the replacement of worn out parts, whereas preventive maintenance is aimed at improving the continuity of operation by reducing accidental stops through periodic inspections of the most critical components (pumps, valves, dampers, combustion grates, pressure parts, bridge cranes and buckets, transformers and electrical substations). Upgrading interventions can be carried out both to improve the performances of the plant and to comply with updates of the applicable normative. For example, in the EU, the issue of updated conclusions on the Best Available Techniques (BAT) requires the reconsideration of the permit to operate the plant, with the introduction of more stringent emission limits, higher energy efficiency targets, etc.

In the following paragraphs, some sections of WtE plants are analysed and their potential failures are discussed.

1.1.1 Waste feeding system

The waste stored in the bunker is fed to the combustor(s) of grate-based WtE plants through loading hoppers, by means of bridge cranes. In fluidized bed-based WtE plants, the RDF/SRF is typically transported through conveyor belts and fed by means of screw-type plug feeders. Both bridge cranes and conveyor belts are normally redundant. Loading hoppers and plug feeders are, instead, critical components. The blocking of loading hoppers in grate-based plants occurs often, but it is an event that can be managed in a limited time, without significantly affecting the operation of the combustion line. The blocking of a plug feeder in a fluidized bed combustor can lead to the shutdown of the line. Therefore, high attention must be devoted in the preparation of RDF/SRF, to avoid the presence of large and/or heavy/hard components incompatible with the use of screw-type plug feeders.

1.1.2 Combustor

The combustor is the core of a WtE facility. Any significant failure of this component typically requires the shutdown of the treatment line. Sometimes, minor failures can be tolerated also for long operational periods (e.g. a few bars of a grate or a few air nozzles of a fluidized bed not working properly).

1.1.2.1. Grate type

The waste entering the combustor must be kept moving and mixed in order to achieve the complete combustion and avoiding high level of CO in flue gas and unburned carbon in bottom ash. Modern grates can be horizontal or sloping, featuring alternate moving and fixed elements that support and transport the waste bed from the inlet section to the ash discharge section. Moving grates are affected by two critical problems: thermal stress and mechanical erosion.

High thermal radiation in the combustion chamber can lead to destructive temperatures for the elements of the grate. Therefore, they must be constantly protected against direct radiation by means of a layer of ash. Moreover, the grate elements (and the internal layer of the waste/ash bed) are cooled down by the primary combustion air, which is supplied underneath the grate and reaches the waste bed by passing through the grate elements. It achieves the double result of sustaining the waste combustion and controlling the temperature of the grate elements. Some manufacturers adopt also water-cooled grate elements.

Mechanical erosion is due to the attrition among moving and fixed grate elements, as well as with hard particles (glass, inert materials, hard metals) contained in the waste. Low-melting metals (aluminum alloys, lead, etc.) in the waste can be harmful too, even if, thanks to the grate cooling by the primary combustion air, they only rarely can melt onto grate elements.

The maintenance plans adopted for grates normally envisage the periodic partial replacement of grate elements, as well as the rotation of medium worn out elements toward less stressed areas of the grate.

The hydraulic system used to move the moving elements of the grate is another critical part of the combustor. For water-cooled grates, the flexible pipes connecting the moving elements to the cooling circuit is another source of frequent failures. However, these two systems are placed on the external side of the combustor, therefore they can often be repaired during short stop or, sometimes, even without the full stop of the line.

1.1.2.2. Fluidized bed type

In fluidized bed combustors the required moving and mixing of the waste is achieved by means of the bed fluidization, which is caused by the high-velocity injection of the primary combustion air through proper-shaped nozzles. The bed is composed of mainly sand, and only in a minor extend waste.

The most critical aspect in the operation of this type of combustor is the risk of agglomeration of the bed, due to the formation of eutectic mixture because of the unpredictable composition of the waste ash. Before reaching the full melting of the ash mixture, the appearance of a sticky behavior is typically enough to produce the sintering of some agglomerates. They compromise the fluidification of the bed, implying the forced stop of the line. The consequent required maintenance intervention is rather demanding, since it implies cooling down completely the bed, emptying the combustor, screening the bed material, refurbishing the bed and reactivating the combustor.

To limit as much as possible the occurrence of this event, the content of ash in the treated RDF/SRF must be limited, the composition and particle size distribution of the sand bed must be chosen properly, some calcium-based reactants like dolomite can be added to the bed, with also other beneficial effects on the fouling of the combustion chamber.

Other critical elements of this technology can be the primary air nozzles. In some types of this combustor, they can be blocked typically by small metallic particles contained in the waste. To prevent this failure, a good de-metallization of the RDF/SRF is crucial.

1.1.3 Steam generator (i.e. boiler)

For the availability of WtE plants, the pressure parts of the steam generator(s) are the most critical elements. Failures of these parts is rather common and can lead to long unplanned stops and highly expensive maintenance interventions. Similarly, the refractory lining largely used inside waste-fired boilers is another critical element.

Conceptually, any waste-fired steam generator can be divided into two sections: the radiant section and the convective section. The former is the first part of the boiler, where, because of the high temperature of flue gas (above 1,000 K), heat exchange is mainly through thermal radiation. In this section, heat exchange surfaces are only waterwalls (i.e. steam evaporators), typically arranged to form the enclosure of the boiler and, sometimes, hanged inside flue gas passes. The convective section of the boiler is downstream the radiant section and features a different arrangement of heat exchange surfaces, which are typically tube bundles exchanging heat mainly through convection.

In grate-based WtE plants, the volume immediately above the grate is called “combustion chamber”. Similarly, in bubbling fluidized bed-based plants, the volume of the bed and the volume immediately above it (called “freeboard”) are designed as combustion chamber. In circulating fluidized bed, the identification of the combustion chamber is conventional.

In modern WtE plants, the combustor chamber is integrated with the steam generator / boiler, being the initial part of the radiant section of the boiler. Therefore, the walls around the grate or that confine the fluidized bed are waterwalls, typically refractory-lined. In older plants, the combustor was adiabatic and often called “furnace” instead of “combustor”. However, its adiabatic walls were also refractory-lined.

Therefore, in integrated steam generators, the combustion chamber is inside the boiler, whereas in adiabatic combustors, the radiant section of the boiler starts immediately downstream of the adiabatic section.

The volume downstream of the last injection of combustion air is named “post-combustion zone”. Its aim is to ensure an adequate residence time to flue gas, above a certain temperature (e.g. in the EU, 2 s above 850 °C, in the USA, 1 s above 950 °C), according to the applicable normative. To meet this requirement, both combustion chamber and post-combustion zone are completely refractory lined even in integrated boilers, so that the heat extraction from flue gas is limited and its cooling is slow enough.

1.1.3.1. Combustion chamber and post-combustion zone

The main problems experienced by these sections of the combustor/boiler are related to the refractory lining. It can be made just in concrete cast or, more often, with tiles. In both cases, very hard materials, like silicon carbide, are normally used.

The part of the lining in direct contact with a fluidized bed is subject to erosive wearing. However, a proper fluid-dynamic design can prevent the erosive wearing of all the other parts of the lining in both grate- and fluidized bed-based boilers.

Most of the refractory lining failures are due to the slagging behavior of fly ash. Melting of fly ash occurs in hot flue gas and the solidification takes place on colder walls, creating deposits. Chemical diffusion changes in time the composition of the deposits that can melt and solidify again many times, thus reacting with the refractory lining material. Heavy deposits and/or differential thermal expansions can generate significant mechanical stress, up to the breaking of the refractory material.

Excessive deposits formation can lead to a forced stop of the line, typically because of the disturbance induced to the combustion process, signaled by high CO emissions. Large deposits detaching the walls and falling into a fluidized bed have the same effect of bed agglomeration, with the need of stopping the operation.

Waterwalls underneath the lining are normally made of bare steel, so that the refractory acts also as protection against the highly corrosive flue gas. Small damages of the lining are enough to cause the penetration of flue gas up to the steel surface, where the corrosion takes place with the generation of significant volumes of metal oxides and other salts. Such volumes exert pressure onto the refractory leading to the worsening of the original damage.

The corrosion mechanism of all iron-containing alloys is typically named “acidic corrosion” and has not yet been fully explained. It is based on the high temperature reaction of iron with halogens, mainly chlorine, with the synergic effects of many chemical species that are present in fly ash (e.g. K, Na). The rate of corrosion at the typical HCl concentrations found in waste-fired boilers (hundreds of ppm) is very fast and it increases exponentially with metal temperature. On a bare steel waterwall, acidic corrosion can thin metal thickness at a rate of millimeters per month, leading to tubes breakage in a few months.

The reparation of refractory lining is a manual operation, which requires many workers, long times, scaffoldings, etc.

1.1.3.2. Radiant and convective sections

The portion of the radiant section without refractory lining and the convective section of the boiler experience some similar problems, first of which is the acidic corrosion of the hottest parts, exposed to the direct action of acid gases (especially HCl) and fly ash deposits. To protect these parts, iron-free protective coverings are applied. The most common type of protection is the cladding with Inconel® 625 alloy. There exist other thermal spraying techniques less widespread and some ceramic protections start being proposed on the market.

The most critical components are -again- waterwalls, after the end of the refractory lining, and steam superheaters. Cladding, thermal spraying and similar techniques can usually be applied manually or semi-automatically on-site at very high costs. The main components of the boiler, like waterwall panels and superheater bundles, can be protected at the manufacturer shop with fully automated and less expensive processes. However, manual application is always needed on-site to cover welds and special components.

The cost of these protections is always relevant (of the order of a few thousand €/$ per square meters), therefore they are economically sustainable only if they last many years. Inconel® 625 cladding on steam superheaters can warrant an economic life[1] with maximum steam temperature of about 440 °C and proper design of the boiler (hottest superheater placed in co-flow arrangement, with flue gas normally below 650 °C). Therefore, steam parameters of WtE plants can be considered "conservative" with respect to those adopted in common steam cycles. Moreover, steam reheating is almost never adopted, to avoid doubling the critical components of the boiler.

Besides breakage of pressure parts, another typical failure of the convective section of the boiler is excessive fouling. This boiler section is normally designed to manage very different fouling conditions, from clean to very fouled conditions going from the beginning to the end of the operational campaign (which, depending on the design of the boiler, can last six months, one or two years).

When fouling is too high, a number of situations can happen: too high pressure drops through the boiler; too high flue gas temperature at boiler exit; too unbalanced flow of flue gas in certain boiler sections. To control fouling, different cleaning system can be used. Convective sections are usually equipped with hammers and/or soot blowers. Radiant sections can use also water cannons. If these systems are not effective enough, controlled micro-explosions can also be used.

[1] The "Economic life" is the lifetime of a component that represents the optimum trade-off between the replacement cost and the loss of production due to reduced performances (e.g. lower performances achieved with conservative steam parameters - i.e. pressure and temperature - cause a loss of production but increase the lifetime of pressure parts, reducing their replacement costs).

1.1.4 Air Pollution Control (APC) system

The Air Pollution Control (APC) system, often called also "flue gas treatment" or "flue gas cleaning system", is a complex sequence of devices: filters, chemical reactors, dry / semi-dry / wet scrubbers, etc. Each device or group of devices is typically targeted to the abatement of a specific pollutant or family of pollutants. APC is needed to warrant the environmental compatibility of plant operation. Moreover, normative provisions typically allow the operation of WtE plants only with proper-functioning APC systems. This condition is continuously monitored by checking the emissions of key pollutants.

When failures jeopardize the effectiveness of the APC system, the plant manager is commonly obliged, by the permit to operate the plant, to stop the feeding of waste and, if the failure cannot be recovered quickly, going to the full stop of the treatment line.

Many devices of APC are redundant, to warrant continuity of operation and, sometimes, also regeneration of the device effectiveness. This is the case of bag filters, which normally feature multiple parallel cells that can be cleaned separately.

In the presence of an SCR system, a very critical failure is the reversible / irreversible poisoning of the catalyst, which can be caused by failure of other devices, error in the management of the system, or burning of unexpected materials. Reversible poisoning can be recovered by means of thermal regeneration, but only few plants can carry out that operation "online". Most plants require the temporary replacement of the catalyst and the regeneration carried out at the shop of the catalyst manufacturer. Irreversible poisoning implies the definitive replacement of the catalyst material, associated to very high costs.

1.1.5 Steam turbine, electric generator, fans, pumps

Steam turbine, electric generator, fans, pumps, etc., are all pieces of equipment that are found in all thermoelectric power plants. In the case of WtE plants, more redundancy is adopted, because of both the great continuity of operation required by this type of plants and the safety of operation. Concerning the latter point, special consideration must be applied to grate-based plants. In this type of combustor, a significant amount of waste is present in the combustion chamber so that, in the case of unexpected stop, the process must be managed properly to avoid undesired emissions and the risk of explosion.

A very critical components of WtE plants is the ID fan. Only a few plants have redundancy of such a component. Failures of the ID fan cause at least a temporary stop of the line and can create the aforementioned risky situation.

1.1.6 Control and monitoring systems

Every modern WtE plant adopts a DCS (Distributed Control System) that is the brain of the plant. It allows the operators have full control of each part of the plant and, often, includes algorithms for the automated optimal management of the plant.

The effectiveness of the control system is undermined by:

- non-stationary combustion caused by the variability of the chemical properties of the waste and the intermittence with which the feeding system introduces the fuel in the combustion chamber.
- the delay with which the control system and the operators can counteract changes in process conditions (the progress of the production of steam is followed by a much slower dynamics of the combustion process, due to the thermal inertia of the combustor/boiler system).

Typically, DCS is also redundant and normal operation and emergency operation are managed by separate systems. Consequently, unplanned maintenance stops due to DCS failures are very rare.

Synergic to DCS is the CEMS (Continuous Emissions Monitoring System), which collects and elaborates all the emission data from the plant stack. Like the DCS, it is also redundant, since most legislations on WtE operation set the requirement of stopping the plant in the case emissions are above the limits or cannot be measured.

1.2 WtE through waste gasification, pyrolysis, plasma, and others

All these technologies have a rather limited diffusion if compared to the conventional mass-burn combustion in grate-based plants, or the energy recovery of RDF/SRF in fluidized bed-based facilities.

Waste gasification is used mainly in Japan and nearby countries. The main driver for the adoption of such a type of technology relies on some normative requirements regarding the leaching behaviour of bottom ash. The adopted gasification systems typically produce vitrified slag featuring very limited release of pollutants during leaching tests. In Europe and USA there has been only a few waste gasification plants that have never reached industrial maturity.

Pyrolysis and other technologies (e.g. plasma) have never been successfully applied at industrial scale.

A general discussion on the features of waste gasification compared to conventional combustion can be found in Consonni and Viganò [1].

They firstly introduce the distinction between “full gasification” and “two-step oxidation”. The main difference between these processes is that in “full gasification” the produced syngas is exploited as good quality fuel into highly efficient internal combustion engines (e.g. gas turbines, reciprocating engines), as well as a valuable base for the synthesis of chemicals or other synthetic fuels (e.g. hydrogen, liquid fuels). “Two-step oxidation”, in the other hand, simply uses the syngas as fuel for an externally fired power cycle, or to produce just heat, with similar results and analogous technologies to the conventional combustion of waste. Even advanced waste combustion technologies, where primary combustion is under stoichiometric, can be regarded as “two-step oxidation”.

The conceptual distinction between “two-step oxidation” and “full gasification” is exemplified in Figure 1.

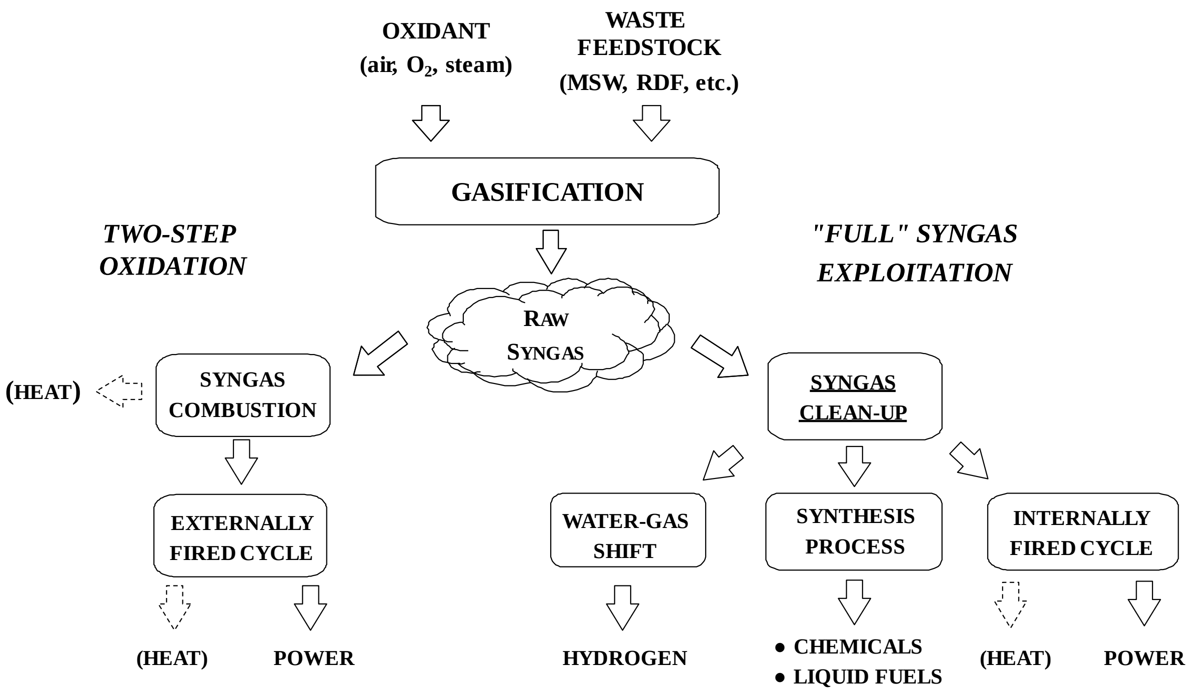

Figure 1: Conceptual distinction between "two-step oxidation" and "full gasification".

The main requirement for a "full gasification" process is to have an effective syngas cleaning, which is still today the main challenge of waste gasification.

Table 1, inspired to the work of Consonni and Viganò [1], reports the main potential advantages of waste gasification with respect to conventional combustion. Each potential advantage is associated to a number of drawbacks that seriously hinder the diffusion of this type of technologies.

Table 1: Potential advantages and drawbacks of waste gasification (inspired to [1]).

#	Potential advantage	Corresponding drawbacks
1	Syngas is easier to meter, and its flowrate is simpler to control than solid waste. Moreover, it is more homogeneous and can produce a more stable and cleaner combustion than solid waste.	It is toxic, flammable, explosive and its handling raises major safety concerns. Moreover, its production and use require, at least, two high temperature devices, which make the plant less reliable, more costly, more complex to control, operate and maintain.

#	Potential advantage	Corresponding drawbacks
2	The reducing environment in the gasifier can improve the quality of solid residues, as well as prevent the formation of oxidised pollutants (e.g. dioxins, furans).	Actual emissions of pollutants depend on how the syngas is cleaned and used. Some low temperature processes may not warrant the thermal destruction of harmful pollutants contained in the waste.
3	After proper cleaning, syngas can be used as fuel for highly efficient internally fired power cycles, as well as for the production of chemicals and other synthetic fuels.	Syngas cleaning is still the unsolved real problem of waste gasification plants. It is very costly, causes energy losses that can cancel the energy efficiency advantages of more efficient downstream processes. Moreover, at the typical scale of waste treatment plants, the efficiency of internally fired cycles (e.g. combined cycle) is appreciably lower than at full scale.
4	After proper cleaning, syngas can also be used as base to produce chemicals and other synthetic fuels.	Syngas cleaning poses the same problems as and even more than those highlighted at the previous point. In fact, chemical processes require cleaner feedstock than internally fired engines. Moreover, they are economically feasible only at much larger scale than those corresponding to waste gasification plants.
5	Pressurised gasification increases the opportunities of achieving high efficiency and reduced costs.	Pressurisation of solid waste poses formidable challenges and no successful industrial-scale application have been made yet.

"Two-step oxidation" processes give up possible advantages no. 3-5, which, theoretically, can be caught only by "full gasification" processes. However, the "full gasification" of waste normally requires oxygen as gasifying agent, because of the limited energy content of waste (air gasification would produce a syngas with only little energy content). The cost of oxygen at the typical scale of WtE plants is very high.

Consonni and Viganò (2012) compared on coherent bases two commercially available "two step oxidations" technologies and a state-of-the-art combustion-based WtE plant [1]. They concluded that such a type of "new" technologies can tend to reach the same performances of conventional WtE being, however, always inferior from the point of view of energy efficiency.

They can feature some characteristics that make them particularly appealing in specific circumstances, like the case of the Japanese requirements on the properties of bottom ash.

