15th International Conference on Greenhouse Gas Control Technologies, GHGT-15

15th 18th March 2021 Abu Dhabi, UAE

Application of CCUS to the WtE sector.

Vincenzo Tota[a], Manuele Gatti[b,c], Federico Viganò[b,c] , Monica Garcia[d] *

[a]*Wood, Via S.Caboto, 15, 20094 Corsico (MI), Italy*
[b]*LEAP Scarl, Via N. Bixio 27/C, 29121 Piacenza (Pc), Italy*
[c]*Department of Energy, Politecnico di Milano, Via R. Lambruschini 4/A, 20156 Milano (Mi), Italy*
[d]*IEAGHG, Pure Offices, Hatherley Lane, Cheltenham GL51 6SH, United Kingdom*

Abstract

Waste management is a very scattered and complex system made up by different plants and facilities that treat / recover / valorize/ dispose different types of waste, e.g. Municipal Solid Waste (MSW) or Special Waste, based on the policies adopted in each country and the available technologies. 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. Therefore, an initial investigation on the potential integration of Waste to Energy (WtE) facilities with Carbon Capture Utilization and Storage (CCUS) should be focused on MSW and plants devoted to its treatment. Only in existing European WtE plants, there is a potential capture of 60-70 millions of tonnes of CO_2 per year, and current large- scale projects prove the technical viability of carbon capture technologies in WtE environments.

The paper summarizes the outcome of a study addressing all the opportunities and challenges related to the application of CCUS to the WtE sector. This study is executed by Wood, with the support of LEAP, and commissioned by IEAGHG . The main objective of the work is to carry out an initial overview of this CCS/CCU opportunity before proceeding to more detailed evaluations. The study is based on both literature information available in the public domain and results of surveys with WtE plants owners.

Before evaluating a possible Carbon Capture application to the WtE sector, the study reviews the current status and diffusion of the WtE business and the plants distribution worldwide, focusing on ten representative countries: South Africa, USA, India, Japan, Germany, Italy, The Netherlands, UK, Norway, Australia. The selection considers several parameters: the urbanization level, the branching of the electricity/heat network, the presence of large scale WtE plants, the potential for CCS/CCU applied to WtE plants and the availability of potential destinations for the captured CO_2. The main challenges in this kind of plants, focusing particularly on reliability, are also identified. The link between WtE and CO_2 emissions is then investigated: firstly, the trends and the tools adopted by WtE plants in reducing CO_2 emissions are analyzed; secondly, a lifecycle assessment approach is described and applied to the local contexts of the ten selected countries. The objective is to estimate the CO_2 savings achievable through energy/materials recovery in a WtE plant, potentially leading to negative lifecycle emissions.

The study then focuses on the possible integration of Carbon Capture within WtE facilities, collecting the information relevant to ongoing projects/initiatives aiming at this integration and identifying its potential challenges and opportunities in the design and the operation of the plants, based on the available literature. The most interesting aspects identified by this analysis are the energy integration and how the introduction of CO_2 capture alters the energy balance of the WtE plant. There are also risks (related for example to financing, public acceptance, need for technology development) and opportunities (e.g. negative CO_2 emissions, effective energy integration) that may arise from a WtE-CCUS integration.

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* Vincenzo Tota. Tel.: +39-02-44862270, *E-mail address:* vincenzo.tota@woodplc.com

Considering that the presence of a regulatory framework on WtE and CCS can be an important driver for this kind of applications, a literature research is also carried out to provide an overview of the regulations applicable to the WtE and CCS sectors in the ten selected countries.

Based on the various aspects analyzed throughout the course of the study, a tool is developed to estimate the potential of the CCUS/WtE integration, focusing on the local context of the ten selected counties. This presentation will include the methodology developed in this study, which aims to be a guide for future CCS projects in WtE plants.

Keywords: Waste to Energy CCU CCS Negative emissions Lifeycle Integration market potential

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1. Introduction

The paper summarizes the outcome of a study addressing all the opportunities and challenges related to the application of CCU/CCS to the WtE sector. This study is executed by Wood, with the support of LEAP, and commissioned by IEAGHG . The main objective of the work is to carry out an initial overview of this CCS/CCU opportunity before proceeding to more detailed evaluations. The study is based on both literature information available in the public domain and results of surveys with WtE plants owners.