Arena et al. (2018) carried out an LCA (Life Cycle Assessment)-based comparison of commercially available waste gasification technologies and a state-of-the-art combustion-based WtE plant. They also concluded that these “new” technologies are inferior to conventional processes also from the point of view of the environmental outcomes [2].

When looking to the potential integration of these “new” technologies with CCS, they, theoretically, open the possibility of applying pre-combustion capture technologies, since intermediate, carbon-containing energy vectors are generated (i.e. syngas, pyro-oils, …). However, as such intermediates are produced, they feature high loads of harmful / pollutant species that typically make cleaning an unavoidable step before capture technologies can be applied.

One of the main problems of all thermochemical processes applied to waste is the content of chlorine, which ends up producing relevant concentration of HCl in flue gas in the case of combustion, in syngas in the case of gasification and pyrolysis. In the case of pyrolysis, chlorine-based compounds are normally found also in the pyro-oils.

In conventional, combustion-based WtE plants, the chlorine content of waste ends up typically 85% into flue gas and fly ash, whereas the remaining 15% into bottom ash. These shares can change depending on the content of alkali and sulphur in the waste (as well as on the combustion conditions like the thickness of the waste bed, temperature and space velocity of combustion air, etc.). This can produce concentration of HCl of hundreds and even thousands of milligrams per normal-cubic meter of flue gas. Such high concentrations of HCl are the main cause of the so problematic acidic corrosion of boilers and all the interested equipment.

Waste gasification and pyrolysis generate flowrates of gaseous products one order of magnitude less than flue gas in combustion. Since the releases of chlorine in the gas phase are similar, the expected concentrations of HCl in gaseous products are one order of magnitude higher than those found in flue gas from waste combustion. The problem of acidic corrosion can become unmanageable. Incinerators for hazardous wastes featuring high concentrations of halogens (more than 1% by mass) often burn a mix of different types of waste to keep the concentration of HCl in flue gas within manageable limits, i.e. to limit the problem of acidic corrosion.

A pre-combustion CCS process applied to a waste gasifier or pyrolizer either should withstand such high concentrations of very harmful species (not only HCl, but also NH_3, H_2S, etc.), or would require very challenging syngas cleaning processes to reach compatibility.

Moreover, the concomitant high contents of halogens and metals in waste generate metallic halogenides, which are very volatile compounds. They are typically removed from flue gas by means of de-dusting processes carried out below 230 °C, i.e. below the minimum condensing temperature of these compounds. In fact, when flue gas is cooled below such a temperature, all these compounds are found in solid or liquid form onto fly ash. The low-temperature abatement of fly ash removes also these compounds.

Since metals (most of which are alkali metals) typically poison most catalysts and many solvents, as well as they are corrosive agents for internally fired engines, the cleaning of any gaseous product from the thermochemical conversion of waste must be carried out at low temperature. All the equipment to cool down such gaseous products must withstand the aggressive environment previously discussed.

In the light of the aforementioned considerations, even if waste gasification, pyrolysis and all the other thermochemical conversion processes entailing the production of syngas open the theoretical possibility of applying pre-combustion CCS processes, and many companies are working all around the world to develop "full gasification" of waste, no full-scale industrial plant has ever entered into operation yet.

The application of post-combustion CCS technologies to the different thermochemical waste conversion processes is analogous to what can be envisaged for conventional WtE plants and, therefore, not worthy of further discussion.

In fact, flue gas from the direct (or indirect, through gasification, pyrolysis) combustion of waste, after normal cleaning, features a certain content of oxygen and nitrogen oxides. Both these species have an impact on, e.g., amine degradation. However, the concentration of nitrogen oxide (and CO_2) is typically lower and the oxygen content higher than in coal-fired power plants, whereas the same characteristics of flue gas are respectively higher and lower than in natural gas-fired power plants. Therefore, flue gas from waste combustion (either direct or indirect) are somewhere in between flue gas from coal and natural gas combustion.

In the case of post-combustion capture, the same problems of amine degradation found in fossil-fuel fired power station can be found - in different extent - also in waste-based processes.

1.3 Results survey on availability in WtE plants

In order to enhance the quality of the review over the challenges of WtE plants operation, specific feedbacks given by plant owners and managers have been elaborated, based on a survey presented by the PREWIN Network[2] in July 2019 [3].

Collected data regard only European plants. However, they cover both the most widespread WtE technologies: grate-based and fluidized bed-based plants. Therefore, most of them can be considered representative of the WtE technologies in general, with the only exception of those data linked to the local characteristics of the treated waste (e.g. LHV). Waste gasification technologies, which have a certain diffusion especially in Japan and Far-East countries, have not been covered by this survey.

A specific questionnaire was prepared with 16 questions including:

- general data over the plant (location, size, age, capacity, steam parameters, average thermal load);
- type of waste input and its characteristics (macro-scale composition in terms of Municipal Solid Waste vs. Industrial Waste and LHV);
- availability (hours of unplanned outage and planned outage);
- Time between 2 planned stops (months) and Length of planned stops (days).

In this section the major results conducted by PREWIN survey are reported.

The survey has been conducted in 2019, collecting data from 257 lines of the most relevant European WtE plants, obtaining hence a comprehensive and representative picture of the current European WtE scenario.

In particular, 242 datapoints have been collected for WtE plants equipped with grate furnace systems and 15 datapoints for fluidized bed lines burning RDF (Residual Derived Fuel) and/or biomass/sludge.

First of all, availability is defined as:

[2] *PREWIN (Performance, Reliability and Emissions Reduction in Waste Incinerators) is a European Network with the mission of supporting progress towards improved performance and reliability of European Waste-to-Energy plants (incineration and co-incineration) while maintaining low or reduced emissions to the environment. LEAP has been part of the network since 2016 as R&D unit, participating to the general meetings held twice a year on specific topics.*

$$Availability\ (\%) = \frac{8760 - UO - PO}{8760}$$

Where:

UO= Unplanned outage (hours/year)

PO= Planned outage (hours/year)

1.3.1 General histograms on average European WtE plants features

All the figures reported in the following are accompanied by 3 key values on top of each graph:

1. **N= number of datapoints examined;**
2. **AV = Average value of the analysed variable/properties;**
3. **MD =Median value of the analysed variable/properties.**

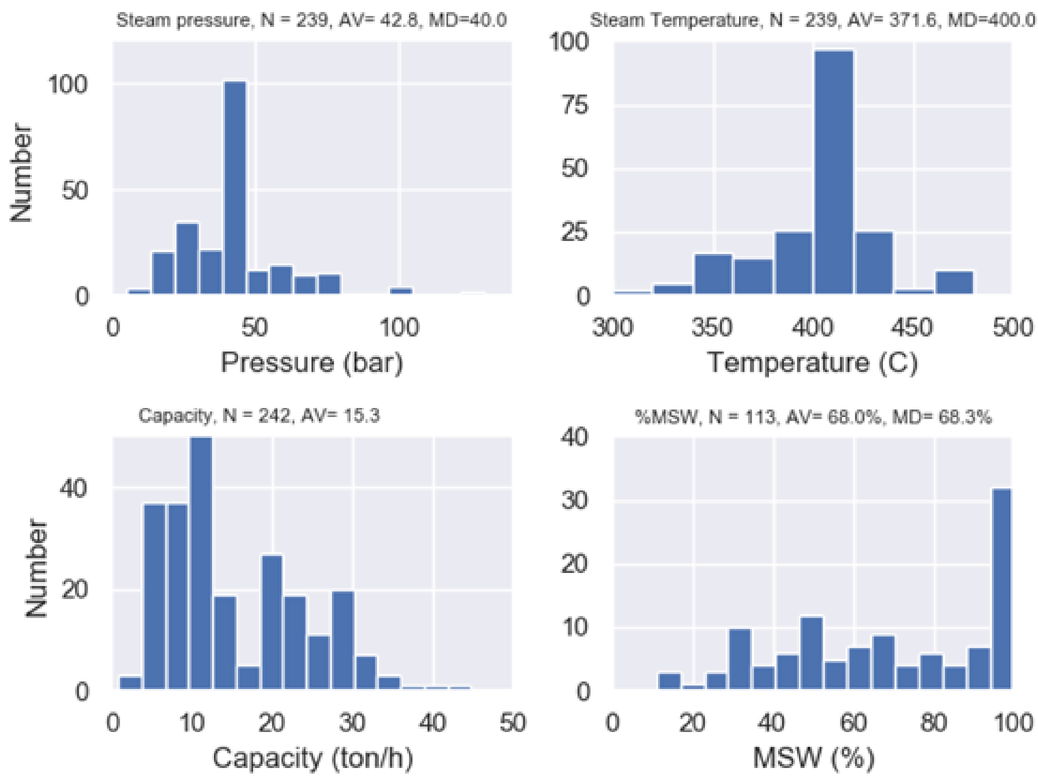

Figure 2: Steam Pressure, Steam Temperature, Capacity and Waste Composition distribution of European WtE plants in 2019

Figure 2 shows that the average design values of steam pressure and temperature for the European WtE facilities considered are **42.8 bars and 372°C**.

The average capacity of treatment lines is **15.3 ton/hr (approximately 135'000 ton/year)**, with the majority of the plants burning almost exclusively (100%) Municipal Solid Waste (MSW). On an average basis, the type of waste burned by the European WtE plants can be considered composed by **70% of MSW and 30% of Industrial Waste**.

The medium age of the European WtE lines is **21.6 years**, meaning that a little bit more than half of the considered lines has started operation before year **2000**.

It is interesting to see in Figure 3 a significant number of newly-born plants with less than 10 years of operation and a remarkable number of WtE facilities still running after 40 or even 50 years of service.

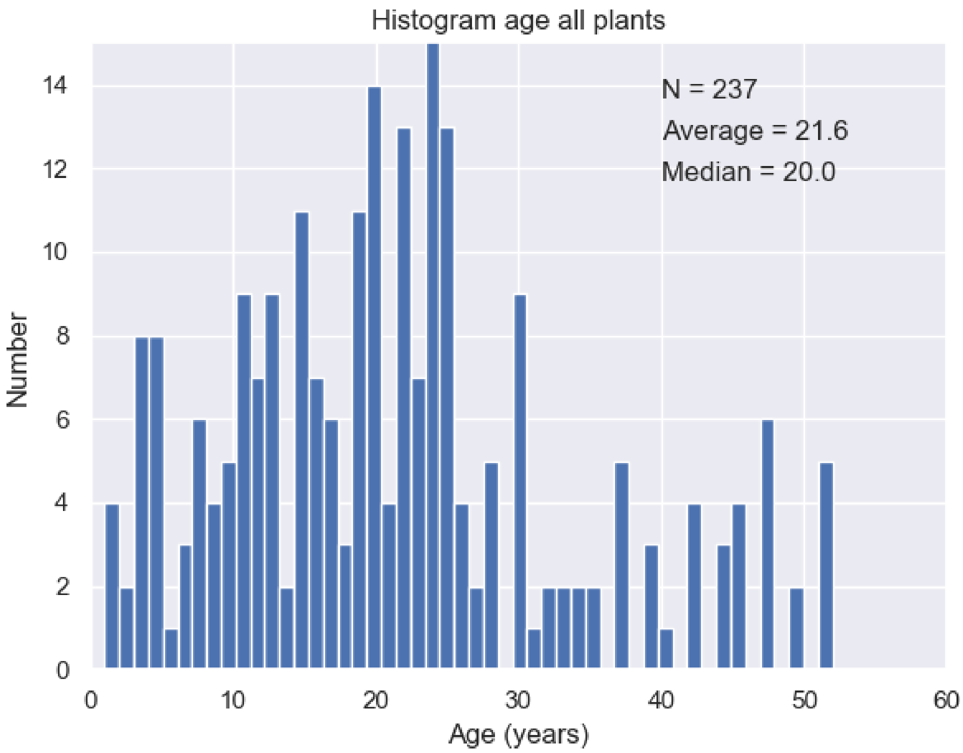

Figure 3: European WtE facilities Age Distribution in 2019

1.3.2 Average LHV of the burned waste

The overall Lower Heating Value (LHV) of the burned waste distribution depicted in Figure 4 follows a rather regular normal distribution curve, with an average value and median of **9.4 MJ/kg**. This is in accordance with the average waste composition showed before, where the majority of the burned waste is primarily MSW that generally present a limited calorific value with respect to typical Industrial wastes.

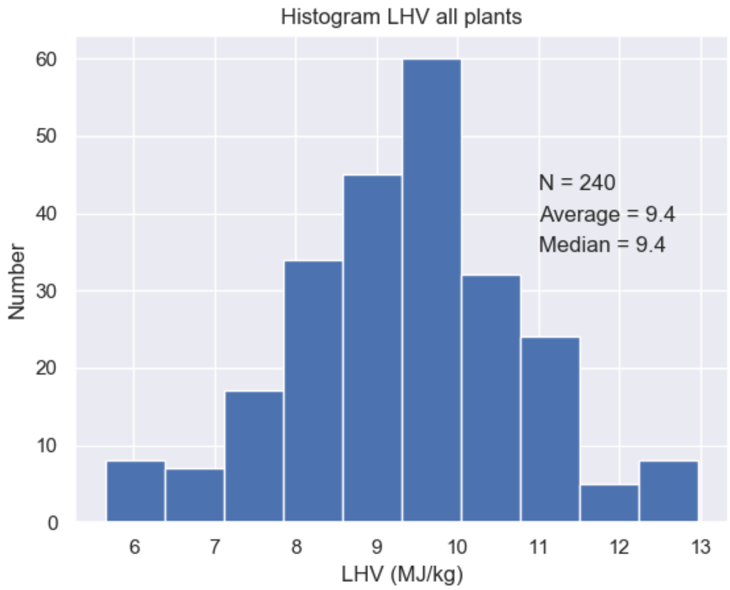

Figure 4: Overall Lower Heating Value (LHV) distribution in 2019

With a closer view, Figure 5 reports the LHV national averages and distribution for **6 different European countries**.

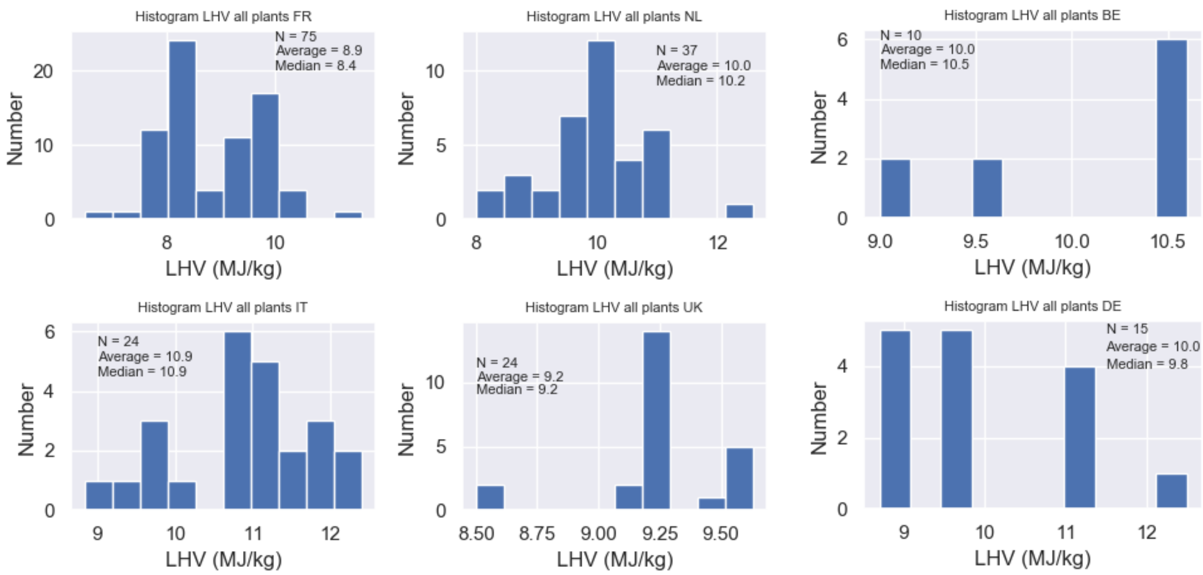

Figure 5- LHV distribution Country Focus in 2019: France, Netherlands, Belgium, Italy, United Kingdom, Germany

Only countries with more than 10 data points have been considered in the analysis and the average LHVs resulted are:

1. France: 8.9 MJ/kg
2. Netherlands: 10 MJ/kg
3. Belgium: 10 MJ/kg
4. Italy: 10.9 MJ/kg
5. United Kingdom: 9.2 MJ/kg
6. Germany: 10 MJ/kg

The slight variations in the LHV, i.e. in the burned waste composition, could also be directly linked to the diverse waste management system implemented in each country.

Figure 6, instead, compares the LHV distributions registered in the initial survey elaborated by the PREWIN Network in 2016 with the latest one under analysis in this report. Although the number of data points is significantly different (123 lines in 2016 vs. 240 lines in 2019), the average LHV has decreased, even though not considerably.

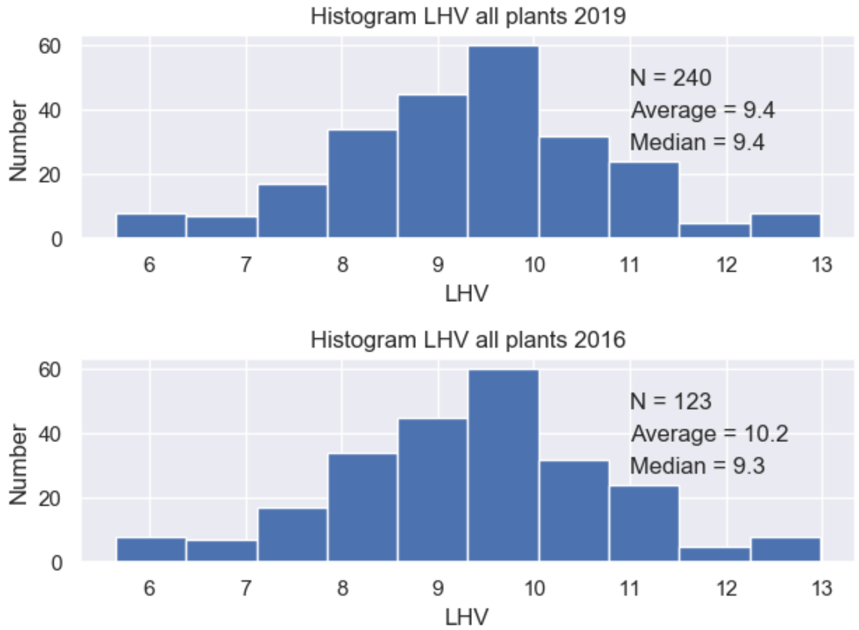

Figure 6: Overall European burned waste LHV distribution (2016 vs 2019 results)

1.3.3 Plant Availability

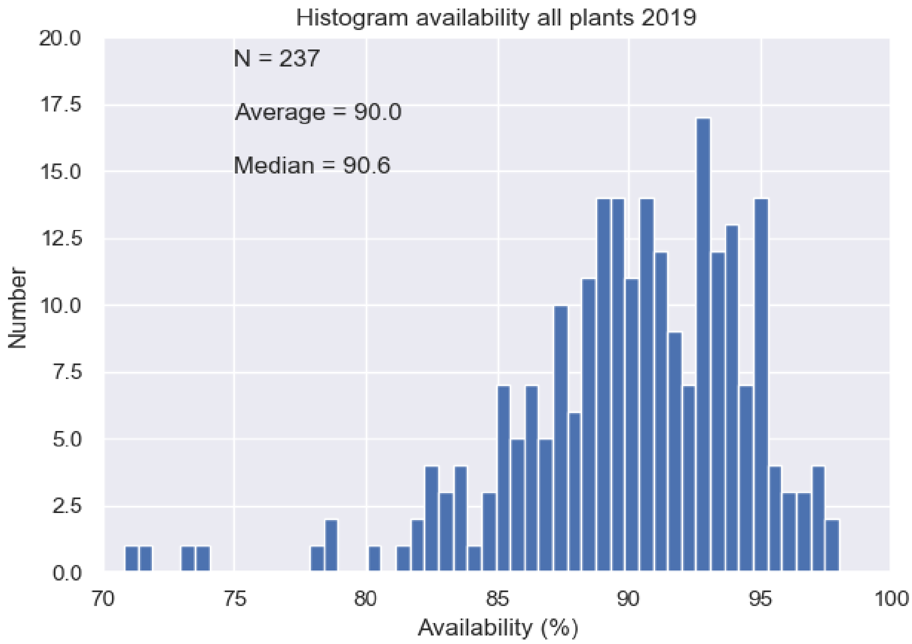

Figure 7: Overall European WtE plants Availability in 2019

Within the 237 WtE line data examined, the average availability registered through the questionnaire has been 90%. Some plants have been able to reach optimal performances, reaching availability values over 95%. 6 availability values have been registered below 70% and these have not been used in analysis, as possible outliers.