The study reviews the current status and diffusion of the WtE business, the plants distribution worldwide and other important aspects related to the integration of CCU/CCS with WtE facilties, focusing on ten representative countries: South Africa, USA, India, Japan, Germany, Italy, The Netherlands, UK, Norway, Australia. The selection considers several parameters: the urbanization level, the branching of the electricity/heat network, the presence of large scale WtE plants, the potential for CCS/CCU applied to WtE plants and the availability of potential destinations for the captured CO_2.

Nomenclature

CCS	Carbon capture & Storage
CCU	Carbon capture & Utilisation
CFB	Circulating Fluidized Bed
CHP	Combined Heat & Power
DCC	Direct Contact Cooler
DH	District Heating
GGH	Gas-Gas Heater
GHG	Green-House Gases
LCA	Life Cycle Assessment
LHV	Low Heating Value
MSW	Municipal Solid Waste
RDF	Refuse Derived Fuel
SCR	Selective Catalytic Removal
ST	Steam Turbine
WtE	Waste to Energy

2. Worldwide overview of the WtE business

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 2016. Table 1 summarizes the situation [1].

Table 2 reports the most significant figures of MSW management for the ten countries selected for this study.

Table 1. Number of MSW WtE plants worldwide [L1].

Region	**No. of plants**
Africa	1
America	92
Asia	1,503
Europe	492
Oceania	1
Total	**2,090**

Table 2. Relevant figures of MSW management for the selected countries [various sources, see notes]. In Italics, results of our evaluations.

	MSW management*			**WtE plants**		
Country	**Production, Mt/y**	**To landfill**	**To WtE**	**No.**	**MSW treated, Mt/y**	**Average capacity, t/y**
Australia	13.8[1]	54%[1]	0%[1]	1[2]	-	400,000[2]
Germany	52[3]	1%[4]	31%[4]	81[5]	22.6[5]	305,000[5]
India	*50-70*[**]	81%[6]	19%[6]	8[6]	n.a.	n.a.
Italy	29.6[7]	23%[4]	19%[4]	39[4]	6.1[4]	*153,000*
Japan	44[8]	n.a.	80%[8]	1,141[9]	*35.2*[8]	*58,181*[9]
Norway	2.42[10]	n.a.	53%[4]	17[4]	1.53[4]	*85,000*
South Africa[11]	49	n.a.	-	0	-	-
The Netherlands	9[12]	1%[4]	44%[4]	13[4]	7[4]	*540,000*
UK	27[13]	17%[4]	37%[4]	42[4]	10.9[4]	*260,000*
USA	262.4[14]	53%[14]	*10.6%*	77[15]	27.8[15]	*357,200*

** MSW final destinations other than WtE and landfill may be recycling and composting.*

*** Rough estimation based only on urban population [various sources].*

[1] 2017 data []. [2] [3]. [3] 2017 data [4]. [4] 2017 data [5]. [5] 2011 data [6]. [6] 2012 data [7]. [7] 2017 data [8]. [8] 2014 data [9]. [9] 2015 data [10]. [10] 2017 data [11]. [11] Refuse classified as "General waste", 2011 data [12]. [12] 2016 data [13]. [13] 2017 data [14]. [14] 2017 data [15]. [15] 2015 data [16].

Some countries, like The Netherlands, have just a few plants with very large capacities, whereas other countries have larger number of plants but of limited size. The situation of Japan is very peculiar: WtE has been historically applied at town level, leading to a huge number of very small plants. Several countries still heavily rely on landfills, hence featuring a significant potential for the growth of the WtE sector. On the other hand, some countries like Germany and the Netherlands have WtE overcapacity, and sometimes they import waste from abroad to feed their plants. Energy recovery is applied in almost all the modern WtE plants. Only a few very small and rather old Japanese plants do not have energy recovery. It is mostly in the form of electricity (i.e., power) production, sometimes Combined Heat and Power (CHP) production and, in a limited number of cases, only heat (e.g., some plants in Norway).

The type and the amount of energy recovered have significant impact on the overall environmental performances of WtE plants, as explained below, in relation to the Life Cycle Assessment (LCA) approach.

3. Link between WtE and CO_2 emissions

3.1. Trends and tools in WtE to reduce CO_2 emissions

By recovering the energy content of waste, WtE plants can contribute to fulfilling the energy needs of a local community, in the form of electricity and/or heat, and to 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.

The main trends and tools adopted by WtE facilities to increase their energy efficiency and contribute to reduce CO_2 emissions, are identified as follows:

- Reduction of the combustion air excess in combination with flue gas recirculation.
- Increase of the steam cycle parameters (e.g. maximum temperature and pressure).

The adoption of Flue Gas Recirculation (FGR) allows a reduction in the amount of secondary air in the range of 10-15% [17], leading to a reduction of the thermal energy loss at the stack and the parasitic load of the plant associated with air and flue gas induced draft blowers. with no penalties on CO and thermal NOx emissions. The control of thermal NOx is achieved by means of both the decrease of the fresh nitrogen supplied to the combustion (less combustion air) and the effect of FGR in maintaining reasonably low combustion temperatures.

Regarding the steam cycle parameters, the heat transfer 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 [18]. The steam cycle conditions at 40 bar and 400°C are typically an economic compromise between power generation efficiency and corrosion rates [19] [20] [21]. This is in line with the average steam cycle operating conditions resulting from the data relevant to Waste-to-Energy plants in Europe, as shown in Figure 1.

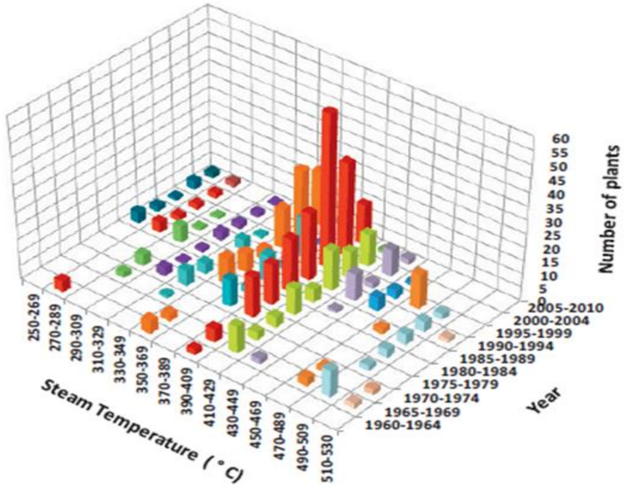


Fig. 1. Steam cycle parameters in WtE plants in Europe in the last 50 years [20].

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 a sensible efficiency improvement, increasing steam conditions above 70 bar / 430°C, 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. Pressure and temperature around 500°C and 90 bars can also be reached by placing a final superheating stage in the boiler [22], protected with SiC monolithic concrete, requiring lower maintenance effort than the Inconel® 625 cladding. 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 [22].

A different method is to adopt an intermediate reheating of the steam coming out of the high-pressure turbine. An operating WtE plant with the steam reheater is the AEB facility in Amsterdam, with SuperHeated Steam at 130 bar /440°C and ReHeated Steam at 330°C. The furnace walls are protected with Inconel cladding to cope with higher wall temperatures driven by higher pressure/temperature on the steam evaporation side.

Another possibility to effectively enhance steam temperature and pressure considering corrosion risk constrains is available with the use of CFB 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.

The different measures previously described are compared in terms of theoretically achievable final electrical efficiency and boiler efficiency, assuming an average Low Heat Value (LHV) for the waste of 10.4 MJ/Kg [19] [21]. Results are shown in Table 3, including the effect of each tool on CO_2 emissions, expressed as tons of CO_2 saved per kWh produced (assuming 0.7 ton of fossil CO_2 generated per1 ton of MSW burned [21]) with respect to the benchmark case.

Examples of Waste-to-Energy plants that have undergone the described improvements are available in the literature. [23] [24] [25] [26] [27].

Table 3. Comparison between tools to improve the Waste-to-Energy plant efficiency and impacts on CO2 emissions

	Primary Air/fuel ratio (kg/kg)	Steam T, °C	Steam P, bar	Boiler Efficiency	Gross Electrical Efficiency	ΔkWh/t waste	Δt CO_2/MWh
Benchmark	1.9	400	40	86.5	26.4	/	/
Reduced Air Excess	1.39	400	40	87.7	26.6	5.55	0.007
High Steam Parameters	1.9	500	90	86.5	30.2	105.5	0.115
Steam Reheating	1.9	420	90	86.5	29.9	97.2	0.107

3.2. LCA of GHG emissions from WtE in the selected countries

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 2.