Even though the investigation in 2016 has been based on less data sets than 2019, it seems that in the last 3 years the average availability of WtE plants has slightly increased of some percentage points as Figure 8 shows.

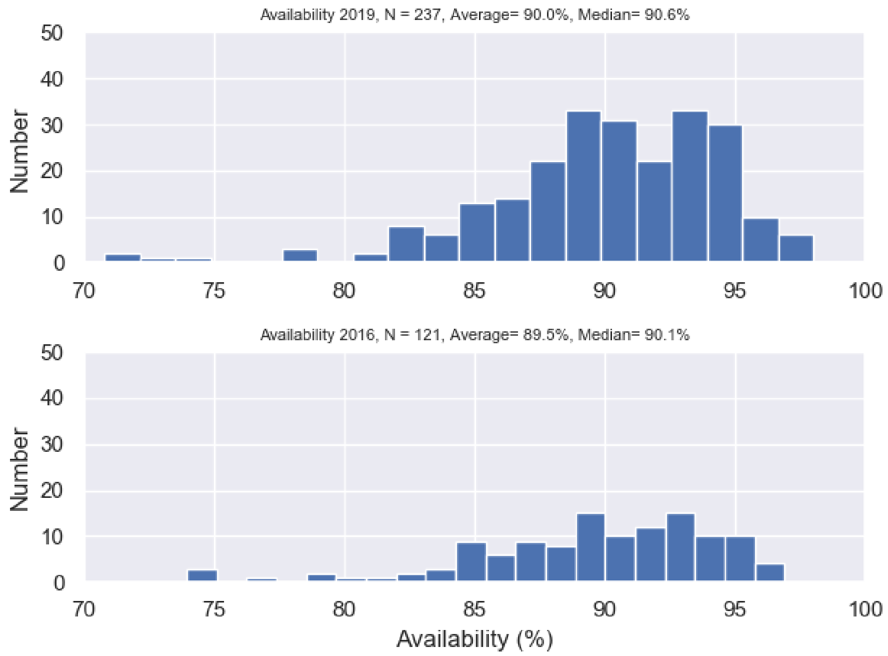

Figure 8: European WtE plants Availability comparison (2016 vs 2019 survey results)

Within 112 WtE lines data examined in 2019, the average number of unplanned outages has been **276.5 hours**, i.e. approximately **11.5 days** per year.

(5 data points of unplanned outage over 1500 hours/year have not been considered in the analysis, as possible outliers.)

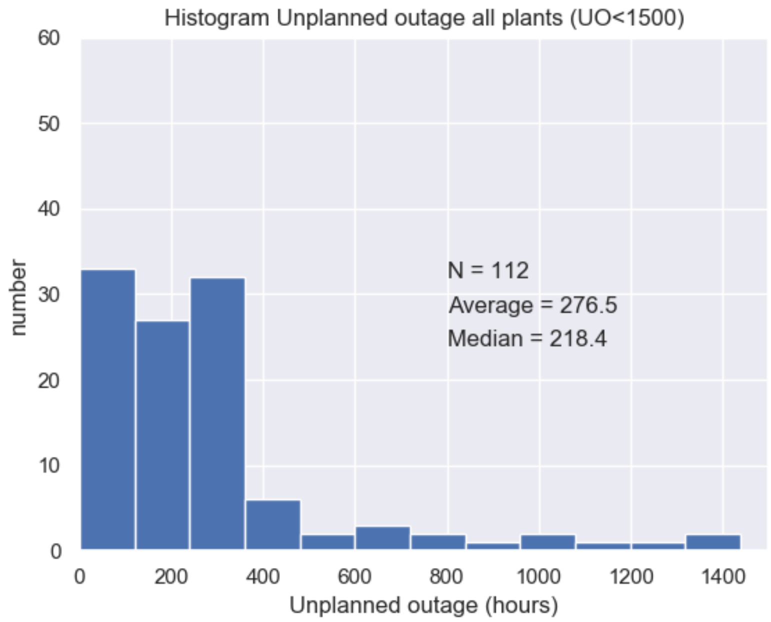

Figure 9: Unplanned outage period distribution

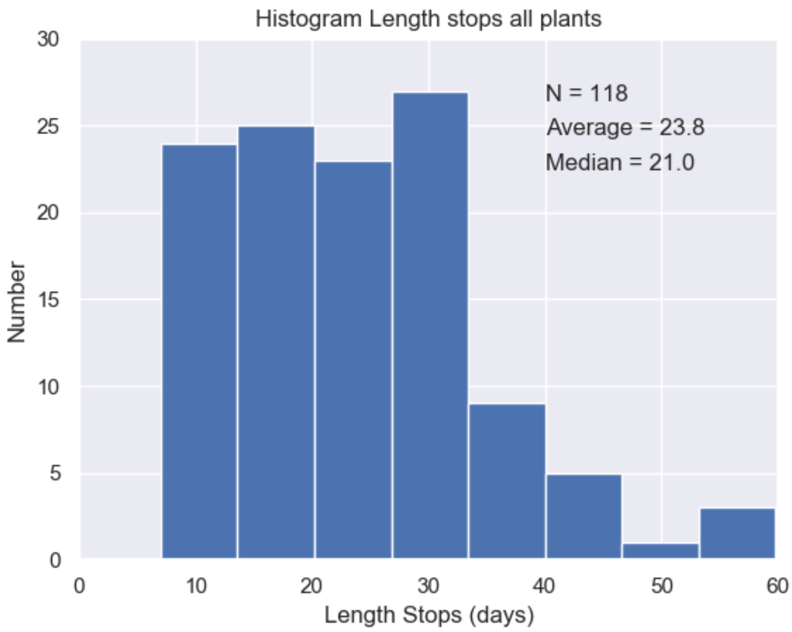

Figure 10: WtE plants Length stops distribution

The average stops for programmed maintenance last **23.8 days**, so roughly 3 weeks and a half overall for a European WtE treatment line.

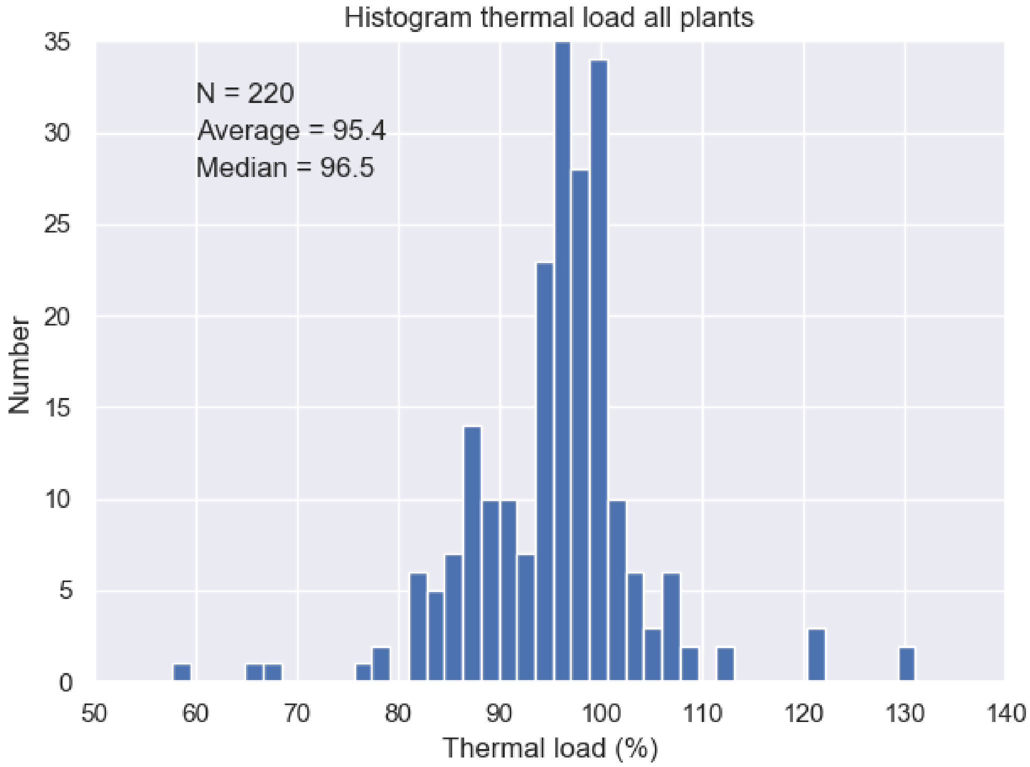

Figure 11: European WtE lines Thermal Load distribution

Figure 11 shows that the average **thermal load is 95.4%**, meaning that whilst some lines run below their design value, few other lines push their operation over their nominal limits.

The latest value has been considered in this analysis in case of a major revamping or retrofit of the plant made by the operator, that consequently brought the original value to a new design level.

Asking the operators if they were using any type of protection in the first pass, over 120 WtE lines covered by the survey, the answers distribution has been:

- Yes: N=107 → correspondent average availability = 90,8%
- No: N=13 → correspondent average availability = 85,3%

(dataset didn't include data Availability below 70%).

A 5% difference could identify that the adoption of a protection system in the first pass of the boiler can definitely have beneficial results in the availability of the treatment line.

Another parameter investigated in the survey has been the **Overall Equipment Effectiveness (OEE)**, defined as:

$$Overall\ Equipment\ Effectiveness\ (OEE) = \ Availabilty\ \times Thermal\ Load$$

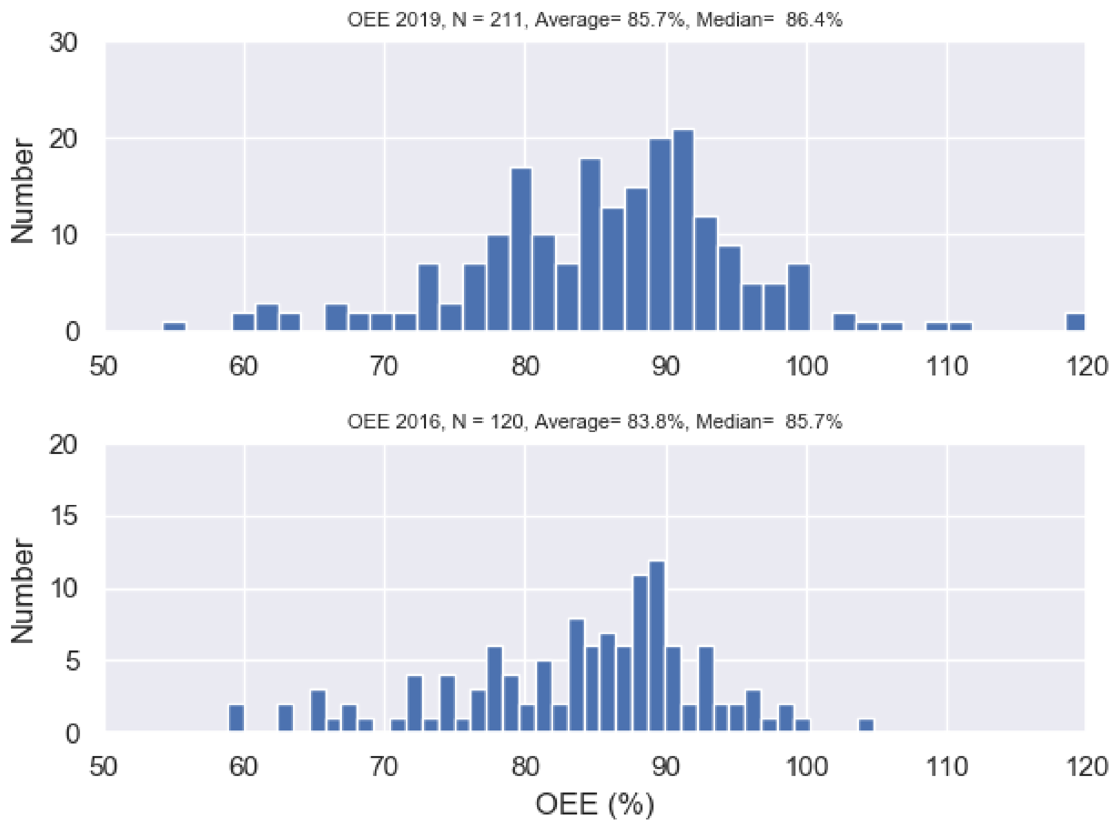

Figure 12: Overall Equipment Effectiveness (OEE) distribution (2016 vs 2019)

Figure 12 shows that the average OEE in 2016 has been 83.8% whereas it is 85.7% in the 2019 survey. The two years cannot be fully comparable as 2019 dataset is more consistent, but an increase of few percentage points can be registered.

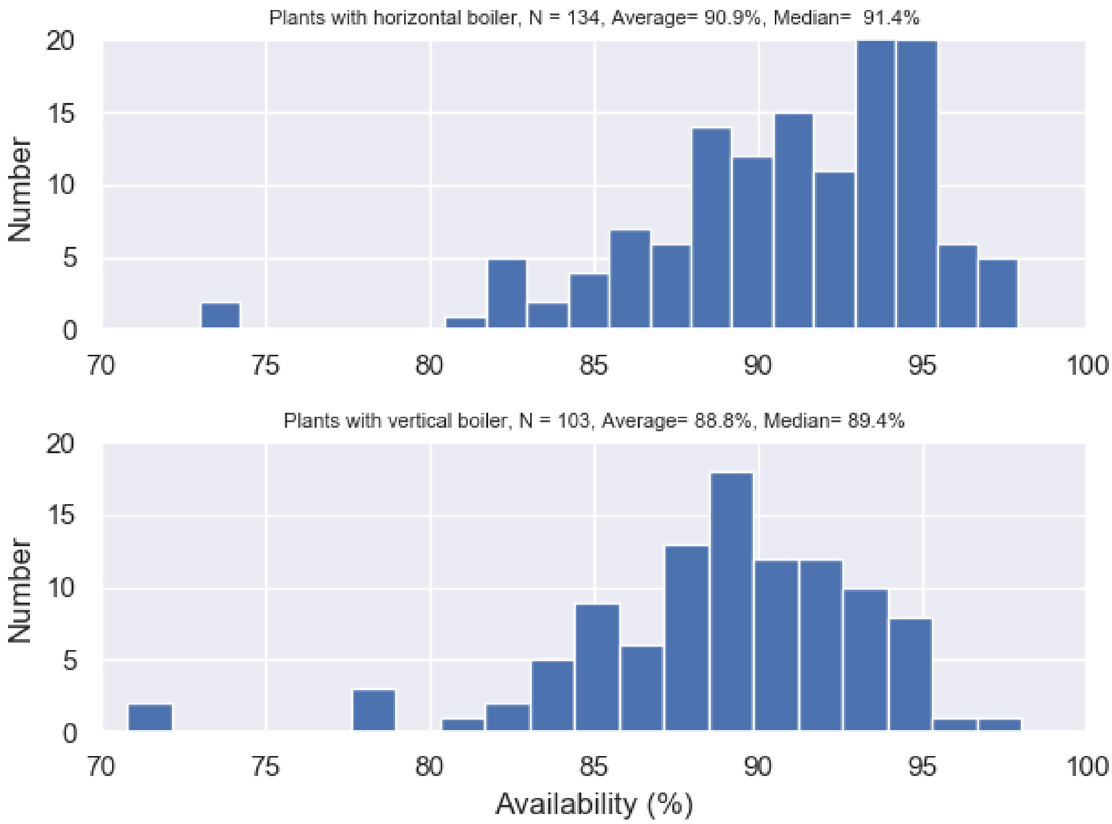

Figure 13: Availability distribution respect to the type of boiler installed: Horizontal vs. Vertical

On the technological side, there is almost an equal division of boiler type among all the European WtE facilities (134 lines with horizontal and 103 with a vertical boiler system).

From these data it appears there is not an evident correlation between availability and boiler type, even though facilities equipped with horizontal boiler seems to have registered higher values of availability.

1.3.4 Availability subplots

The following graphs explore the major parameters under examination inside different sub-categories or class, trying to identify whether any possible correlation exists between these variables.

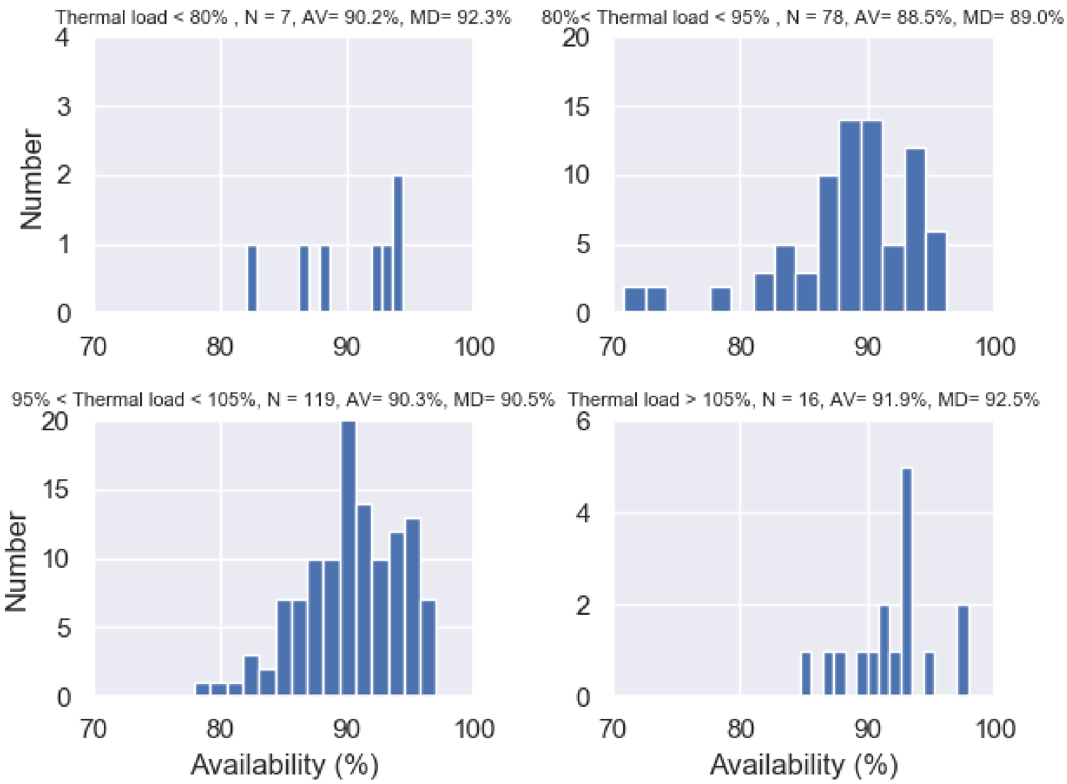

Figure 14: Availability distribution for 4 different class of thermal loads

From these data it doesn't seem that a clear correlation between the thermal load, representative of the exploitation of the line capacity, and the availability exists.

Similarly, the survey showed that it seems that no correlation exists between the age of the plant and the availability.

Younger plants could be more reliable on new components but could have less experience in the ordinary operation, i.e. older plants can have more critical issues due to the effects of aging on various parts, but they can have a better control in the operation overall thank to a stronger experience developed through the years.

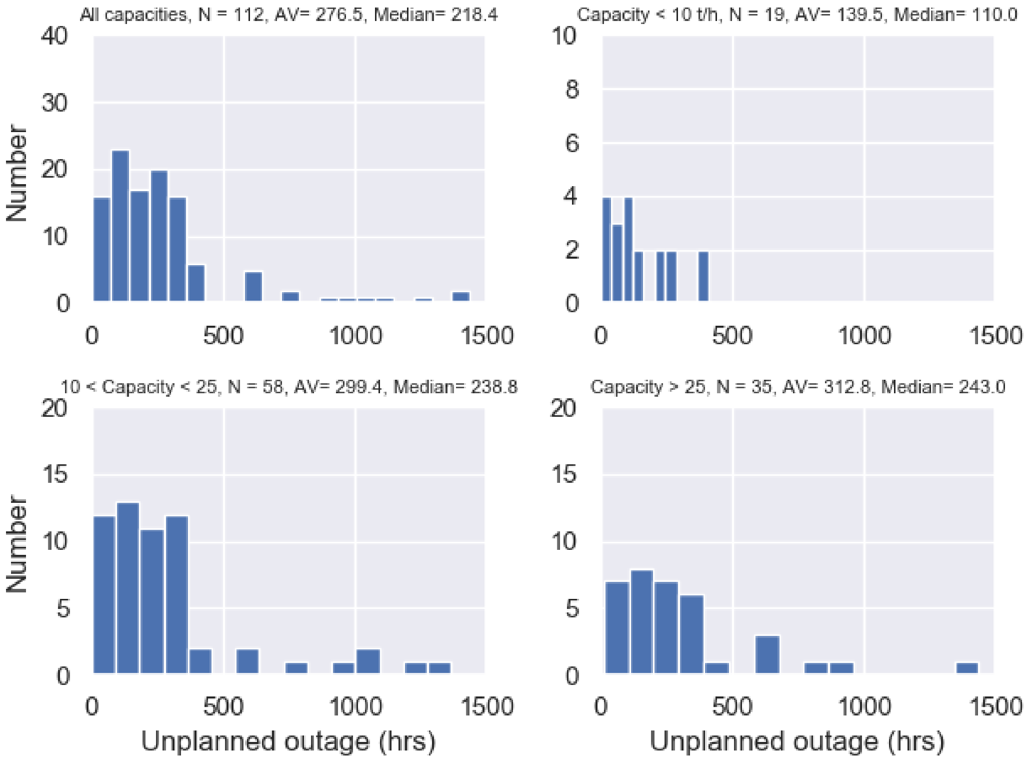

Figure 15- Unplanned outage hours distribution for 4 different class of WtE plant capacity (ton/hr)

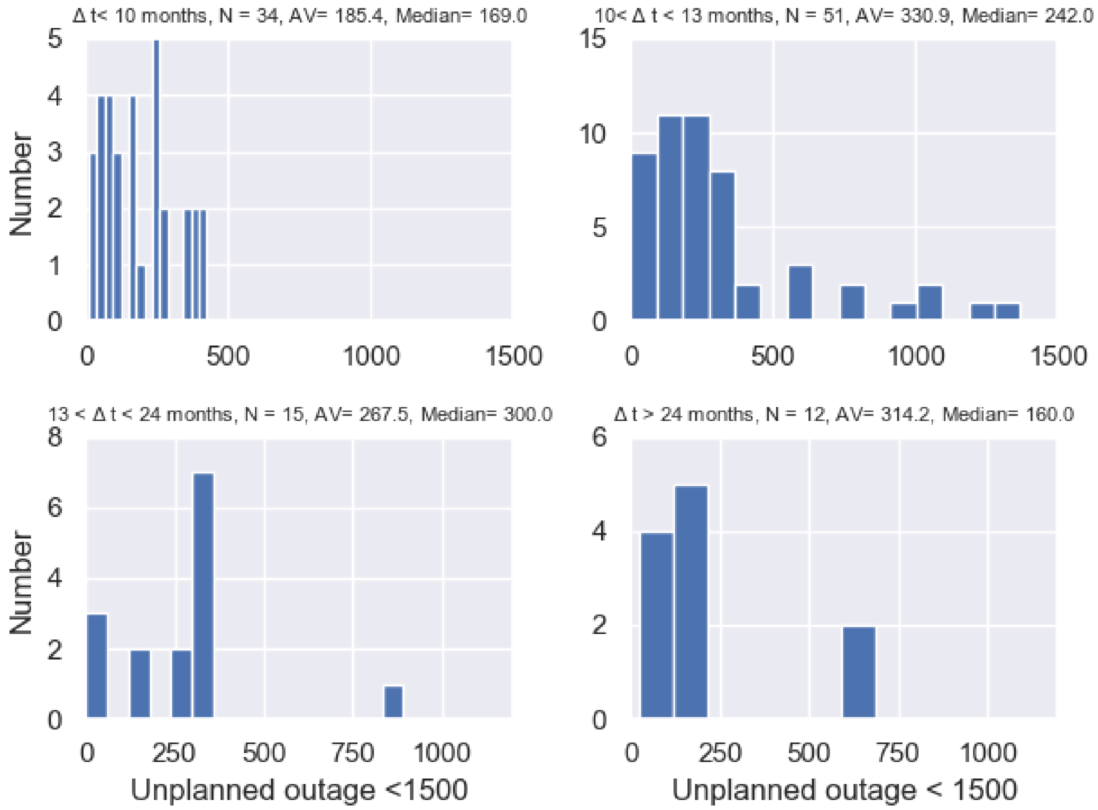

Figure 16- Unplanned outage hours distribution for 4 different class of time length between two consecutive programmed stops (Δt expressed in months)

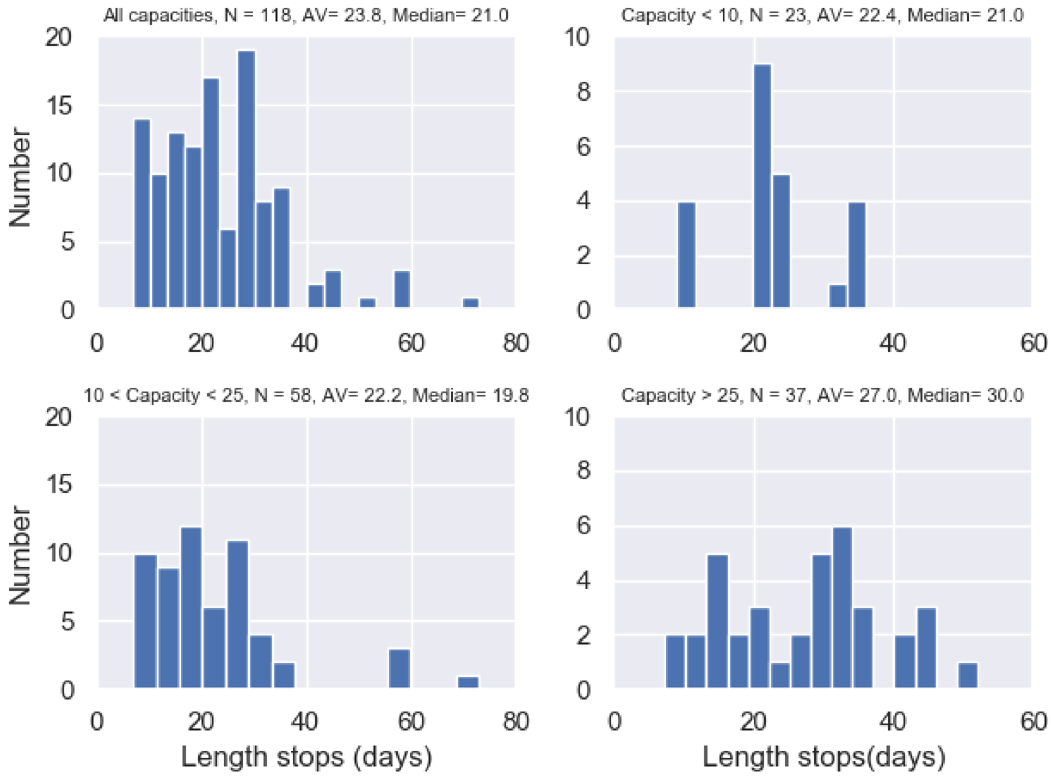

Figure 17: Programmed stop length (days) distribution for 4 different class of WtE plant capacity (ton/hr)

From Figure 17 it seems that bigger plants, i.e. WtE plants with a capacity greater than 25 ton/hr (approx. 220'000 ton/year) require longer stops than smaller ones.

Bigger plants have an average duration of stops of 27 days, slightly higher than smaller plants that on average require 22 days.

In addition, the average time between two programmed stops in European WtE lines resulted to be from the survey **12.7 months** overall. This means that WtE facilities need to have a major stop for general maintenance approximately **once a year**.

Furthermore, some plants reported in the survey to carry out the major stop every 2 years or even more. These are few exceptional cases as the common practice is to stop **every year (≃ every 12 months)**.

2. Identify the operation challenges linked to adding a CCS/CCU system to the WtE plant

The interest in integrated system as WtE-CCS or WtE-CCU is linked to the idea of developing a Negative Emission Technology (NET), giving CO_2 a secondary use and continuing in decarbonising power industry..

The capture and successive storage or utilisation of CO_2 have opportunities and drawbacks related to additional costs, operation and plant changes, finding a "CO_2 market", which make the integration of the two systems challenging. In this task, in sequence, the operation challenges, the risks and the opportunities of the integrated system are discussed.

2.1 Integration challenges

The integration of a CO_2 capture system on an existing waste to energy facility may require some process modifications or retrofits to meet the operating Requirements for the CO_2 capture

Examples of process modifications involve the operating costs, the environmental control, the energy integration to cite few of them. In details, in the following, the main integration challenges are to be discussed: the modification of flue gas pre-treatment, the changes in chemicals handling, the energy supply, the stop of operation to interconnect the equipment and the spatial area necessary to build the capture section of the plant. Where different actions are necessary if the CO_2 is used for storage or for further industrial applications is underlined.

2.1.1 Gas pre-treatment

The flue gas leaving the boiler of a waste to energy plant is mainly composed by particulate matter (or dust), SOx in form of both SO_2 and SO_3, NOx, HCl, HF, Hg and other heavy metals, which presence or not depends on the type of waste.

The flue gas treatment is mandatory for existing incineration plants to fulfill the emission limits imposed by EU Directive 2010/75 on emission limits of incineration plants. Table 2 lists the limit of main pollutants from waste incineration and the daily emissions from some waste to energy plants.

Table 2. Emissions limit imposed by EU Directive and daily average emissions from WtE plants. *For WI plants exceeding 6 tons/h of input waste, the emission limit is 200 mg/Nm^3 **[4]**

Pollutant	**Emission limit EU 2010/75, mg/Nm^3** [5]	**Emissions from WtE, mg/Nm^3,** [4]	**Emissions from Wte Mainz (GE), mg/Nm^3** [6]	**Emissions from Wte Brescia (IT), mg/Nm^3** [7]	**Emissions from Wte Napoli (IT), mg/Nm^3** [7]
Total Dust	10	0.1-10	0.43	0.39	0.30
HCl	10	0.1-10	0.40	3.49	1.92
HF	1	0.1-1	n.a.	n.a.	0.12
SO_2	50	0.5-50	6.17	1.98	1.92
NOx	400*	30-200	130.31	48.53	49.74
CO	50	1-100	2.42	6.04	7.70
Hg	0.5	<0.05	0.0007	n.a.	n.a.
As, Cr, Ni	0.5	<0.05	n.a.	n.a.	n.a.
Cd	0.05	<0.05	n.a.	n.a.	n.a.
NH3	10	n.a.	0.38	1.41	0.70

The typical flue gas cleaning to comply with environmental regulations in a European waste to energy is generally composed by:

- ESP or bag filter to remove the solid particles;
- SCR or SNCR (in the boiler) for NOx compounds;
- WFGD or Semi-dry FGD for acid gases as Sox and HCl;

In further details for the WtE plants reported as examples in Table 1, the Flue Gas Cleaning configuration could differ. The WtE located in Brescia (IT) is designed to meet the environmental limits with a system composed as follows [8]:

- a SNCR ammonia injection in the boiler for NOx control

- a bag filter for dust particles capture with activated carbon injection to adsorb micro-pollutants as dioxins and heavy metals
- a dry lime injection reactor for Sox, HF and HCl removal

At Mainz (DE), the flue gas cleaning systems is composed by several cleaning stages as [9]:

- SNCR with ammonia injection in the first pass of the boiler as deNOx unit
- High-dust catalytic converter to reduce surplus ammonia that has not reacted
- Semi-wet scrubber with lime milk injection to separate acid gases
- Fabric filter with activated carbon to remove dioxin, furans and dust
- Double stage water scrubbing to remove residual flue gas components as well as mercury

Diversification of these two examples are found in Amsterdam WtE where in sequence a electrostatic precipitator and a fabric filter are found to remove the dust and solid pollutants from the flue gas; in Spittelau WtE (AU) where the electrostatic precipitator is followed by two-stage wet scrubbers to separate HCl firstly and Sox secondly, a catalytic SCR as deNOx; in Paris plant Issy les Moulineaux, the air pollution control is composed in sequence by an electrostatic precipitator, a dry sodium bicarbonate reactor to capture SO_2, an activated carbon adsorption bed and a fabric filter to remove the remaining particles, and in tail-end a SCR unit for NOx compounds [9].

A summary of possible typical alternatives in FGT for WtE plants is reported in Table 3.

Table 3- Summary of FGT in WtE plant without CO_2 capture. ESP: electrostatic precipitator; FF: fabric filter; AC: activated carbon

Type of Plant	Flue Gas Cleaning		
w/o CO_2 capture	SNCR	ESP	Wet Scrubber
	SNCR	FF+AC	Wet Scrubber
	SNCR	ESP	Semi-dry scrubber
	SNCR	FF+AC	Semi-dry scrubber

When a post-combustion CO_2 process is added to the existing WtE, the flue-gas pre-treatment is a critical step. In fact, most absorbent liquid used in the process may be affected by flue gas composition. SOx and NOx can react with amine absorbents, forming heat-stable salts, which are difficult to regenerate and reduce the solvent available for CO_2 capture, while particulate matter (PM) can cause equipment blockage, foaming of the liquid absorbent [10]. Reference is also made to the overview carried out in task 3 of the study.

The capture solvents impose stringent limitations on the flue gas composition at absorber inlet, to keep the degradation of the solvent to acceptable levels. The following reference values (coming from previous porjects/studies executed by Wood on Carbon Capture, adopting various technologies) are suggested:

- Maximum SO_2 concentration: 10 ppm
- Maximum NOx (as NO_2) concentration: 20 ppm
- Maximum total dust concentration: 10 ppm
- Maximum HCl concentration: 10 ppm

In existing waste to energy plants, the flue gas cleaning is designed to meet the environmental limit imposed by regulations, as can be seen in Table 1. Although in many cases the WtE plants emissions are sensibly lower than EU limit, their emissions are still too high for the integration with a PCC plant. The more stringent pre-treatment needs would require some modifications/upgrades of the existing flue gas treatment system. According to performances expressed as removal efficiencies of each technology reported on BAT of 2006 [4], the concentrations necessary for the requirement of the PCC can be typically achieved with a bag filter for dust particles, a semi-dry scrubbing system for acid gases and a SCR for de-Nox process. However, several configurations could be applied.

Table 4 lists the most likely different combinations of cleaning technologies for WtE-PCC plants.

Table 4- Different combination of Flue Gas Cleaning in presence of CO_2 Capture. ESP: electrostatic precipitator; FF: fabric filter; AC: activated carbon

Type of Plant	**Flue Gas Cleaning**		
With CO_2 capture	SCR	ESP	Wet scrubber multi stage
	SCR	FF+ AC	Wet scrubber multi stage
	SCR	ESP+ FF+AC	Wet scrubber multi stage
	SCR	ESP	Semidry Scrubber

	SCR	FF+AC	Semidry Scrubber
	SCR	ESP+ FF+AC	Semidry Scrubber

The equipment that are mostly subjected to a retrofit are the deNOx and deSOx processes. In fact, for the total dust concentration, the removal efficiency of both Electrostatic Precipitators (ESP) and Fabric Filters (FF) is typically high enough to meet the necessary concentration, considering that solid particles are partially removed with scrubbing process too.

As far as NOx emissions are concerned, the majority of existing WtE use the combination of SNCR with flue gas and flue gas recirculation, which reduces NOx by 50-80% [10]. However, the low NOx concentration of inlet of CO_2 absorber can be reached only with a more efficient technology, namely the SCR. In WtE plant that have project of CO_2 capture integration as Alkmaar (NL), Rotterdam (NL), Oslo Fortum (NW) have to consider placing a SCR in the FGT sub-system. The SCR is usually placed after the dust removal unit in a tail-end configuration, mainly because it is preferable to remove the other contaminants in the flue gas to avoid unacceptable levels of SCR catalyst poisoning. From in-house data, the reduction of NOx concentration below 20ppmv, corresponding to 90+% NOx capture levels, is achievable only increasing NH3/NOx ratio well above the stochiometric. The drawback of such an arrangement is the increase of ammonia slip production: in the last stages of deNOx unit, the NOx concentration is very low, and the reagent is in excess. The ammonia slip causes several issues as health effects, visibility of stack effluent and catalyst deactivation. In fact. as the ammonia slip increases, the catalyst activity decreases [11] [12] [13]

For deSOx, in the carbon capture context, the necessity of very low SOx concentration requires a revamp of existing desulphurization technology or a replacement. The retrofit of an existing abatement system might have significantly different implications depending on the adopted technology.

For example, Wood inhouse data for Wet Limestone FGD, available from previous studies on coal power plant with and without carbon capture, suggest that the major equipment dimensions in the design with CCS do not differ from the design without CCS. The difference is mainly related to reagent consumption and by-product generation, , as discussed in para 2.1.2, and the need for a further water spray plate in the absorber and a new additional slurry circulation pump.

The following highlights from real cases of integration of carbon capture with WtE provide an example of how the flue gas cleaning system upgrade was addressed in relation to this type of retrofit.

In the Hengelo WtE (NL), the flue gas leaving the boiler meets in sequence the electrostatic precipitator, a scrubber reactor with sodium bicarbonate injection, the fabric filter to remove the remaining solid particles and at the end, the SCR, as described in Task 1.

The Klemetsrud WtE plant in Oslo (NW) has three treatment lines. Two of them are designed with a SNCR deNOx system, while the third line that was built more recently and is undergoing a project for integration with carbon capture. The flue gas cleaning of the third line is composed by an electrostatic precipitator, wet scrubber for acid gases, SCR and activated carbon bed for dioxins [14]. The wet scrubber for acid gases removal is actually composed by 4 scrubbing stages: in the first two, the acidic pollutants as HCl and heavy metals are separated, the SO_2 is removed in the third stage, while the last one is used to capture the remaining particles though a venturi system [14].

Table 5 compares four example of Flue Gas Cleaning operating in WtE plant in Europe and the modifications necessary as retrofit to meet the CO_2 capture needs.

Table 5- Retrofit modifications of WtE examples for CO_2 capture plant integration

WtE	Retrofit	Example
Lines 1&2 w/o Carbon Capture: -ESP -Spray Dryer -Wet Scrubber -FF -SCR	Line 3 w/ CC: -ESP -Spray Dryer -ESP -Wet Scrubber -SCR	Hengelo [15] [16] [17]
-SCR -ESP -Wet Scrubber (multi-stage)	No modifications	Klemstrud [14]

Regarding flue gas handling more in general, another implication of the integration of a Carbon Capture with an existing WtE is related to the flue gas blower. The additional pressure drops of a carbon capture, in the range of approx. 80-120 mbar, would require a retrofit of the flue gas blower. Whether this is a revamping of the existing unit or a full replacement should be evaluated case by case.

2.1.2 Chemical handling

When the capture plant is integrated with an existing WtE, as described in 1.1.1, the flue gas pre-treatment needs revamping or changes. In case of revamping, a larger amount of reagents for both deSOx and deNOx have to be handled, as well as, more by-products from FGT are produced.

For reference, Wood estimated from in-house data of technical evaluation of wet deSOx unit for a coal plant with and w/o CO_{2v} capture, that the revamp of a reference European existing wet deSOx unit would require the injection of roughly 10% more of lime to increase by about 4% the removal efficiency, leading to a 4% increase of gypsum by-production. For a SCR, assuming that a solution at 50% of ammonia in form of urea is used, Wood estimated that the increase of deNOx efficiency of about 10% to meet the CO_2 solvent requirements is achievable with a roughly 10% increase in urea consumption in the SCR. In fact, for a SCR, the mass of reagent is a linear function of removal efficiency, as well as, the volume of catalyst needed [18].

The integration of carbon capture system requires a further chemical handling related to the necessity of making-up the operating losses of the capture solvent itself. Based on in-house data, Wood estimated that the solvent make-up is in the range 0.2÷1.0 kg of solvent per ton of CO_2 captured. Assuming an average figure of 0.6 kg_solvent/t CO_2, for a number of operating hours in a year of 8000 h (more than 90% of the year), and a captured CO_2 flow of 35 t/h[3], it was estimated a solvent make-up of approx. 13 t/y. If the make-up solvent is transported by trucks of 30 m^3 capacity, the amount of solvent make-up will require just 1 truck delivery per year.

2.1.3 Spatial Integration

Of course, the integration of CCS/CCU system in an existing WtE requires space for the construction of a new Carbon Capture unit.

A standard PCC system is composed by a Direct Contact Cooler, the CO_2 absorber, the solvent regenerator, the solvent circulation pumps, the heat exchangers and all the flue gas ducts to connect the WtE to the capture unit, and the capture unit to the stack.

Based on inhouse data taken from a feasibility study for a coal power plant with post-combustion CO_2 capture, Wood has estimated that an indicative foot print of an amine-based CO_2 capture unit for the retrofit of a 20 MWe net power WtE would be approx. 25 m x 40 m (excluding CO_2 compression and liquefaction, if any).

Regarding spatial integration, one of the main issues that can have a significant impact on the retrofit is the possible presence of a gas-gas heater (GGH).