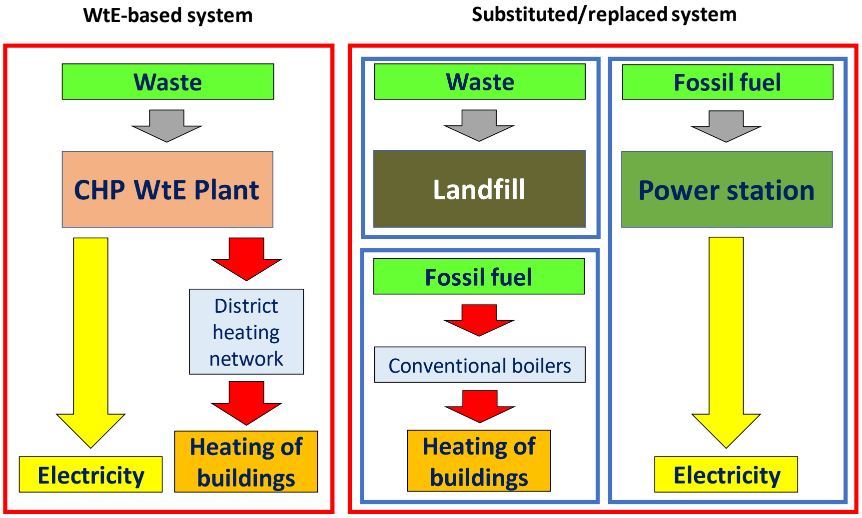


Fig. 2. Simple representation of the systems to be considered when applying LCA to a CHP WtE plant.

The rigorous LCA of a WtE plant requires a huge amount of very specific information. However, the result is mainly determined by just a few contributions:

- Direct emissions due to the discharge of flue gas to the atmosphere (+).
- Avoided emissions associated with the production of useful effects (-).
- Avoided emissions associated with the alternative management/treatment of the waste (i.e., landfilling) (-).
- Potential avoided emissions associated with the possible recovery of solid residues (-).

Such contributions may represent an additional environmental burden (when they are positive, +), as well as a reduction in the environmental pressure (when they are negative, -).

This simplified LCA is applied at country level, by considering specific figures of representative WtE plants and projecting them to the totality of WtE plants in the country.

Concerning the direct emissions due to the discharge of flue gas to the atmosphere, only the fossil CO_2 emissions must be considered. In fact, a significant share of the carbon contained in MSW is biogenic, being a constituent of biological or biological-derived materials (e.g., food waste, paper and cardboard, natural textiles). As a rule of thumb, biogenic energy content and biogenic carbon content of MSW are roughly 50% and 60% respectively. However, based on an indicative composition of the waste treated by WtE in each country, both carbon intensity and biogenic share are estimated. The effect of the possible waste pre-treatment, with the production of Refuse Derived Fuel (RDF) or Solid Recovered Fuel (SRF), is also considered by taking into account the associated CO_2 emissions on an average basis (in terms of electricity consumption, GHG gas emissions from the landfilling of residues, etc.).

The avoided emissions associated with the production of useful effects depend on two key factors: (i) the energy efficiency of WtE plants, which defines the amount of electricity/heat produced per ton of treated waste; (ii) the fuel mix for electricity/heat production in the specific country considered. The first factor is quantified based on the available data on electricity / heat production from waste in the specific country. The second factor is determined base on the carbon intensity of electricity in each country and considering the possible substitution of heat from natural gas combustion.

As replaced, alternative treatment of the waste, landfilling is considered, since WtE plants are normally fed with non-recyclable waste. Therefore, an estimation of the avoided GHG landfilling emissions is carried out considering the possible recovery of biogas to produce electricity (and, thus, the associated GHG emissions avoided) as well as the fugitive emissions. Moreover, the same characterization of the waste based on the biogenic share is considered to determine the biogas production and composition by means of a First Order Decay (FOD) method (Tier 2) [28].

The potential avoided emissions associated with the recovery of solid residues (metals - ferrous and non-ferrous - from bottom ash, and inert fraction to be used as, e.g., feedstock for cement or concrete production, road background, replacing gravel, sand, or clay) is considered for those countries where the recycling industry is more advanced.

Table 4 summarises the results of this simplified LCA applied to the selected countries.

Table 4. Results of the simplified LCA applied to the selected countries (negative values mean saved emissions).