The GGH, in fact, transfers the heat from the raw flue gas to the de-carbonized gas before sending the latter stream to the atmosphere. The installation of a Gas-Gas Heater is necessary when the flue gas temperature after the CO_2 absorber is not high enough to ensure an adequate gas buoyancy and dispersion in the atmosphere and avoid the “plume effect” that lowers the social acceptance towards the WtE. For example, the Klemetsrud WtE-CC plant has foreseen the construction of a GG Heater to increase the decarbonised gas temperature from up to 75°C.

[3] consistent with the capacity of the reference plants analyzed by Wood as part of this study (see task 3)

Its installation, in-between the WtE stack and the absorber, makes the flue gas ducting more complicated. For instance, the straightforward solution of discharging the flue gas directly from the top of the absorber is not possible if the configuration includes a GGH.

2.1.4 Energy supply

For the integrated system WtE-PCC, the solvent used to purify the flue gas of CO_2 is regenerated at high temperatures. The heat duty necessary for the regeneration depends on the type of solvent, but on average ranges between 3 and 4 GJ/t_ CO_2. It means, as described in section 2.2 of task 3.2, an amount of about the 50% of steam produced that is exported from the Steam Turbine and supplied to capture reboiler.

A part of operative and investment costs, the energy penalty imposed by post-combustion capture is a challenging barrier to the integration of such system with a WtE.

When the Waste to Energy is energetically integrated with the local community with district heating, the fraction of steam used for capture unit is theoretically subtracted to the district heating system, i.e. the consequent lack of energy supply should be balanced with other sources (renewable or not). As discussed in Task 3, the energy conflict in the WtE-PCC system can be partially or totally handled by improving the heat recovery through flue gas condensation and/or heat pumps.

To overcome this energy conflict, some WtE plants have also chosen to capture CO_2 preferably during summer, when the district heating demand is lower, and reduce the CO_2 capture during winter, as is done in Alkmaar plant in the Netherlands. The drawback of this solution would be a peak of CO_2 emissions in atmosphere from the WtE plant during winter, however, depending on the nature of the alternative sources for domestic heating, this may not be a disadvantage in absolute terms.

However, the connection of a CO_2 capture unit downstream an existing WtE generates some other operating challenges that could alter the operation of incinerator, especially when it is designed to produce electricity as main product. Two main types of issues are briefly analyzed:

- Steam throughput (i.e. load) in the last stages of the steam turbine after the retrofit;
- Hardware modifications required to the steam turbine

Regarding the first point, it is useful to refer to the net 20 MW_E WtE plant used as reference for review and discussion in Task 3. This plant is designed to produce 106 t/h of High-Pressure steam at 440°C and 61 bara, which is sent to the inlet of the Steam Turbine. At the turbine exhaust, the flowrate sent to the condenser is 78.8 t/h at 42°C and 0.08 bara. When the CO_2 capture is integrated with this plant and a huge amount of the steam is exported for the CO_2 solvent regeneration, the LP steam sent to the last expansion stages and the condenser is reduced. Assuming that the minimum turndown allowable for this part of the steam cycle is approx. 30% of the design throughput (i.e. approx. 24 t/h in the case), in line with Wood experience for previous projects, Wood analyzed that, with the CO_2 capture in operation, there could be constraints in turning down boiler load , to fulfill the minimum load requirement of the low-pressure section of the steam turbine. This could be an important limitation in terms of operating flexibility of the whole WtE. It has to be remarked that the criticality is mainly with the steam turbine itself. The same type of issue on the condenser can be more easily overcome: if the condenser is air-type, the amount of air fed to the condenser can be adjusted by modulating/switching off the fans on some selected cells; if it is water-type and the cooling water system configuration includes multiple pumps, one or more pumps can be shut-down.

As far as the hardware modification required by the retrofit to an existing steam turbine, the following issues may arise from the need to extract a significant amount of steam at a pressure level of around 6-7 bar:

- The distance between stages could be too short in order to allocate the extraction nozzle This aspect could be a main issue especially for a reaction turbine type expansion stages, which are typically closer to each other for fluid dynamic reasons with respect to action type expansion stage. If the space is too tight to allow the installation of such a relatively large extraction nozzle, many parts should be rebuilt such as the entire casing, the shaft, etc. It is remarked that, for power generation, the reaction type stages are widely used, especially at the low-pressure section of the turbines.
- The stage downstream extraction would be unbalanced (especially for reaction type turbine this could be again a big issue)

These high-level considerations are very preliminary, being the outcome of an initial brainstorming. Specific evaluations should be developed case by case with the support of the original equipment manufacturer. There could be even the risk that a full replacement of the machine is necessary; for example, at Boundary Dam, the Unit 3 retrofit to implement the CCS required the implementation of a new steam turbine [19].

2.1.5 Stop of operation

The integration of CCS/CCU system in an existing WtE needs to stop the WtE plant to allow interconnecting the new CO_2 capture system with the WtE plant and the commissioning/starting-up the CO_2 plant.

During the construction phase of the CO_2 capture unit and relative pipeline to transport the CO_2 in a different geographic area for storage or in an industrial plant for an utilization, the stop of the incineration process is not strictly necessary. The scheduled plant stop for planned maintenance can be exploited to implement in the waste to energy plant the modification necessary for the WtE-PCC integration. Example of a list of action that can be planned during the scheduled stop of a WtE are:

- Tie-ins on flue gas duct at the end of FGT;
- Extension of flue gas duct after the FGT with connection to PCC;

- Tie-in to connect the CO_2-free flue gas pipeline with WtE stack;
- Tie-in on cooling water circuit and other utilities.

The duration of the scheduled maintenance of a Waste-to-Energy plant is typically about 3 weeks on average on a yearly basis. This time-frame is expected to allow the execution of the above listed tie-ins without further stop of operation. However, other modifications that could be required, namely to the flue gas blower and, especially, to the steam turbine, are more challenging to handle. It is unlikely that a normal planned outage is enough for their realization.

In fact, the modification or substitution of gas fan (ref. para. 2.1.1) has to be done when the WtE unit is stopped, and the time necessary for the operation may be longer than the period covered by scheduled maintenance. The Steam Turbine retrofit could result to be the most difficult operation for all technical issues related to the large steam extraction to be implemented, as described in para. 2.1.4.

As a further general consideration, the construction works of CO_2 capture unit will require some civil works, especially in relation with the foundations of the new equipment. It is crucial that during the design phase any possible interferences with the existing foundations and underground works are checked and avoided as far as possible, as their management during construction phase could lead to a sensible extension of the duration of the WtE shutdown period.

After the completion of CO_2 unit construction and the plant modification in the WtE section, based on Wood experience, a further stop of about 2.5÷3 months would be needed to complete the commissioning of CO_2 capture unit and the initial start-up the integrated plant.

2.2 Risks

The risk elements of an integrated system are listed below and will be one by one discussed, underlying, were possible, the difference between the storage or the utilisation of the CO_2:

- Emission of harmful compounds
- Public acceptance
- Technology development
- More challenging financing

2.2.1 Emission of harmful compounds

The post-combustion carbon capture applied to a power plant or a WtE has a beneficial effect on the environment for the reduction of GHGs emissions, but at the same time, it can potentially cause additional harmful emissions, which are not GHGs.

Generally, the emissions are classified in two types: point of discharge and fugitive. The point of discharge encloses the intentional, predictable and quantifiable releases of harmful compounds from an equipment; the fugitive emissions are related to unpredictable and unexpected releases from equipment or piping or process items as valves [20]. These potential harmful compounds released from the post-combustion carbon capture would be additional emissions to the WtE ones.

Starting from the point of discharge type, it concerns the emissions from:

- Top of the CO_2 absorber
- Waste of process solution from the reclaimer
- Top of regeneration unit

The flue gas entering the capture unit would be composed by CO_2, CO, HCl, SOx, NOx, dust and other carcinogenic substances as acetaldehyde, chloroform, benzene and trace of metals as arsenic, cadmium, which are toxic as well.

At the top of the absorber, vapours of process solution can be formed, depending on the operating conditions and on vapor pressure of chemical composing the solution itself. The main component of vapours is the solvent. Its vapours are toxic for both humans and environment.

Based on Wood experience with some licensed and commercial amine solvents , the amine-based solvents can be harmful by themselves and require high attention in handling. They can cause:

- Long-term damage at aquatic environment
- Strongly harmful if swallowed
- Skin irritation
- Eye damage
- Sterility

The solvent degradation products are harmful components as well. The majority of them have a vapor pressure at 20°C higher than water and tend to vaporize at top of the absorber, therefore, if they are present, they are found in the process vapours in the form of formic acid, acetone, ammonia, butanone et al.

The degradation of amines can have two origin [21]:

- Thermal in the regeneration unit
- Oxidative triggered by the presence of O2 and enhanced if SOx or NOx are present.

It has been estimated that oxidation degradation consumes 0.3-0.73 kg MEA/t CO_2 captured [22], while thermal degradation accounts for 20-30% of total amine losses [22]. Considering that thermal degradation takes place mainly in the stripper, reboiler, reclaimer or piping connecting the lean/rich amine heat exhanger, the maximum operating temperature of these units is imposed to avoid thermal degradation in excess to the amine losses figure mentioned above .

From tests carried on CO_2 capture pilot plants, the ammonia is the major harmful degradation compound emitted from the capture process. The ammonia is formed by oxidative degradation of MEA solvent caused by oxygen and triggered from relatively high metal ions concentration in the flue gas. The degradation action of metal ions can be controlled with a reclaiming of the solvent. [23]. The reclaimer waste contains, in addition of metal ions, toxic substances as mixture of heat-stable salts as sodium nitrate or ethanoic acid salts, organic materials and trace of Sulphur [22] [20]. Oxidised mercury is expected to be absorbed in the solvent and found in the reclaimer waste, as well as, the corrosion inhibitors added to delay the degradation of the solvent. The concentration of all these substances in the amine recirculation system has to be controlled to avoid accumulation in the carbon capture system [24], for example, the reclaimer is used when the concentration of heat-stable salt anion is 1.2% wt [20].

The vapours of amine-based solution emitted in the atmosphere go through secondary reactions in the air and, in presence of nitrogen oxides, can produce nitrosamine and nitramine. These compounds are pollutants for the environment and harmful for human health because are classified as cancerogenic. This kind of components are present in the capture solvent and water washes as well.

For ammonia-based solvents as chilled ammonia or aqueous ammonia, it has not been recorded formation of degradation products.

The fugitive emissions regard the unintentional release of process fluids during the plant operation for leaks or working losses. Leakages are caused by corrosion, excessive vibration, damages of process equipment. Working losses occur, for example, when the storage tank of the absorbent solvent is filled or when the thermal expansion of the solution vapours in the tank is triggered by the temperature increase during the day.

The fugitive emissions are the smallest fraction of possible harmful releases from the capture unit. The accidental emissions generated from emergency losses or accidents during operation might happens, but they probability is lower than those discussed.

The heavy metals concentrations in a municipal waste is much higher, especially for mercury, cadmium etc., compared with fossil sourced and natural gas. It means that the concentration of heavy metals to be removed in the flue gas pre-treatment is higher, and the probability that a higher metals ion concentration could be present in the capture solvent is higher.

The harmful emissions from CO_2 capture can be controlled and avoided with specific technologies. Some licensed processes, as MHI, have declared that their CO_2 capture process is zero amine emission system thanks to the use of a special reagent in the water washing section that captures the degradation products [25].

Conventional methods applied to control the solvent emissions are:

-A wash water, especially if done with acid water, reduces the concentration of ammonia in the vapour phase. This technology requires a modification of absorber unit, which is composed by three contacting zones: the bottom one for the contacting between the flue gas and the amine solution, the middle one for water washing and the top one where the gas is washed with acidic aqueous solution.

- destruction and/or removal of nitrosamine by means an advanced oxidation process (AOP), even though this mechanism needs further investigation to understand if operating conditions and composition of flue gas affect the success of the technology or not

-a mist eliminator installed at the top of the absorber , which captures the liquid droplets in the gas phase

2.2.2 Public Acceptance

According to IEA, the Carbon Capture and Storage could provide a reduction of 19% of CO_2 global emissions within 2050 [26]. The barriers that hinder this result are based on the technological costs and on the social acceptance. Several researches conducted on social acceptance on CCS have identified the main factors that influence people in level of awareness of climate issue, knowledge, experience, perceived costs, risks and benefits, trust in technology promoters or opponents. Generally, the feeling and awareness of need to reduce the emissions of CO_2 are well perceived from people, but at same time, they want to know about other alternatives and the major concern is that the investment in CCS might displace the investments in renewable energy technologies.

In 2012, MIT carried a social survey in the US on global warming and technologies to face it. People confirmed that they were aware of environmental issue and there is the need to act in time. However, from the survey it came out that people have a deeper knowledge on hybrid cars, solar and wind energy, which are technologies they are willing to invest money in, as indicated in results in Figure 17.

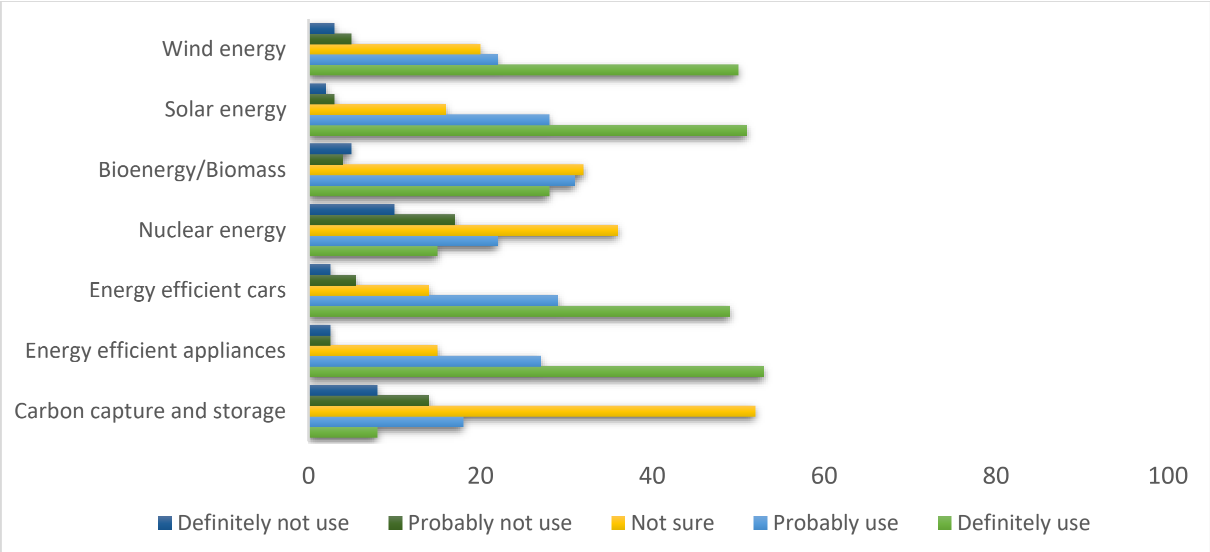

Figure 18- Social proposed solution for global warming **[27]**

Figure 17 indicates the percentages of level of willingness of people to design project facing the climate change choosing among wind energy, solar energy, bioenergy, CCS, cars efficiency and energy efficient technologies. The highest values were obtained for wind and solar energy, for new cars and more efficient technologies. The high uncertainty towards the CCS (almost 50% of not sure) is due to lack of information, advertisement and promotion, public campaign on the subject.

Social actions are necessary to increase the public support and recognize that economic activities associated with CCS contribute to climate change [28]. The lack of public acceptance, in fact, can cause delays or even cancellation for many projects. At same time, the social acceptance drives towards external funding and helps the project in going forward.

Figure 18 represents the reaction of people to a hypothetic proposal of US Government to invest 3.4 billion of US dollar in a CCS project applied at a coal-fired power station and other industrial facilities. The figure is from MIT survey [27].

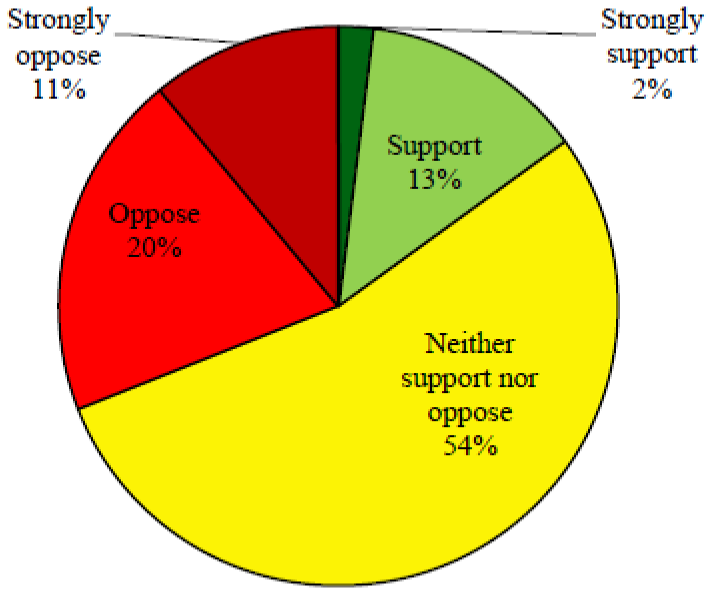

Figure 19- Social support or opposition to CCS project **[27]**

The public opposition in CCS technology is quite high for concerns about risks of leakages or over pressurization of storage sites [29].

To face this social concern, the Intergovernmental Panel on Climate Change (IPCC) analysed the status of CO_2 storage sites and the probability that the injected CO_2 is retained over 100 years is very likely 90-99% [30]. Moreover, the CO_2 within the rock undergoes physical transformation, which traps it in a more “secure” form. For example, the CO_2 can be mineralized as calcium carbonate within the pore space of the rocks.

A similar survey was done for 12 EU countries to understand the attitude towards the CO_2 capture and storage. Figure 19 compares the percentages of knowledge and information among the chosen countries on the causes of climate changes.

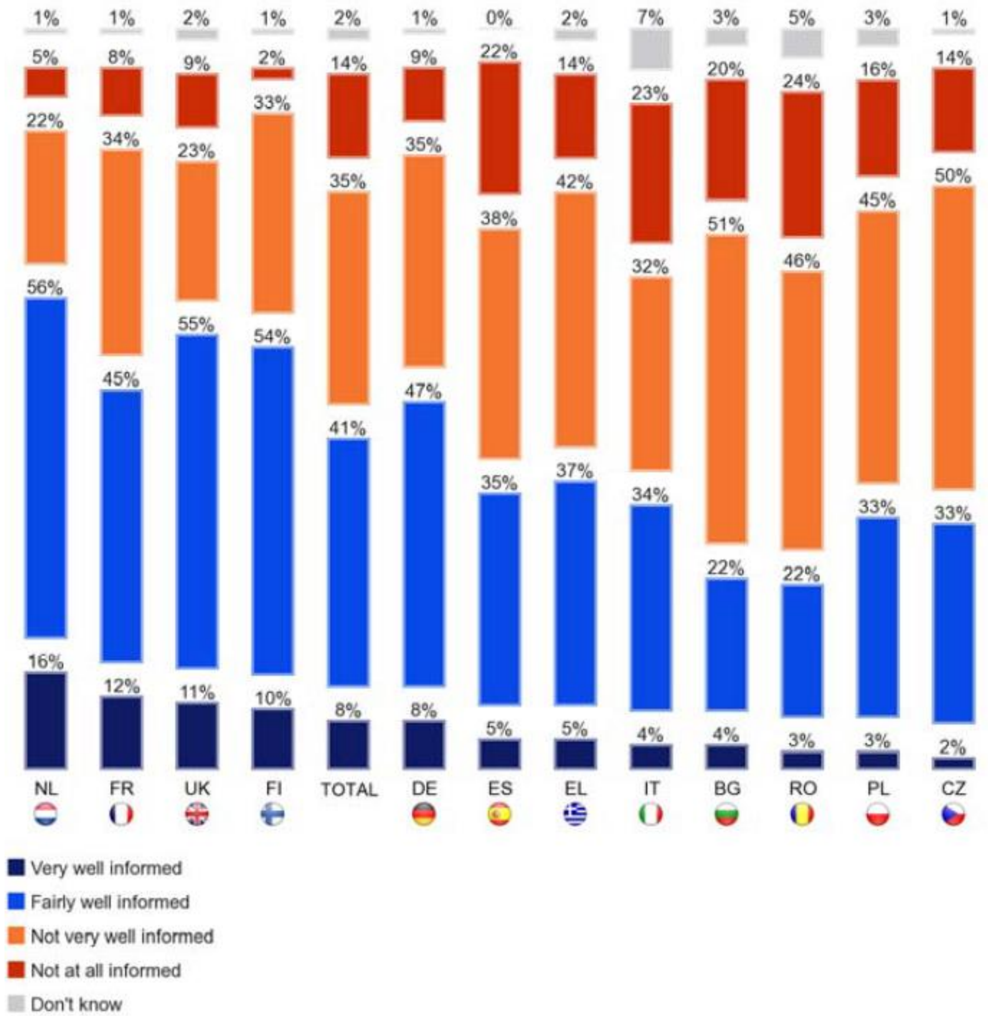

Figure 20- Level of awareness on climate changes causes in 12 EU countries [31]

UK, Finland and Netherlands have the highest proportion of people who felt well informed on the subject, while Romania and Bulgaria resulted to be less informed states. Italy showed the highest proportion of people that didn't know whether or not they were informed.