	Current fossil $CO_{2,eq}$ emissions (t_{CO2} / t_W)					**Potential contribution from CCUS**
Country	**WtE Stack***	**Replaced electricity/heat**	**Avoided landfill**	**Bottom ash recovery**	**TOTAL**	
Germany	0.521	-0.299	-0.585	-0.060	-0.424	-1.017
India	0.663	-0.252	-1.600	-0.020	-1.209	-1.117
Italy	0.555	-0.292	-0.565	-0.060	-0.363	-1.041
Japan	0.497	-0.399	-0.600	-0.060	-0.562	-1.001
Norway	0.497	-0.478	-0.600	-0.060	-0.641	-1.001
The Netherlands	0.521	-0.304	-0.585	-0.060	-0.427	-1.018
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

* *Also including the indirect emissions to produce RDF / SRF when applied.*

Results show that the savings in terms of equivalent CO_2 emissions associated with the WtE practice already lay in the range of -0.35 ÷ -0.65 ton of $CO_{2,eq}$ per ton of waste, even without Carbon Capture (therefore, WtE is a beneficial practice for the environment). This is primarily due to the very relevant GHG emissions savings associated with the avoidance of MSW landfilling, which typically overcompensate the direct fossil emissions at the stack of WtE plants. The production of useful energy (electricity / heat) further improves the overall outcome.

Considering the integration of a CCU/CCS system with the WtE, roughly additional 1 ton of $CO_{2,eq}$ per ton of waste can potentially be saved. Actually, some evaluations shown in the following paragraphs highlight that such a potential can be caught only partially, because of the energy penalty associated with CO_2 capture.

4. Overview of ongoing WtE + CCU/CCS projects

A literature search to provide an updated overview of CCS/CCU integration with WtE plants has been carried out, focusing on:

- Listing and classifying ongoing CCS/CCU projects integrated with WtE facilities.
- Identifying the key technical information on current WtE plants (where available).
- Investigating the major challenges reported by the company managing the WtE plants.
- Ascertaining the CCS/CCU project status: pre-feasibility, feasibility, engineering, under construction, operating, on-hold, stopped, etc., as well as possible projections.
- Reviewing the CO_2 capture technology adopted / under evaluation / proposed.
- Quantifying the amount of CO_2 to be captured yearly, the CO_2 avoidance rate and the CO_2 capture plant size.
- Disclosing CO_2 planned destinations (storage, EOR, utilization) and transportation mean.
- Retrieving economics and financial information when available.
- Pinpointing the major challenges for CCS/CCU implementation.

Information has been taken from public reports and private interaction with the plant operators (via a questionnaire specifically defined). Table 5 summarises some representative outcomes of this survey. The most significant result regards the capture technology, which always relies on some amine-based scrubbing of flue gas.

Table 5. Results of the survey on the ongoing WtE+CCUS projects.

Country	**Plant**	**Total Waste Processed [t/y]**	**Total CO_2 Produced [kt/y]**	**CO_2 capture plant type**	**CO_2 capture plant status**	**Total CO_2 Captured [kt/y]**	**Removal Target**	**CCUS Technology**
Japan	Saga City-Japan	74,010	54 (220 t/day reported)	Chemical absorption based on specific amine solvent	Full-scale plant in operation since 2016	2.5 (10 t/day reported)	80-90%	Gaseous CO_2 stored in a 100 m3 buffer and delivered via pipeline to nearby algae cultivation
The Netherlands	HVC-Alkmaar Project 1	682,412	674	Amine technology	Ongoing	4	N.A.	Liquefied CO_2 for greenhouse horticulture
	HVC-Alkmaar Project 2	"	"	Amine technology	Feasibility study	75	60%	Liquefied CO_2 for greenhouse horticulture
The Netherlands	AEB Amsterdam	1,284,164	1,268	Amine technology (MEA based)	Feasibility study	450	90%	Feasibility study
The Netherlands	AVR-Duiven	360,635	400 (reported)	Amine technology (MEA based)	Plant Start-up	50-60	90%	Liquefied CO_2 for greenhouse horticulture
The Netherlands	AVR Rozenburg	N.A.	1,153	N.A.	N.A.	800	N.A.	FEED Study ongoing based on the operator's experience in Duiven
The Netherlands	Twence-Hengelo	608,000	600 (estimated)	Amine Absorption by Aker solutions	Full-scale project under engineering study	100	N.A.	Liquefied CO_2 for greenhouse OR to produce formic acid OR to be mineralized into construction materials
Norway	Fortum-Klemetsrud	375,000-400,000 (reported)	430-460 (reported)	Shell Cansolv engineered and built by Technip (reported)	Concept study completed. Pilot tests ongoing since Feb 2019. FEED ongoing	414	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)

5. Integration challenges

5.1. Energy integration and penalties

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, two theoretical study cases (Cases 1 and 2) have been developed, starting from Wood inhouse reference projects, to estimate of the impact of CO_2 capture system on energy production in a WtE plant, where 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.