Figure 20 compares the level of favour in using alternative sources of energy [31].

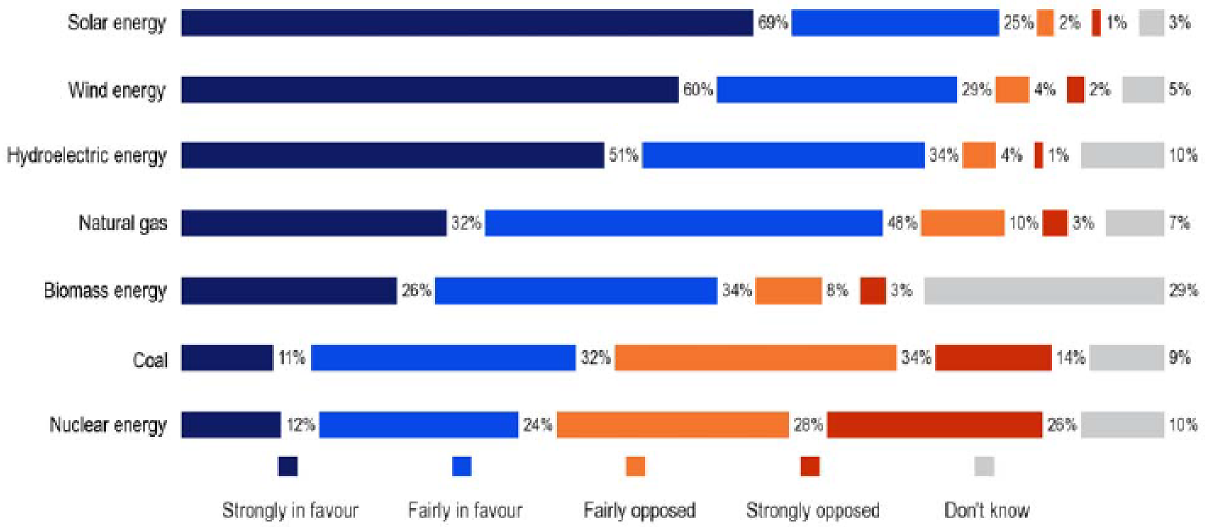

Figure 21- Favor or opposition in Europe towards the alternative sources of energy [31]

The 94% of Europeans? was favour in solar energy and the 89% in wind energy. The favour in natural gas was 80% but 32% strongly favour compared to the 69% of solar energy. The less popular source of energy was nuclear with more than half of participants opposed to it.

Regarding the CCS, the average awareness and knowledge of EU-states on Carbon Capture and Storage is really low, as indicated in Figure 21.

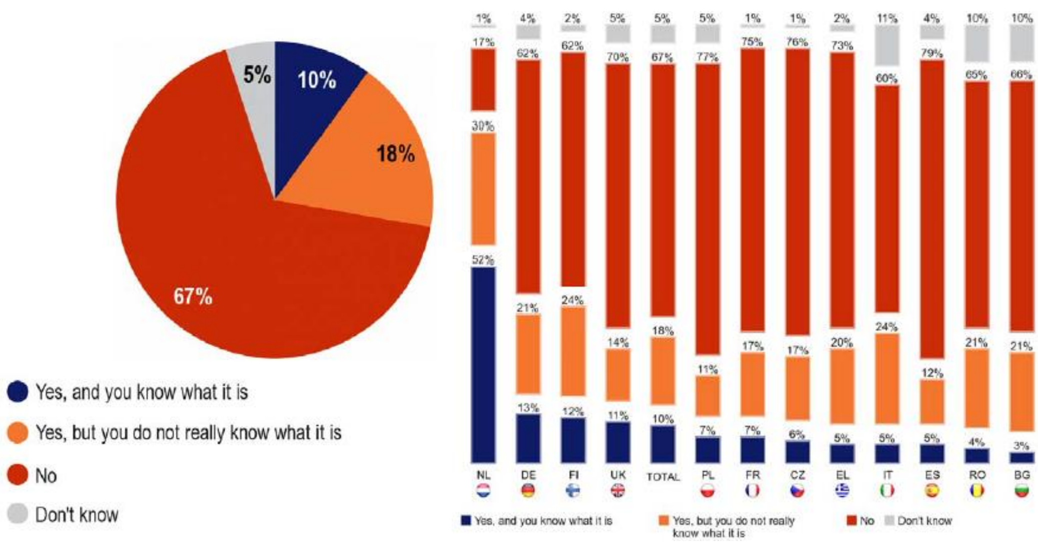

Figure 22- Level of knowledge on CCS in European countries **[31]**

Two thirds of survey participants have not heard of CCS. This result reflects the scarce diffusion and communication of what is the CCS in the major of EU states. The Netherlands is the only region where over half of respondents knew what CCS was, followed by Germany, Finland and UK. In fact, the figures above are in accordance with the CCS projects development or proposal made in last years.

Among the ones that know what CCS and its benefit in terms of GHGs emissions reduction, the level of concerning for risk of leakages is high, as reported in Figure 22.

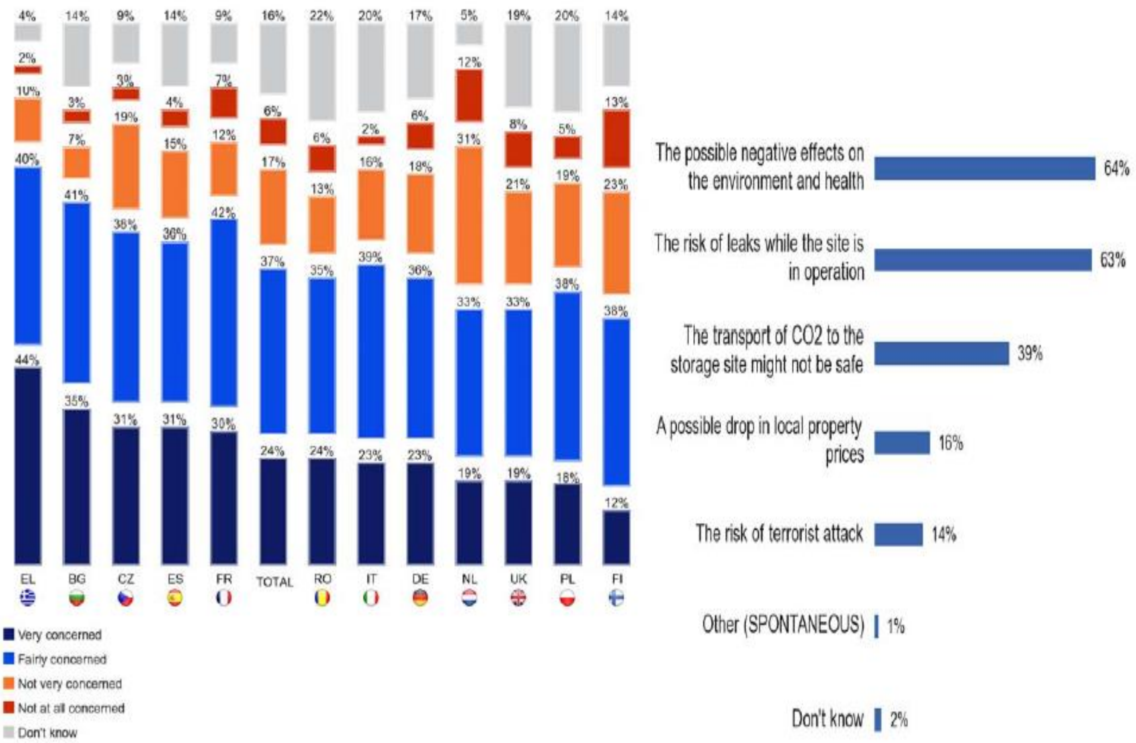

Figure 23- Comparison of level of concerning about CCS in EU states (left) and causes of concern (right) **[31]**

In Europe, the highest level of public acceptance in CCS is in Norway. In fact, in the country, the public perception of CCS is generally positive with a recognition of the value of CCS as climate abatement technology. Nevertheless, the perceived risk of CO_2 leakages, the political and NGOs support made a big difference in securing the public acceptance for CCS [32]. Outside Europe, there is a high public engagement in CCS in Australia, where the 45% of people interviewed on the subject affirmed that the advantageous of CCS as carbon reduction option outweigh eventual risks [33].

Quite different is the scenario in Japan, India and South-Africa. In fact, in both South-Africa and India, the general public is unaware of CCS. In India, the main barrier is the investment cost, which is more prohibitive for the country. For the diffusion and development of CCS, the international cooperation is a must for India [34]. In South Africa, the World Bank and the Department of Energy (DoE) are undertaking a study to increase the public acceptance by including communities and politics in public events on climate change [35]. In Japan, the public perception of global warming is high and the level of knowledge on what is CCS is about 25%. However, the public perception on use of CCS as global warming action is around 10% [36].

In light of all this information, the basic issue is the low level of awareness and knowledge of the matter.

The same concern is found towards the Waste-to-Energy plants, as well. The average idea for municipal waste incinerators is that WtE plants are more pollutant than landfills, even though the existing plants have demonstrated that there are no health risks for people and a better environmental impact. The movement “Not in My Back Yard” was born to contrast the projects of incinerators in towns for the hypothetical risk of bad odours and release of harmful substances. In fact, as explained in Article 55 of EU Directive 2010/75, applications for new permits for waste incineration plants shall be available to public to comment on the applications before competent authority takes a decision [5].

Ad-hoc campaigns and communications on the matter has helped in some countries to reduce the social opposition, as in Austria, where the social acceptance towards the WtE was helped by constructing facilities that are work of art in the city. Examples are the Spittelau plant in Vienna, the Copenhagen facility with the ski lane in Denmark, and the Brescia plant, which has a harmonious integration with the surrounding environment.

2.2.3 Technology Development

The integrated system WtE-CCU or CCS success and global spread is dependent on technological development of each step.

Regarding only the post-combustion carbon capture process, the existing plants are all based on amine-process, which is the readiest technology to meet a CO_2 removal efficiency at least of 90%. f The application, for example, of an adsorption TSA process after a Waste-to-Energy would reduce i) the energy consumption for the CO_2 capture, ii) save the fee necessary to use the licensed solvents thanks to affinity of commercial activated carbons towards the CO_2, iii) more energy would be available for local energy integration, but the mentioned capture technology is not ready for industrial/commercial scale, with a TRL of 6 estimated on pilot plant tests [37]. Among the amine-based technologies there are differences correlated mainly to the solvent and process design. The main companies that have developed commercial CO_2

capture system are Shell, MHI, Fluor, Aker solutions, BASF Linde et al. [37] . In fact, MHI has 12 commercial plants, which captures CO_2 from natural gas, oil fired boiler and coal-fired power plants as Petra Nova. Shell has 2 commercial plants, one being Boundary Dam facility, where Shell is testing an innovative capture system that removes both CO_2 and SO_2. Fluor has licensed 27 units so far in the industrial sector from dilute sources and in addition, the Econamine FG Plus is the only solvent used to capture CO_2 from gas turbine exhausts. Both Aker solutions and BASF-Linde tested their own solvents only on pilot plants [37]. Aker solutions recently presented also modular solutions ("Just Catch") for a CO_2 capacity range of 40,000÷100,000 tons per annum.

Once the CO_2 is captured, most of existing projects on reducing GHGs emissions are based on storage (CCS) and EOR (which can be regarded as a type of utilizations, i.e. CCU) more than other utilizations (CCU).

The advantage of Carbon Storage is that the final destination. i.e. the storage site, of the CO_2 is well known as well as how to develop the process. Contrarily, the carbon utilisation has theoretically a lot of potential applications but just few are industrially ready. However, the main advantages of Carbon Capture and Utilization is the higher public acceptance (for detail refer to section 2.2.2) and the easier economics. The European Union has developed a ranking of CO_2 utilization applications and their Technological Readiness Level (TRL), reported in Table 6 [38].

Table 6- TRL status of CCU technologies and CO_2 applications **[38]**

CCU category	Application	TRL
CO_2 to fuels	Methanol and methane production	4-8
	Formic acid production	5
	Algae cultivation	3-5
	Helioculture	3
	Photocatalytic reduction of CO_2 (metallic and not)	3
	Nanomaterial catalysts	2-3
Enhanced commodity production	Enhanced geothermal system with CO_2	4

CCU category	Application	TRL
	Supercritical CO_2 power cycles	3
	Urea yield boosting	9
	Methanol yield boosting (conventional)	9
CO_2 mineralisation	Mineral carbonation	3-7
	Sodium bicarbonate	6
	CO_2 concrete curing	5
	Bauxite residue carbonation	8
CO_2 as chemicals feedstock	Polymer processing	3-5
Others	Food and beverage	9
	Horticulture	9

Along with TRL, it is also worth to focus on scale of utilisation; EOR is the largest in terms of utilisation considering MTPA of CO_2 captured from Industry and Power plants. The other technologies mentioned in Table 6 are much smaller scale

The increasing attention towards the GHGs emissions has driven the development of new technological roads for the CCU: the development of catalysts that makes the conversion processes more efficient, the use of renewable energy (as wind or solar) to support the energy demand of CO_2 transformation.

The CCU technologies would allow to use the CO_2 as an alternative to fossil-fuel-origin feedstocks or by converting it in product as chemicals or fuels [39]. The problem is that the purification of flue gas from CO_2 is more expensive than petroleum or natural gas uses as sources of raw material as well as the transformation of CO_2 in chemicals is energy-expensive, and in fact the TRL of these kinds of processes is below 6 (industrial pilot scale).

The formic acid production, urea yield boosting, and production of building materials are the CCU markets with the major funding and incentives [39]. The maximum TRL of 9 is reached with re-utilization of CO_2 in food and beverage industry and in horticulture. For both applications, it is not necessary to reach a high purity grade of CO_2 and it makes the process more accessible. For examples, in The Netherlands and in Japan, the CO_2 captured is sent to farming fields to enhance crops growth, as described in task 3, while in USA, it is sold to a food industry.

2.2.4 Challenging financing

The investment for a CCS or CCU plant is one of major barriers for their development. The integration of a post combustion carbon capture system is estimated to cost, at full commercial scale, on average 65 euro/ton of CO_2 abated for a natural gas combined cycle and 60 euro/ton of CO_2 abated for a coal fired plant [40] The quoted figures, calculated as Cost of Avoided CO_2 emissions (CAC) as per IEAGHG standard methodology, do not take into account transportation and, in case of geological storage and EOR, injection costs and any benefits from the recovered oil. These have to be considered too. In addition, especially for CCS, absence of legal framework for site handling, variety of process operating conditions, transport and storage infrastructure, and the uncertainties related to storage sites leakages can make the investment more risky and challenging, [41].

The transportation from the plant to site could be by pipeline or by shipping, and the choice mainly depends on the distances to be covered. For the pipeline, the different combinations are listed in Table 7, that reports the cost of CO_2 transport depending on the pipeline capacity (Mt CO_2/yr) and location (onshore or offshore). As expected, the lowest cost of transport refers to the onshore pipelines having higher capacity

Table 7. Cost of pipeline **[41]**

Type of pipeline	**Capacity, Mt CO_2/y**	**Cost range, \$/t CO_2/250 km**
Onshore	3	4-11
	10	2-4
	30	1.3-2
Offshore	3	7-15
	10	3-5
	30	2-2.5

The cheaper storage location is an onshore depleted oil and gas field thanks to the re-use of existing wells. The typical cost ranges for several possible storage site types are in Table 8, where the storage cost includes the initial exploration, site assessment, site preparation (as drilling). The offshore costs are on average higher because of wells, pumps and platforms necessary to handle the site itself [42].

Table 8. Cost of storage site **[41]**

Type of storage site	**Cost range, $/t CO_2**
Depleted Oil-Gas field onshore- reusing wells onshore	1.6-11
Depleted Oil-Gas field- no reusing wells onshore	1.6-15.7
Saline formation onshore	3-18
Depleted Oil-gas field offshore- reusing wells offshore	3-14
Depleted Oil-Gas field offshore- no reusing wells offshore	4.7-22
Saline formation offshore	9-31

The economic return of capture, transport and storage of CO_2 is represented by the emissions savings and relevant local political incentives and support, the removal of CO_2 emitted during the process that cannot be reduced otherwise. Differently, the CO_2 capture, transportation and re-utilisation of CO_2 for the Enhanced Oil Recovery has as additional economic benefit related to the sale of the recovered oil.

When (and if) technologies on carbon dioxide utilisation will be more widely commercially available, these may have a double revenue source: the earning from the gas sale and the benefit associated with any carbon pricing mechanism. However, although the CCU processes are technically feasible, the lack of a stable business case make the CCU projects risky, because the CO_2 market is not stable and long-lasting enough.

As discussed in section 2.2.3, the CCU projects on-going are focused on farming re-use. In the Netherlands, to reduce the project costs the less expensive options are the utilisation of an existing pipeline or use of CO_2 in a factory nearby the WtE. The Duiven Waste to Energy owned by AVR has expanded the plant with a PCC and Utilisation sub-system. The carbon capture is planned to be operative in August 2019 and the aim is to feed the horticultures plants with the CO_2, once it is liquefied. The transportation would be done by truck.

The Amsterdam WtE is planning to transport the CO_2 removed from the flue gas to Rotterdam Harbour and to the farming industries by an existing pipeline OCAP that collects CO_2 from several industries for horticoltural use (OCAP stands for Organic Carbon-dioxide for Assimilation of Plants).

For the Dutch government, the re-use of CO_2 in horticulture is an incentive to plan subsidies, as discussed for the Amsterdam CCU project. This is an example of how, to sustain the investment, it is necessary a joined work of industry, government, academia and NGOs: academia to improve the existing technologies, as the CO_2 capture, to reduce the costs; the industry to invest in CCS thanks to the funding of government and the NGOs to support the projects and promote them [42].

For some projects in the USA, the public acceptance of CO_2 storage and CO_2 use as EOR has been a catalyst. For example, the EOR project Petra Nova in Texas costs approx. 1 billion of US dollars, but a part was financed by US department of energy (DOE) after that local community supported the project and pursued for funding. The state of Texas reduced the tax on oil if it is produced by EOR, and the barrels of recovered oil repay the entire project.

Table 9 compares for some major CCS/CCU project the main barriers and enablers [43]. To make a clearer distinction about their fate, the projects that have been cancelled/shelved are marked in red.

Table 9- Enablers and risks for some CCS/CCU projects, data taken from [43]

Project	Enabler	Risks/Barriers
Boundary Dam	Federal GHG emissions regulation, government support, revenue stream, public acceptance	Cost
Don Valley	EU support, shared infrastructure	EU support, Government support, shared infrastructure
Illinois Industrial Carbon Capture and Storage	Government support	Permitting

Project	Enabler	Risks/Barriers
Peterhead	Government support	Government support
Petra Nova (formerly NRG Energy Parish CCS Project)	Government support, revenue stream	Oil price
ROAD	Government support, EU support, private support	European Union Alowwance (EUA) price
Texas Clean Energy	Government support, revenue stream, private support, community support	Oil price

The oil price is an example of how some factors can be identified at same time as enabler and barriers of a project. Beyond costs and pursuing of funding, for CCU project involving the EOR, the big risk is the oil price, because it influences the profits or the economic losses of the process.

Similarly, the government economic support can have a heavy role in developing or not a CCS or CCU project. For example, the Peterhead project in UK was a post-combustion CCS plant retrofitted with a combined cycle power station and co-founded by UK government to go through FEED phase. After a while, the government retired its support to the project, which is stopped at the moment. Nevertheless, it has to be remarked that government support may not be limited to co-funding. As outlined in a recent report prepared for the Department for Business, Energy and Industrial Strategy (BEIS) [44], mainly focuses on ICC (Industrial Carbon Capture) initiatives, but also applicable to Carbon Capture in the Energy sector, government may support these initiatives in several manners, ranging from co-funding through definitions of schemes where the costs are passed to other parties as well. Possible business models include direct support to cover additional operating costs and guarantee some certain returns to the additional investment cost, tax credits, CCS tradeable certificates, creation of low carbon markets models etc.

In Europe only a third of oil and gas fields capacity is useable for CO_2 storage, and most of these are located far outside the shores, thus increasing a lot of the potential transportation costs [42]. One example of WtE-CCS plant in Europe, i.e. the Fortum Oslo project foresees firstly, a CO_2 transportation from the WtE by a 7 km long pipeline to the Oslo Harbor and, then, the shipping to the storage site, which is far from the plant.

2.3 Opportunities

The project opportunities of adding a CCS/CCU to a WtE plant listed below and will be one by one discussed, underlying, were possible, the difference between the storage or the utilisation of the CO_2:

- Sales of CO_2 emission permits
- Market of waste materials
- Effective energy integration

Beyond the listed opportunities that will be discussed in detail, referring to the review reported in para. 2.1.1, it is worth to remark that an the integrated system WtE-CCU/S allows to reduce the harmful emissions to the atmosphere. In fact, to avoid the solvent degradation, the acid gases, dust and NOx are removed from the flue gas at concentrations below the emission limits imposed by most stringent legislation before entering the capture unit.

2.3.1 Sales of CO_2 emission permits

In EU, the main tool to enhance the reduction of CO_2 emissions is the Emission Trading System (ETS), which is a European Commission initiative started in 2005 to. The participation at the ETS is mandatory for all EU members plus Island, Liechtenstein and Norway.

Every year, the European Commission makes an amount of CO_2 emission allowances available for each country. The basic idea is that at the end of the year, the total emissions of CO_2 or equivalent N2O and PFCs have to be covered by owned emission credits. Each credit allows to emit 1 ton of CO_2 or equivalent, and each ton not covered by allowances has to be paid.

The first phase (2005-2007) was a “learning by doing”. The industrial sectors interested by emission trading were the power generators and the energy-intensive industries with a power output larger than 20 MW. Almost all allowances available were distributed among the participants for free, and the penalty to pay for extra emissions was 40 euro per tonne.

The second phase (2008-2012) included the aviation sector and exclusively the flight in the European area were affected by ETS. The penalty for non-compliance was 100 euro per tonne of extra emission. In this phase, the union registry and the international auction system were included.

Considering that the amount of free allowances diminishes each year and at same time the permitted CO_2 emission become more constricting, the probability that a generic state produces more CO_2 than those allowed is high.

In this scenario, there are three options:

1) Invest on technological improvement of existing power industries or construct new and more efficient facilities
2) Pay the penalty for each tonne not allowed
3) Buy extra emission credits

The third option opened to emission trading market. In fact, the greener countries, which are the regions where the CO_2 emitted is lower than those allowed, can sell the surplus of credits to deficit states. The trading is made by public auction and all credits exchanged are reported on the Union Registry.

At the moment, the EU ETS is at phase 3 (2013-2020) that have implemented the following modifications:

1) Harmonised rules for auctioning
2) Linear reduction of 1.74% of available allowances each year
3) Inclusion of more "energy based" industries
4) Rewards and funding for innovative and renewable energy technologies

The name of industries that are not able to cover all their CO_2 emissions with allowances are public according to the idea of "named and shamed". In 2015, an average of 26 million of credits was exchanged by auction every day, for an average yearly total of 6.6 billion of credits. It means about 49 billion of euro paid from countries and earned by EU.

For the phase 4 (2021-2030), the EU ETS will reduce by 2.2% each year the allowances and will continue to help the industries to move towards the low-carbon technologies. The aim is to reach a CO_2 emission reduction of 21% in 2020 and of 43% in 2030, compared with emissions in 2005.

The Waste-to-Energy sector is presently not included in the ETS program. In Europe, the drivers for Waste-to-Energy plants are indirect. The optimization of a WtE and an efficient heat recovery generate a reduction of energy produced by fossil sources, which contributes in lowering CO_2 emissions from power industry and less allowances are needed from such facilities.

In the same scenario, the integration of a Waste-to-Energy plant with post-combustion carbon capture with storage or utilisation technology will increase the economical (and environmental) benefits. When a CO_2 Utilization plant is built downstream a WtE, the CO_2 trade creates an economic revenue for the WtE owner, while the CO_2 storage becomes advantageous if incentives in storing CO_2 are available for plants' owners.

Outside Europe, other cap and trade systems have been established and, differently from Europe, they include the Municipal Waste facilities. In South-Africa, the Carbon Tax Act was issued in May 2019 [45]. It aims to reduce carbon emission of 34% in 2020 and 42% in 2025. Among the sectors included in the regulations there are the municipal waste facilities. In the same way, the California Cap and Trade program and the Japanese ETS include in their emissions allowances sectors the incinerators [46] [47].

For WtE-PCC plant located in cited locations, a typical CO_2 capture rate of CO_2 of at least 90% would have the further benefit of accounting for negative CO_2 emissions, as, on average, approximatively the 50% of carbon in a WtE is from biogenic source (as discussed in Task 3).

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However, since some greenhouse gas emissions are very difficult and/or expensive to avoid (such as methane emissions from livestock and heavy transport emissions), CCS could add additional (and perhaps larger) value by enabling the facilities which burn or process large amounts of biogenic source fuel (on its own or in combination with fossil fuel) to have net negative greenhouse gas emissions. Negative emissions could offset more expensive and impractical emissions in other sectors. This would reduce overall costs of achieving a given emission reduction target (e.g. carbon neutrality) and therefore the political viability of setting such targets and the accompanying policy measures (assuming that costs would remain a major driver in public policy).

2.3.2 Market for waste materials

WtE plants themselves can exploit some opportunities of recycling waste materials, with consequent benefits from both the economic and the environmental stand points

An example is the AVR waste to energy plant in Rozenburg (Rotterdam), which has only the 3-4% of solid by-products that cannot be re-used. The bottom ashes of waste boiler are composed by minerals, metals and unusable materials. The minerals, which represent the 90% of ashes, are re-used to produce paving stones. The amount of residues in a year can produce paving stones equivalent to a surface of 400 football fields. Moreover, the waste water, which is usually rich of raw materials, is thermally treated in furnaces to recover heat and materials. The materials mostly recovered from waste water are rare metals, like molybdenum that are sold for catalysts in chemicals production [48].

In broader terms, the re-use of solid by-products is an example of waste management and integration within the society. In fact, generally, the bottom ashes from the boiler and the fly ash from ESP can be usually used as secondary building material after a weathering treatment to stabilize the material by changing the mineralogical characteristics [49].

The Twence Waste to energy plant in Twente (NL) washes the bottom ashes for sale to construction industries.

The integration of a WtE plant with a Carbon Capture can drive additional opportunities in terms of marketing the waste materials from the integrated facility.

One opportunity is related to how the integration with CO_2 capture can drive the application of flue gas purification technology that are able to generate valuable by-products. This concept is applied in Boundary Dam, a 824 MW coal-fired plant in Canada, but the same principle could be adopted in a WtE facilities [50]. The Boundary Dam plant is composed by four operating stations, and the Unit 3 is integrated with a CCS system. The CO_2 is captured, compressed and transported through 66 km long pipeline to an enhanced oil recovery site. The CO_2 that is not sent to the EOR site, is transported to an injection and storage site 2km far from the plant.

The SO_2 removed from the flue gas is used as feedstock for a 50 ton per day sulphuric acid plant production locally placed. It is done with a Shell Cansolv licensed technology with uses two licensed solvents to remove simultaneously CO_2 and SO_2, replacing any other DeSOx processes. The economic revenue and an environmental benefit are from the re-use of SO_2 and storage of CO_2 and from the lower emissions in the atmosphere [51] [52].

The application of Carbon Capture to a WtE also generates additional waste water, mainly due to the condensation of water contained in the flue gas in the direct contact cooling upfront the CO_2 absorber, similarly to fossil fuel power plants. This additional waste water stream can be effectively treated in the Waste Water Treatment plant for re-utilization. This option, aiming at minimizing the overall water usage in plants with CCS, was studied by Wood on behalf of IEA GHG, as reported in IEAGHG Report 2010/05 [53].

Another opportunity regarding materials re-utilization is related to the CO_2 itself. For instance, two plant are here described as examples: Petra-Nova EOR facility and the Twence Waste to energy plant in The Netherlands. Petra-Nova is coal plant operating since 30 years and in 2013 the Gas Generation Unit was built. This unit was integrated with a post-combustion carbon capture system, which captures 1.6 Mtpa of CO_2 when it operates at 100%. The CO_2 is transported by 130 km long pipeline to recoverable reserve in Texas. The EOR generates a cash flow, which reduced the footprint of GHGs emissions [54].

In Twence, the CO_2 is captured in a solvent absorption-regeneration cycle and is used to produce sodium bicarbonate with soda. The soda in aqueous solution and the CO_2 are sent in two reactors to produce sodium bicarbonate, which is stored in tanks. The latter feeds the flue gas cleaning scrubbing reactor and purifies the flue gas from the WtE of acid gases as HCl, HF and Sox. The slurry is collected in the bottom of scrubber, while the flue gas and the CO_2 freed from the sodium bicarbonate is sent to CO_2 capture plant.

The scheme of the WtE-CCU process is in Figure 24.

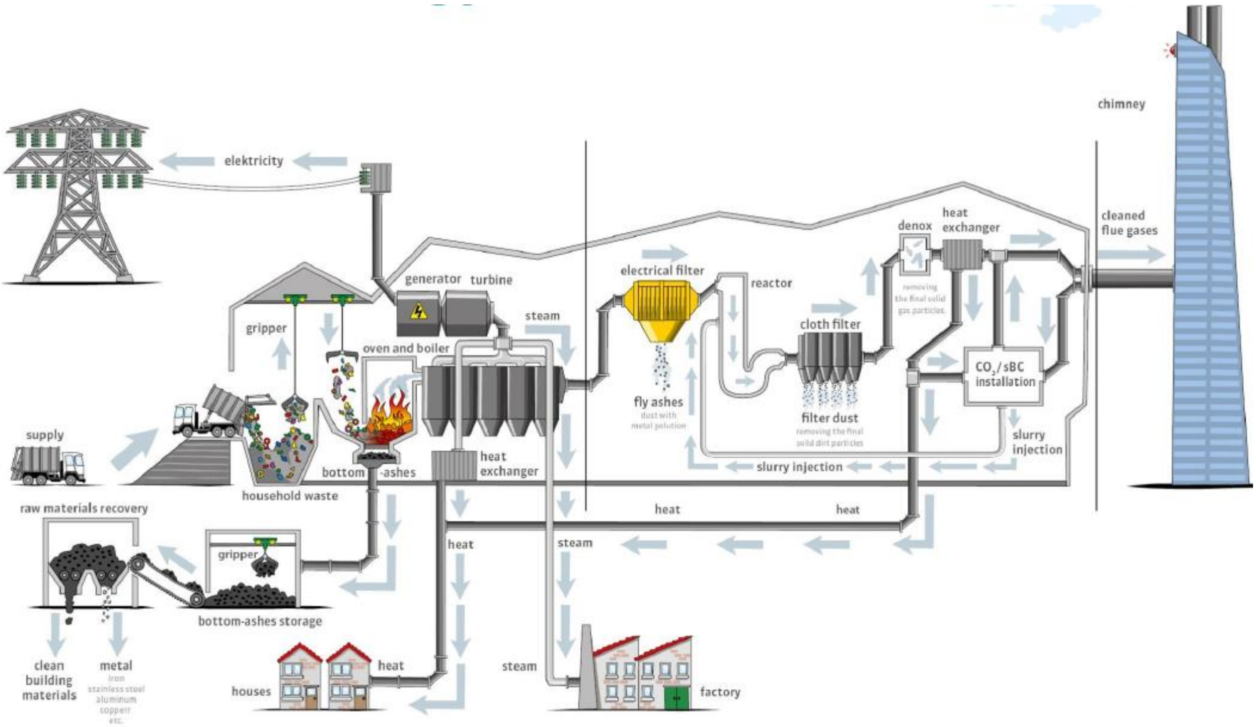

Figure 24- Twence WtE-CCU process scheme [55]

2.3.3 *Effective energy integration*

The energy integration of a storage or utilisation plant of CO_2 within the waste to energy entails the consume of almost 60% of steam produced in the boiler, accordingly with estimations made on existing WtE plants and reported in Task 3. The main source of energy consumption, as discussed in Task 3, is the CO_2 capture system because of the heat duty necessary for solvent regeneration. The remaining steam is used as source of energy for local neighbourhood, as it is highly spread in the northern Europe where the waste energy is transformed in district heating.

As already discussed in Task 3, for a WtE with district heating integrated with PCC, the energy conflict between the District heating and the CO_2 capture can be smoothed by exploiting additional heat recovery option in the plant. In fact, the heat in the Direct Contact Cooler released from flue gas before the carbon absorber is available at low temperature and is considered a low-grade heat. However, this amount of heat can be upgraded by means of? a heat pump to a and adequate level for supplying the District Heating, transferring the energy from the water loop of the Direct Contact Cooler to the District Heating. The theoretical energy balance associated with this heat integration is reported in section 2.2 of task 3.

This approach could be successfully adopted also in retrofitting to Carbon Capture a WtE plant originally designed to produce electricity only, provided that possible users of relatively low temperature heat are found in the neighbourhood.

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TABLE OF CONTENT

1. Introduction

The objective of the present study is to understand both the issues and the opportunity pertaining the application of CCS/CCU to WtE plants. This analysis is regarded as an essential first step before proceeding to a more detailed evaluation.

During the execution of the main study tasks, Wood has reviewed various technical, environmental economic, regulatory and social aspects related to this WtE-CCU/CCS combination.
As many of the studied features may have a different impact on WtE/CCS integration depending on the geographical location and local context, the purpose of this conclusive task is to elaborate a tool to evaluate potentiality of WtE-CCU/CCS integration at a country level, based on criteria depending on the geographical location. The developed tool is then applied to the ten countries selected for this study. However, it is remarked that the tool intended as universal, i.e. it could be potentially applied to any country worldwide.

2. WtE-CCU/CCS Market potential

The study has been focused on the integration of a post-combustion CO_2 capture facility with a Waste-to-Energy plant. The majority of the technical and economical parameters discussed throughout the study were analyzed from a retrofit perspective, i.e. assuming to integrate a new CO_2 capture unit with an existing WtE. Based in the outcome of the previous tasks a number of criteria were identified for an evaluation of the potential in a certain local context (i.e. at country level)

The proposed methodology intends to rank each country against the selected criteria, assigning a weight to each criterion (relative to 100%). The logic for assigning weighting to the different criteria is detailed in the next sections, being the given weight a function of its relative importance in the evaluation process. For each criterion, a score is given to each country, ranging from 1 to 10.
The score of each criterion is then multiplied by its relative weight to obtain the "weighed score" of the criterion. The final score of each technology is the sum of all the weighed scores of the different criteria.
The maximum theoretical score that a country could achieve is 10. The final score of each country will be a quantitative indication of the expected country potential in relation to the application of CCS/CCU to WtE, especially in relative terms with respect to the other countries.

The adopted criteria are described in para. 2.1. The application of the methodology to the ten countries is then discussed in section 2.2.

2.1 Criteria Overview

Based on the review carried out in the previous tasks, the following criteria are identified to have a significant influence in determining the potential of integrating the CCU/CCS in an existing WtE, depending on the geographical location. The weight given to each criterion is also reported

1. Opportunity for CCS/CCU (weight = 20%);
2. Possible integration with District Heating (weight = 10%);
3. Local CO_2 emission factors for power and heat generation (weight = 10%);
4. CCU/CCS regulation and Carbon pricing mechanisms for WtE (weight = 20%);
5. Diffusion of WtE (weight = 15%);
6. Social acceptance of WtE and CCU/CCS (weight = 10%);
7. WtE Regulation: NOx and SOx emission limits (weight = 10%);
8. Average WtE plant size (weight = 10%);

The criteria are further described below. Also, for each criterion, some possible options are listed and preliminarily ranked to outline the rationale behind the scoring.

2.1.1 Opportunity for CCS/CCU

The criteria "Opportunity for CCS/CCU" relates to the possible destination of the captured CO_2. The availability of storage sites for the captured CO_2 or the presence of CO_2 off-takers in the same geographical area as the plant would make the initiative easier from the techno-economic point of view and increase its potential. For this criterion, three options are considered:

- None: once captured, the CO_2 would have no opportunity to be stored/used nearby the WtE plant.
- Storage site nearby: the CO_2 can be transported and stored in a geological site, better if this is a depleted oil/gas field (where existing wells can be re-used)
- Market for CCU: there is a potential for utilizing the CO_2 as EOR, production of chemicals, crops cultivation

Table 1- Options and relative mark for Opportunity for CCU and CCS Criteria

Criteria	option 1	option 2	option 3
Opportunity for CCU/CCS	None	Storage site nearby (CCS)	Market for CCU
Ranking	1	6-7	8-10

In a ranking scale among them, the lowest value of "1" was assigned to the first option, because it makes not economically advantageous the investment associated with a post-combustion capture system requires. Increasingly higher scores are given to the second and third option, respectively, for the revenues of these opportunities. As discussed in the study, , the re-use of captured CO_2 in a different productive process is a further incentive in investing in a capture system, at least in the short term. However, in the medium/long term, when established, the CCU markets will saturate quickly, especially if Carbon Capture from energy and industrial sectors becomes a diffused practice.

The scoring takes into account also the availability of CO_2 pipeline infrastructures in the countries, which is anyway strictly linked to the presence of geological sites and CO_2 off-takers/users.

2.1.2 Integration with District Heating

The Waste-to-Energy plants can be three different outputs: electrical generation (EL), heat generation (HP) and combined electrical and power generation (CHP). Among the options including the supply of heat, the integration with District Heating (DH) is one of the most common. When a CO_2 capture plant is constructed downstream a WtE, as deeply discussed in the report, on one hand, a significant fraction of the produced heat is used to regenerate the absorbing solvent, but, on the other hand, the integration with a capture unit requires further flue gas cooling (typically in a Direct Contact Cooler) that represents an additional heat source. It is of primary importance to understand whether and how this heat can be effectively utilized, assuming that the heat potentially recoverable from the DCC cannot be elevated to the temperature level required by the solvent regeneration in the CO_2 Capture Unit, with reasonably acceptable energy efficiency solutions, If the WtE plant is originally integrated with a DH system, DCC heat can be elevated at the temperature levels typically required by modern DH systems via a heat pump. If the plant is not integrated with DH, there is no easily available heat sink, as the condensate pre-heating is already typically done against flue gas in the standard design of the thermal cycle.

For evaluation of this criterion each country is analyzed against its trend to utilize WtE for DH, which is also related to the local meteorological conditions .

Table 2- Options and relative mark for Integration with District Heating

Criteria	option 1	option 2
Integration with DH	High	Low
Ranking	10	1

2.1.3 Local CO_2 emission factors

The CO_2 emission factor represents the grams of CO_2 emitted per kWh of electricity produced. The energy generated by WtE facilities replaces the generation form other sources, including fossil fuels. As the waste has a significant biogenic fraction (typically 50%), an avoidance of net CO_2 emissions is associated with the use of WtE. The higher the local CO_2 emission factors for electricity and heat generation in a country, the higher is the CO_2 avoidance benefit associated with WtE, especially if integrated with CCSU. ,

For this criterion, three main options are considered for the scoring: high value of emission factor, medium and low values, as in Table 3. Accordingly with emission savings opportunity, the lowest and highest marks were assigned to low and high emission factors, respectively. However, it has to be noticed that, even in national energy markets that are already decarbonized, the electricity production from WtE coupled with CCS, can be effectively utilized to stabilize the electrical system, thanks to the programmability features that is lacking in several renewable sources. For this reason, the countries with the lowest CO_2 emission factors are not penalized excessively penalized in the scoring, as shown in Table 3.

Table 3- Options and relative mark for CO_2 emission factor Criteria

Criteria	option 1	option 2	option 3
CO_2 emissions factor	High	Medium	Low
Ranking	9-10	7-8	5-6

2.1.4 CCU/CCS regulation and Carbon pricing mechanisms for WtE

The Carbon pricing is a terminology that covers all Carbon Tax and Cap&Trade programs relative to GHGs emissions,. Nowadays, several Cap&Trade programs are active, and they cover the same types of process emissions from power generation, civil aviation and waste incineration.

Cap&Trade programs (also known as ETS; Emission Trading Systems) entail the distribution at participating states of "emission credits", each covering1 ton of CO_2 emitted. All tons of CO_2 emitted and not covered by the emission credits must be paid.

If an ETS is in place and is extended to WtE facilities, this is doubtless a driver for the investments in combined system WtE- CO_2 capture,
Four main options are considered for this criterion and are listed in Table 4. The total absence of an Emission Trading System is valuated with lowest mark, while the highest value is assigned to an ETS program that includes both the Waste-to-Energy sectors and incentives for Negative Emission Technologies (NET) . In the middle, there are the Cap and Trade systems that cover the WtE but not the NETs, and the programs, which do not include neither of them.