Case 1 represents the retrofit to 90% CO_2 capture of a WtE plant based on grate-boiler, The performance of the plant retrofitted to CO_2 capture are summarized in Table 2. The estimate of the Heat Demand by the capture unit is based on an average regeneration duty of 3 GJ/t CO_2. The captured CO_2 is delivered in liquid state at 20 barg. This case is useful in showing how significant is the energy penalty of retrofitting a WtE to 90% CO_2 capture. Hence, it is crucial to find in other heat recovery sources the integrated WtE-CO_2 capture plant. One potential source is surely the residual energy of the flue gas discharged at the stack.

In Case 1, the flue gas is discharged to the atmosphere at a approx. 150°C. 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 not be a critical issue. The flue gas condenser should be placed in the final part of the gas path after the FGT where the flue gas is already largely purified from contaminants, as the condensation of these species like SO_x, NO_x and HCl could anyway enhance the corrosion risk of duct and heater coils. The adoption of such a system could be effective in WtE plants both with and without carbon capture.

In case of carbon capture integration, the flue gas cooling down to approx. 40°C is a necessary step due to the requirements of the utilized solvent. Although the heat recovered from a flue gas stream of 150°C cannot be effectively used in the CO_2 capture, that typically requires thermal energy at approx. 120-140°C for solvent regeneration, there are means to recover this heat to a useful effect. This is demonstrated in the study Case 2, developed by Wood starting from the configuration of Case 1 and assuming that the plant can be integrated with a District Heating (DH) network. In this case, after the boiler, the flue gas is purified in a treatment sequence composed by bag filter for dust removal, semi-wet reactor for soluble acid gases and SCR for deNOx, followed by flue gas condensation.

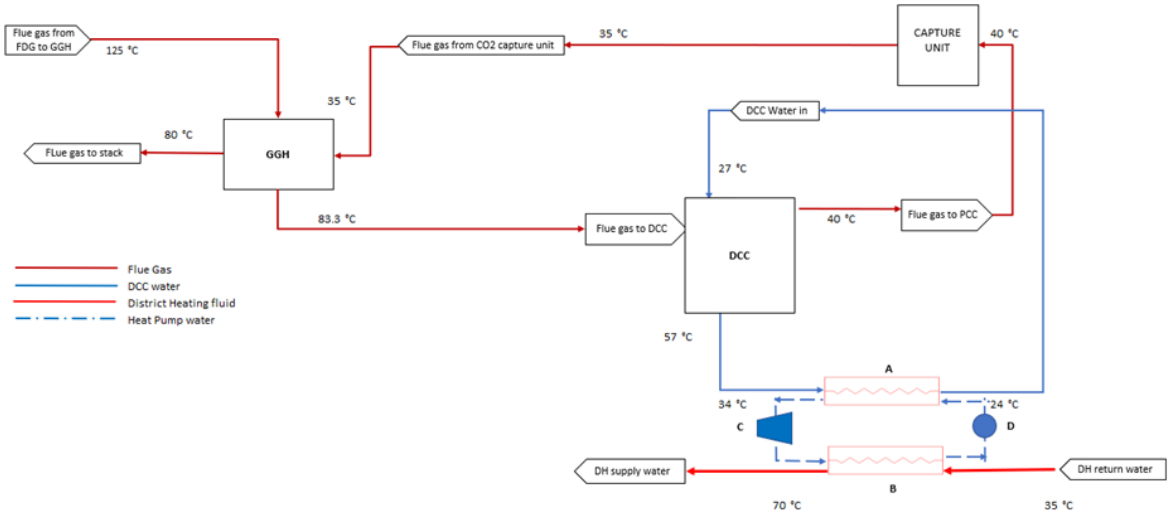


Fig. 3. Simple representation of the systems to be considered when applying LCA to a CHP WtE plant.

The effective energy recovery from the significant amount of low temperature heat available from flue gas condensation is achieved through a heat pump, designed to supply hot water at 70°C to a modern DH system with an assumed COP of 5.5. The full scheme of thermal integration of the flue gas cooling with the heat pump and district heating is shown in Figure 3, where the GGH is a Gas-Has Heater and the DCC is a Direct Contact Cooler. The intercooling of the CO_2 offers the possibility to recover additional heat to the DH system.

The resulting energy balance is shown in Table 2. Compared to Case 1, the electric energy penalty is further increased by 2.7 MWe, 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 MWth) to the local community, recovering waste heat.

Table 6. Energy balance of Study cases 1 and 2

	Case 1	Case 2
Net Electricity production [MWe]	20	20
Net Electrical Efficiency before retrofit	24.4%	24.4%
Steam Turbine Throughput @ 61 barg / 420°C [t/h]	102	102
Heat Demand CO_2 Capture [MWth]	26.4	26.4
Steam Turbine Extraction for CO_2 Capturet @ 6 barg [t/h]	45	45
Equivalent Electricity Production Penalty CO_2 Capture [MWe]	6.8	6.8
CO_2 Compression & Liquefaction Electricity Consumption [MWe]	3.2	3.2
Heat Pump Electricity Consumption [MWe]	_	2.7
Net Electricity production w/ CO_2 capture [MWe]	**10**	**7.3**
Heat Pump Duty to DH [MWth]	_	15.1
Overall DH Duty [MWth]		**17.8**

A similar solution has been proposed and is going to be implemented in cogeneration WtE plant at Klemestrud (Oslo), to resolve the energy conflict between Carbon Capture and DH when the plant is retrofitted to CO_2 capture.

5.2. . Other 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 include the flue gas pre-treatment and the steam turbine.

The flue gas leaving the boiler of a waste to energy plant is mainly composed by N_2, O_2, CO_2, H_2O and other species in minor amounts, such as particulate matter, SO_x in form of both SO_2 and SO_3, NO_x, HCl, HF, Hg and other heavy metals, whose presence depends on the type of waste. When a post-combustion CO_2 process is added to the existing WtE, the flue-gas pre-treatment is a critical step. In fact, flue gas components like SO_x and NO_x 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 [29]. 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, referred to dry flue gas at 6% O_2, are used in the study:

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

In existing WtE plants, the flue gas cleaning is designed to meet the environmental limits imposed by regulations, Although in many cases the WtE plants real emissions are sensibly lower than these limits , including the European plants, their emissions may be still too high for the integration with a PCC plant. The more demanding pre-treatment needs would anyway require some modifications/upgrades of the existing flue gas treatment system.

As far as NO_x 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% [29]. However, the low NO_x concentration of inlet of CO_2 absorber can be reached only with a more efficient technology, namely the SCR. WtE plants pursuing initiatives of integration with Carbon Capture, like Alkmaar (NL), Rotterdam (NL), Oslo Fortum (NW), are considering the installation of a SCR in the FGT. 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 SO_x 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.

Regarding the possible impacts onto the Steam Turbine, two main types of issues are briefly analyzed, both linked to the reduced steam throughput in the last stages of the steam turbine after the retrofit.

- Hardware modifications required to the steam turbine
- Further operational constraints

Even in case no modifications were necessary, the plant retrofit could impose some constraints in terms of operating flexibility. Making reference to the study Case 1 previously described, assuming that the minimum turndown allowable for the condensing section of the steam turbine is approx. 30% of the design throughput (in line with Wood experience for previous projects), with the CO_2 capture in operation, a steam extraction of approx. 45% of the total throughput could impose serious limitation in turning down the boiler load, 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 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, in the coal fired plant at Boundary Dam (Canada), the unit 3 retrofit to implement CCS required the installation of a new steam turbine [30]; similarly, at Klemestrud (Norway) the full replacement of the steam turbine is envisaged for lines K1-2 of the WtE plant to allow steam extraction for the solvent reboiler.

5.3. . Main opportunities

The retrofit to Carbon Capture may lead a WtE plant to achieve negative greenhouse emissions as, on average, approximatively the 60% of carbon in a WtE is from biogenic source, i.e. carbon neutral. Since some greenhouse gas emissions are very difficult and/or expensive to avoid (such as methane emissions from livestock and heavy transport emissions), Carbon Capture 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 gas emissions. Negative emissions in these plants 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).

WtE plants can typically exploit some opportunities of recycling waste materials, with consequent benefits from both the economic and the environmental standpoints. The integration of a WtE plant with a Carbon Capture may 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, but the same principle could be adopted in a WtE facilities [31]. The SO2 removal is based on the Shell Cansolv licensed technology which uses two licensed solvents to remove simultaneously CO_2 and SO_2, producing sulphuric acid as valuable by-product from the DeSOx process [32] [33].

Another opportunity is related to the use of the captured CO_2 itself. For the Dutch government, for instance, 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 [34].

However, it must be remarked that now the CO_2 utilization markets are limited in size, so they might be saturated very quickly by CCU initiatives.