Table 4- Options and relative mark for CCU/CCS regulation: Carbon pricing for WtE

Criteria	option 1	option 2	option 3	option 4
CCU/CCS Regulation: Carbon pricing for WtE	No	Yes	Yes (incl. WtE)	Yes (incl. negative CO_2, WtE)
Ranking	1-3	4-6	7-8	9-10

2.1.5 WtE diffusion

The Waste-to-Energy diffusion has been selected as a criterion for the WtE-CCU/CCS market potential because the higher the diffusion of WtE plants, the higher is the potential of the local market. For this criterion, as shown in Table 5, two options were identified: a low diffusion and a high diffusion.

Table 5- Options and relative mark for WtE diffusion

Criteria	option 1	option 2
WtE diffusion	Low	High
Ranking	1-5	6-10

2.1.6 WtE and CCU/CCS social acceptance

The social acceptance of WtE and, mainly, of CCS can be at same time a barrier or an incentive for relative projects. In fact, public movements as "Not in My Back Yard" and the negative advertisement of CCS due to risk of CO_2 leakages has influenced the diffusion of WtE-CCS technology worldwide. For this criterion, two main options were considered, i.e. "High" and "Low" as shown in Table 6. However, as previously discussed in this report, , ad-hoc campaign have helped in some countries to reduce the social opposition to this kind of initiatives, so there is a number of intermediate scores that can be considered.

Table 6- Options and relative mark for WtE and CCU/CCS social acceptance

Criteria	option 1	option 2
WtE and CCS social acceptance	Low	High
Ranking	1-5	6-10

2.1.7 WtE Regulation: NOx and SOx emission limits

The Flue Gas Treatment sequence of equipment downstream the boiler of WtE is designed in a way to respect the pollutants emission limits from waste incinerators. When the post-combustion CO_2 capture system is integrated with the existing WtE, a retrofitting of FGT maybe is required. In fact, the solvent used to purify the flue gas of CO_2 has generally a very low tolerance towards dust particles, SOx, NOx, HCl and HF, and lower pollutants concentrations are necessary at the back-end of FGT system. As discussed in the report, the removal efficiency of dust particles is typically high enough to suit the capture system too. On the contrary, the SOx and NOx technologies maybe subject to some modifications.
The extent of these upgrades, in a retrofit perspective, is expected to be lower if the initial SOx and NOX emissions limits for the WtE are stricter.. For this criterion, two options were considered, i.e. “High” and “Low” emissions limits as shown in Table 7.

Table 7- Options and relative mark for WtE Regulation: NOx and SOx emission limits

Criteria	option 1	option 2
WtE Regulation: NOx/SOx Emission limits	High	Low
Ranking	1	10

2.1.8 Plant capacity

The plant capacity stands by the average amount (tons/year/plant) of waste burned by the WtE plants operating in each country. From a financial standpoint, considering that the implementation of a post-combustion CO_2 capture system represents a significant investment, larger-scale WtE plants are favoured by the economies of scale. Although the specific carbon capture cost is expected to be lower for larger plants, the higher absolute investment cost may represent a barrier. In such a case, a possible solution could be to design the CO_2 capture unit only for a slip-stream of flue gas existing the boiler.

As in Table 8, for this criterion, two macro options were considered: high plant capacity and low plant capacity. It was not defined a reference benchmark, though the scale from low to high is a relative comparing ranking among the ten countries.

Table 8- Options and relative mark for plant capacity

Criteria	option 1	option 2
Plant Capacity	High	Low
Ranking	10	1

2.2 Application of criteria to the geographical contest

2.2.1 Opportunity for CCS/CCU

Table 9 indicates the ranking among the ten countries for the criterion related to the opportunities for CCS and CCU.. This criterion has a weight of 20%, due its relative importance in the evaluation of scenarios including carbon capture.

Table 9- Relative country-based ranking of opportunity for CCU and CCS

Criteria	weight %	Italy	The NL	UK	Norway	South Africa	Germany	Australia	Japan	India	USA
Opportunity for CCU/CCS	20%	6	9	8	8	6	8	7	7.5	6	9

In the Netherlands and in Japan, the main opportunity for the CO_2 is the re-use, mainly for agricultural fields in both countries, as projected in AVR plants of Rozenburg and Duiven and at Saga City plant. However, in The Netherlands, the development of storage resources and CO_2 pipeline infrastructures [1] is more advanced than in Japan, therefore a higher score ("9") is given to The Netherlands with respect to japan ("7.5").

In Germany, there is a remarkable social opposition to CO_2 storage has been registered, anyhow there are a few projects for post-combustion capture foreseeing, a re-utilization of the CO_2 in chemical plants as feedstock. For these reasons, a value of "7.5" was assigned to Germany.

On the contrary, Norway and Australia are focused on under-sea storage thanks to the availability of many storage sites nearby their shores. USA, where the undeground sites are mainly on-shore, is scored higher ("9") than Norway ("8") and Australia ("7") because the large availability of storage sites is not exploited only for CO_2 storage but for Enhanced Oil Recovery too, as done in PetraNova project in Texas, and there is a considerably larger number of existing CO_2 pipeline, some of which are hundreds of kilometers long [1].

At the moment, in South-Africa and India there are no operating WtE and many projects to build WtE plants and change the waste management are ongoing. However, this is not taken into account for ranking against Opportunities for CCU/CCS, being part of other criteria . In fact, in both cited counties, the score is sufficient ("6") due to the ongoing development projects and pilot plants on re-use of captured CO_2 from fossil sources as feedstock for ammonia synthesis or to produce fuel-ethanol .

Italy, scored with a "6", is characterized by the scarce incentives in CCS, but also by the development of the few projects on reuse of CO_2 as feedstock.

The UK has shown a hybrid behavior, going towards both CCS (with six large scale projects trials and several storage sites identified) and CCU.

2.2.2 Integration with DH

The integration with DH was analyzed by evaluating, firstly, the percentage of WtE plant combining heat generation with electricity production (i.e. Combined Heat and Power, CHP) with respect to the overall number of existing WtE facilities in the ten countries. The percentages are shown in Table 10.

Table 10- Percentage of existing WtE plant with CHP output- Source LEAP database

	Italy	The NL	UK	Norway	South Africa	Germany	Australia	Japan	India	USA
# WtE	39	13	42	17	1	81	0	1141	8	78
% CHP	24	38	14	100	0	51	0	n.a.	0	21

In Norway, all WtE plants are clearly integrated with local communities from the energetic standpoint. In Germany and Netherlands, the DH is still well spread, while the percentage is obviously lower for southern European countries, as Italy, where the DH is partially integrated and only in the north-Italy. In UK and in USA, the WtE are mainly used for electrical energy production. In Japan, there are CHP-WtE facilities, but they are less widespread than in Europe, and it is unknown a specific number of CHP plants. For South-Africa, India and Australia, the scenario is different. In Australia, there are no operating WtE plants and, among the on-going projects, just one (Pilbara-New Energy) is designed for a combined output. In South-Africa, of course, the district heating is not present at all, while in India there are projects to improve the country development with more WtEs-CHP facilities.
Based on these considerations, Table 11 shows the ranking among the ten countries.

Table 11- Relative country-based ranking for the integration with DH

Criteria	weight %	Italy	The NL	UK	Norway	South Africa	Germany	Australia	Japan	India	USA
Integration with DH	10%	7	8	5	10	1	9	3	4	2	6

2.2.3 *CO_2 emissions factors*

The ranking evaluation of ten countries for the CO2 emission factor (i.e. average of CO2 emissions for unit of energy generated) is based on emission factor published by IEA for electricity production including CHP systems in 2017 and 2018 [2] [3], listed in Table 12.

Table 12- CO_2 emission factor for national contexts in 2017 and 2018 published by IEA **[2] [3]** n.a.= not available

	Electricity (incl. CHP) g CO_2-eq/kWh	
Country	**2017**	**2018**
Australia	742.9	714.3
Germany	416.7	404.8
India	718.1	n.a.
Italy	325.7	301.9
Japan	522.3	485.0
Norway	8.3	8.3
Netherlands	437.0	420.3
South Africa	899.6	n.a.
UK	245.3	228.1
USA	421.1	409.4

Table 13 reports the ranking of each country and a comparison among them is done. The weight of this criteria on the overall potential estimation is set at 10%.

Table 13- Relative country-based ranking of **CO_2** emission factor

Criteria	weight %	Italy	The NL	UK	Norway	South Africa	Germany	Australia	Japan	India	USA
CO2 emissions factor	10%	7	8	6	5	10	8	9	8	9	8

According with data in Table 9, Norway and South-Africa have the lowest and highest CO_2 emission factor, respectively, and they represent the two extreme cases of this evaluation. As already mentioned, the countries with the lowest CO_2 emission factors are not excessively penalized in the scoring as in those national contexts the electricity production from WtE coupled with CCS, thanks to the its programmability, can be effectively utilized to stabilize the electrical system.

2.2.4 CCS regulation: Carbon pricing for WtE

The evaluation of carbon pricing regulation for the ten countries is in Table 14. The weight of this criteria on the overall potential estimation is set at 20%.

Table 14- Relative country-based ranking of CCU/CCS Regulations: Carbon pricing for WtE

Criteria	weight %	Italy	The NL	UK	Norway	South Africa	Germany	Australia	Japan	India	USA
CCU/CCS Regulation: Carbon pricing for WtE	20%	6	6	6	6	9	6	6	9	1	9

In India, there is no kind of Emission Trading System and the lowest value was assigned, accordingly with Table 3. South-Africa, Japan and USA have different Cap and Trade systems all of them applicable to ing Waste Incinerators as well, , but not considering the Negative Emission Technologies. It is worthy specify that the American Cap and Trade program is actually active only in California State. The EU member states participate to, the EU-ETS, a similar one being followed by Australia as well. The EU-ETS is about the GHGs emissions from energy-intensive industry, civil aviation and power generation and does not presently include the WtE sector, at least for Municipal Solid Waste and Hazardous Waste (whilst plants fed with other special wastes can be included). For this reason, the EU-ETS, is scored with "6".

2.2.5 WtE diffusion

The ranking comparison among the ten countries for the WtE diffusion is based on the figures reported in Table 15. The main indicative parameter is the amount of waste burned in WtE plant in the country in one year.

Table 15- Evaluation of WtE diffusion

	Italy	The NL	UK	Norway	South Africa	Germany	Australia	Japan	India	USA
# WtE	39	13	42	17	1	81	0*	1141	8	78
Amount of Waste burned in WtE, #/Mtons/y	6.1	7.0	10.9	1.5	0	22.6	0**	54.6	2.2	27.8

(*) There is actually no operating plants in Australia, but 5 important project are under development to be in operation within 3-4 years for a total capacity of 1.8 MTPA.
(**) In the next 5-7 years several WtE plants can be put in operation for an overall potential treatment capacity of 33000 t/d (9.6 MTPA).

Based on results in Table 15, the ranking among the countries is reported in Table 16. The weight of this criteria on the overall potential estimation is set at 15%.

Table 16- Relative country-based ranking of WtE diffusion

Criteria	weight %	Italy	The NL	UK	Norway	South Africa	Germany	Australia	Japan	India	USA
WtE diffusion	15%	6	6	7	4	1	8	3	10	5	8

South-Africa has one WtE plant (bio-methane production) in operation since 2019 nearby Cape Town and it is, in fact, the country with less WtE diffusion due to the high rate of landfilling in the country. In Australia, there are no operating WtE plants but 5 important projects are under development, so they are considered but with a lower weight in the scoring . In India, nowadays just 8 WtE plants burn municipal waste, while the 80% of waste is sent to landfilling. In USA, in spite of the large amount of waste produced, the landfilling and the recycling are the two main waste management solutions, which explains the low WtE diffusion in the nation. Even though the landfilling is banned in Germany, the WtE diffusion is not at very high levels, because the waste is mainly recycled and/or composted.
The score for Italy is a weighted average of the very different conditions occurring in the three main geographical areas. In fact, 26 of 39 WtE plants are located in the North of the country, while the remaining are placed in the Center Italy (7 of 39) and in the South (6 of 39). In this way, in terms of WtE diffusion, the North of Italy should be marked with a value higher than 6, while the South and the Center with a value of about 3.

2.2.6 WtE and CCU/CCS social acceptance

Table 17 summarizes the percentage of social acceptance towards CCS in ten countries. Data in Table 17 are results of social surveys, previously discussed in the report.

Table 17- Public acceptance of CCS **[4], [5], [6], [7], [8], [9]**

	Italy	The NL	UK	Norway	South Africa	Germany	Australia	Japan	India	USA
Public Acceptance, %	18%	43%	29%	54%	Very Low	24%	45%	10%	Very Low	13%

Based on results in Table 17, the ranking among the countries is reported in Table 18. The weight of this criteria on the overall potential estimation is set at 10%.

Table 18- Relative country-based ranking for social acceptance.

Criteria	weight %	Italy	The NL	UK	Norway	South Africa	Germany	Australia	Japan	India	USA
WtE and CCUS social acceptance	10%	3.5	8	5.5	10	1	4.5	8.5	2	1	3

It is interesting to note that the results in Table 9 regarding the countries with major opportunity for CCS/CCU show a good match with the figures reported in Table 18. In fact, Norway, UK, The Netherlands and Australia, which are investing a lot in CCS are the countries with the higher social awareness and acceptance towards the geological injection of CO_2. The 13% of public acceptance in USA indicates the exploitation of storage site widely spread outside American shores mainly for EOR, because of social fear of CO_2 leakages from CO_2 sites. The Netherlands is the European country with the highest public knowledge of what is the carbon capture and storage (52%) which explains the high acceptance of such technology.
Italy and Germany are in similar scenario, where people are not well informed and, for those who are aware of global warming issue and benefits associated with CCS, the risks associated with the technology overcome its utility. This negative trend becomes more relevant in Japan, India and South-Africa, which have the lower acceptance levels.

2.2.7 WtE Regulation: NOx and SOx emission limits

The emission limits of NOx and SOx for the ten countries are shown in Table 19, which is an extrapolation of Table 1 in Task 2, where detailed emission limits are reported.

Table 19- SOx and NOx emission limits. USA values are referred to California State

	Italy	The NL	UK	Norway	South Africa	Germany	Australia	Japan	India	USA
SOx, mg/Nm^3	50	40	50	50	50	50	50	60	200	30
Nox, mg/Nm^3	200	180	200	200	200	150	200	217	400	150

<u>Note</u>: the emissions limits refer to dry flue gas @ 11% O_2 in EU, whilst in the other countries the reference O_2 content is 10%.

The ranking among the countries is reported in Table 20. The weight of this criteria on the overall potential estimation is set at 10%.

Table 20- Relative country-based ranking for WtE regulations: SOx and NOx emission limits.

Criteria	weight %	Italy	The NL	UK	Norway	South Africa	Germany	Australia	Japan	India	USA
WtE Regulation: NOx/SOx Emission limits	10%	7	8	7	7	7	8	7	6	1	9

The maximum ranking was not assigned because none of the countries has emission limits very close to CO_2 capture systems tolerance. California in USA is the country with lower emission limits, while India is the worst in this scenario. It means that an eventual integration of a PCC system would require an intensive upgrade of the FGT. The remaining states stay on average values that can easily allow the fulfilment of the CO_2 capture systems requirement through slight modfications.

It is anyway important to remark that in EU countries, the permitting process for WtE plants requires the emission limits to be in line with the Best Available Technologies (BAT), the new version having been approved very recently. This could generate further synergies with the possible integration with carbo capture, however, the single countries may adapt their emission limits in different manner and extent.

2.2.8 Plant capacity

The plant capacity, expressed as ton/day burned, was estimated as average of all operating WtE plants in each country. Data were furnished by LEAP. For Australia, where no operating plants are present, but there are important projects under development, the value in Table 21 is a projection into the near future and its weight is smoothed in scoring the country against this criterion.

Table 21- Average plant capacity for each country

	Italy	The NL	UK	Norway	South Africa	Germany	Australia	Japan	India	USA
Plant Capacity, t/d	524.7	2001.2	1012.6	304.6	550	1036.9	1096.1	237.4	1087	1217.1

The country-based ranking is in Table 22. The weight of this criteria on the overall potential estimation is set at 5%.

Table 22- Relative country-based ranking for Plant Capacity

Criteria	weight	Italy	The NL	UK	Norway	South Africa	Germany	Australia	Japan	India	USA
Plant Size	5%	4	10	5	2	3	6	5	1	7	9

2.2.9 Overall results

Table 23 summarizes all criteria so discussed in the previous paragraphs.

Table 23- Overall WtE-CCU/CCS country-based potential

Criteria	weight %	Italy	The NL	UK	Norway	South Africa	Germany	Australia	Japan	India	USA
Opportunity for CCU/CCS	20%	6	9	8	8	6	8	7	7.5	6	9
Integration with DH	10%	7	8	5	10	1	9	3	4	2	6
CO2 emissions factor	10%	7	8	6	5	10	8	9	8	9	8
CCUS Regulation: Carbon pricing for WtE	20%	6	6	6	6	9	6	6	9	1	9
WtE diffusion	15%	6	6	7	4	1	8	3	10	5	8
WtE and CCUS social acceptance	10%	3.5	8	5.5	10	1	4.5	8.5	2	1	3
WtE Regulation: NOx/SOx Emission limits	10%	7	8	7	7	7	8	7	6	1	9
Plant Size	5%	4	10	5	2	3	6	5	1	7	9

The overall potential estimated for each country is shown in Table 24. It is calculated as weighted sum of all the scores for each considered criterion.

Table 24- WtE-CCU/CCS market potential

Italy	The NL	UK	Norway	South Africa	Germany	Australia	Japan	India	USA
5.95	7.60	6.45	6.70	5.20	7.25	6.05	6.85	3.80	7.85

The countries with the highest potential in WtE-CCU/CCS are USA, The Netherlands and Germany, thanks to generally high ranking for most of the adopted evaluation criteria. A very good potential is also expected for Japan, Norway and UK.
The lowest potential is envisaged for India, mainly penalized by the lack of environmental policies regulating CO_2 capture and the relatively low WtE diffusion.

3. Other than location factors

During the various analyses carried out in the course of this study work, it has come out that other than location aspects may also affect the feasibility of integrating a WtE plant with a carbon capture unit. Two main factors have been identified and are briefly described in the following paragraphs:

- Incineration technologies
- Greenfield vs retrofit, as the study has been executed from a retrofit perspective, i.e. assuming to integrate a new CO_2 capture unit with an existing WtE, but it is worth to explore the differences that could arise in case an entirely greenfield integrated facility.

3.1 WtE technologies

The two most diffused incineration technologies are the grate combustion and the fluidized bed (mainly circulating) combustion.
This short para not meant to outline a comprehensive comparison between fluidized bed and grate technologies, but just to highlight which main features of one technology type with respect to the other may be beneficial for the combination of WtE with Carbon Capture.

The most significant difference between the two main technologies is represented by the environmental performance: The fluidized bed technology, especially in the Circulating (CFB) version, is typically characterized by lower NOx and SOx emission from the boiler itself, making easier to achieve the stringent limitations required by CO_2 capture solvents to prevent degradation. In further details:

- Thermal NOx formation is limited by the lower combustion temperature, the staged combustion approach and the possibility to effectively recycle the flue gas in the combustion zone.
- Fluidized bed boilers offer the possibility to abate SOx and HCl in-furnace through the injection of sorbents in the fluidized bed

Other differences could have minor impact in the perspective of integrating the WtE with a carbon capture. For example, with respect to energy efficiency, leading to lower CO_2 emissions per kWh produced, the Fluidized bed are characterized by higher efficiency of the steam cycle (due to higher boiler efficiency and the possibility to achieve higher steam parameters), however, this advantage may be off-set by the higher electrical consumption of the waste pretreatment section, which is typically simpler with the grate, depending on the waste characteristics.

3.2 Greenfield versus retrofit

The comparison between greenfield and retrofit scenarios in the integration of a WtE facility with a carbon capture unit shows some advantages for the greenfield, mainly related to the possibility to face more easily the following challenges:

1. Resolve spatial integration, as the greenfield scenario offer the possibility for an optimized lay-out with fewer constraints
2. Optimized and ad-hoc design for flue gas cleaning
3. Elaborate strategies of energy integration with the boundaries, as the heat demand of the capture unit, which typically competes with heat integration with the boundaries (e.. District heating) is known since the beginning of the plant design phase
4. Steam Turbine design and operating philosophy in relation to the significant steam extraction to support the heat demand by the CO_2 capture.

All the above-mentioned factors would lead to a lower investment cost of the greenfield solution if compared with the overall cost (WtE plus carbon capture in different steps) of the retrofit solution. On the other hand, the large capital expenditure in a single investment step would represent a stronger barrier in the greenfield case than the retrofit scenario.

4. References

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Pure Offices, Cheltenham Office Park, Hatherley Lane,
Cheltenham, Glos. GL51 6SH, UK

Tel: +44 1242 802911

mail@ieaghg.org
www.ieaghg.org