6. Assessment of market potential

During the execution of the study, various technical, environmental economic, regulatory and social aspects related to the combination of WtE with CCU/CCS were reviewed.

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 the study. However, it is remarked that the tool intended as universal and could be potentially applied to any country worldwide once the relevant key information is collected

The majority of the technical and economical parameters discussed throughout the study, focused on the integration of a post-combustion CO_2 capture facility with a Waste-to-Energy plant, 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 various study tasks, a number of criteria were identified for the evaluation of the potential in a certain local context (i.e. at country level). The proposed methodology intends to rank each studied country against the selected criteria, assigning a weight to each criterion (relative to 100%). For each criterion, a score is given to the 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.

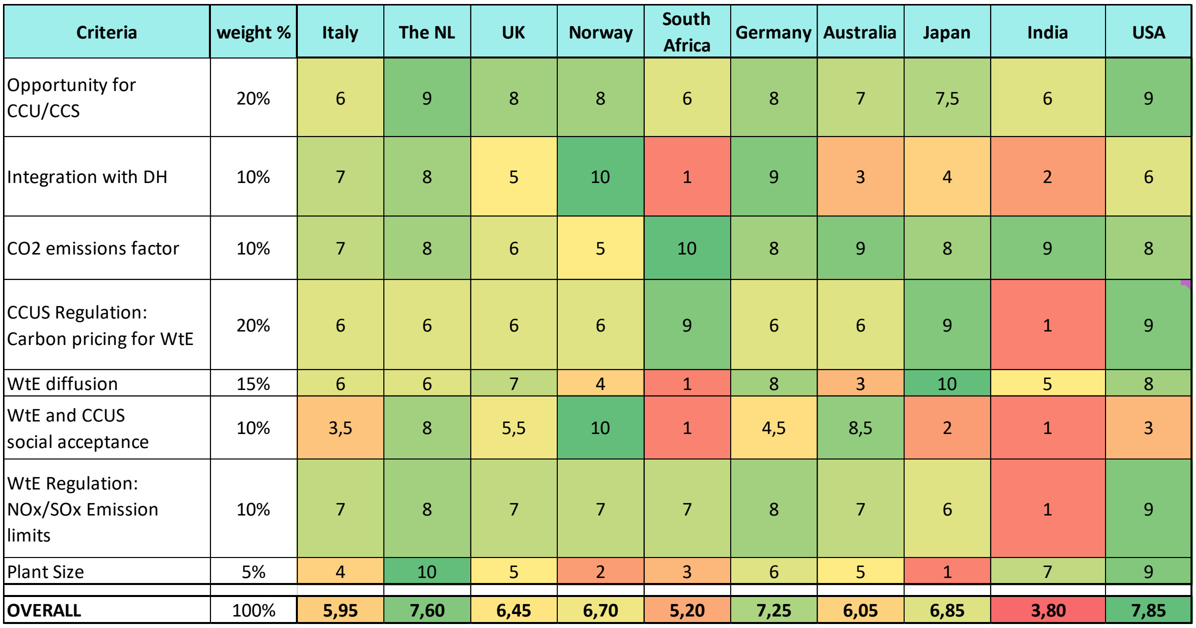
The following criteria are identified to have a significant influence in determining the potential of integrating the CCU/CCS in an existing WtE, depending on the geographical location. The relative weight attributed to each criterion is also reported:

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

2. Possible integration with District Heating (weight = 10%) – The trend of each country to utilize WtE for DH is evalaued, which is also related to the local meteorological conditions. As previously discussed in the paper, the DH can be an effective sink for the heat recovered from flue gas cooling upfront the CO_2 capture.
3. Local CO_2 emissions factors for power and heat generation (weight = 10%) - The higher the local CO_2 emission factors for electricity and heat generation in a country, the higher is the CO_2 emissions avoidance benefit associated with WtE, especially if integrated with CCSU.
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: NO_x and SO_x emission limits (weight = 10%) - The extent of the upgrades required in the FGT systems, in a retrofit perspective, is expected to be lower if the initial SO_x and NO_x emissions limits for the WtE are stricter.
8. Average WtE plant size (weight = 10%) – Carbon Capture retrofit in larger-scale WtE plants are expected to be favoured by the economies of scale.

Table 7 summarizes the outcome of the application of the ranking for all the discussed criteria.

Table 7. Energy balance of Study cases 1 and 2



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
OVERALL	100%	**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.

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