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Negative Emissions in the Waste-to-Energy Sector: an overview of the NEWEST-CCUS programme

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Abstract

The deployment of Carbon Capture and Storage technologies in the waste management sector can make municipal and industrial waste a strategic resource for climate change mitigation. The generation of energy, in the form of electricity and heat, via the processing and incineration of waste already avoids methane emissions from landfill. The addition of CCS to Waste-to-Energy plants with CO_2 capture levels close to 99% can reduce their CO_2 emissions to the atmosphere close to zero. With CCS, biogenic carbon in waste becomes a domestic source of negative emissions with a supply chain that would complement other negative emission technologies, such as Bio-Energy with CCS (BECCS).
The NEWEST-CCUS project is an ongoing €2.5M multidisciplinary (2019-2022) project involving academics and researchers from six organisations and four European countries. It seeks to improve understanding of technologies and opportunities for negative emissions in the waste-to-energy sector. This paper outlines the broad range of activities undertaken by the consortium in response to key challenges facing the sector.

Keywords: Waste, Energy, CCUS, Negative Emissions, BECCS,

1. Introduction

Addressing climate change and the sustainable management of waste are two important societal challenges, as recognized by the 2015 Paris Climate Agreement and by the EU Action Plan for a Circular Economy Package [1]. Yet the capacity of the waste management sector to generate negative emissions is poorly characterised. In return, national net-zero carbon dioxide policies rarely account, at the time of writing, for the possible contribution of the sector.

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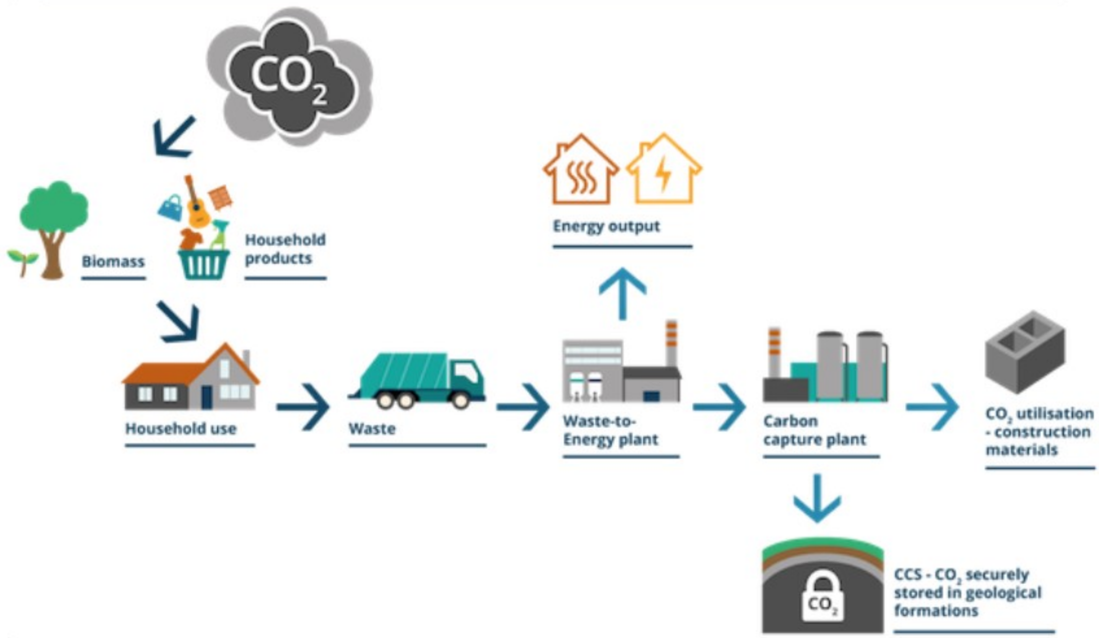

Fig. 1*: Negative emissions in the Waste-to-Energy sector are created by biomass residues entering the value chain, incinerated to recover energy and the biogenic carbon of biomass being permanently stored away from the atmosphere*

With up to 65% of global waste from biogenic origin [2], up to 80% for Municipal Solid Waste (MSW), a mixture of household and commercial waste, and more for other types such as waste wood, the use of Carbon Capture and Storage (CCS) with Waste-to-Energy (WtE) would create negative carbon sink over the lifecycle of waste [3]. WtE plants provide incineration, reducing the volume and weight of waste, destroying various contaminants. They also provide energy recovery by thermally treating household and commercial waste that remains after waste prevention and material recycling.

Unlike the service of waste disposal, waste as a resource is, however, of moderate value today, mostly an energetic value recovered via incineration. If untaxed, landfilling is the most common way of disposing of waste and has numerous issues, including local pollution to local soils and rivers, and the uncontrolled release of potent greenhouse gases such as methane to the atmosphere.

As landfilling is being phased out in certain jurisdictions, e.g. in Europe, municipal solid waste of biogenic origin could become a strategic domestic resource to achieve net-zero targets, providing a valuable and much needed fraction of BECCS, as shown in **Fig. 1**, by using a domestic resource without further impacts on land availability. In a carbon constrained world aggressively chasing greenhouse gas emissions and deploying Negative Emission Technologies (NETs), the highest value to society of waste might be locking away its biogenic content, as well as its fossil content, from the atmosphere.

This paper discusses important questions for deployment of CCS in the Waste-to-Energy sector and presents a dedicated programme of research undertaken in the NEWEST-CCUS project.

2. Negative Emissions in the Waste-to-Energy Sector: Technologies for CCUS - The NEWEST-CCUS project

NEWEST-CCUS is a 3-year collaborative R&D project funded by the ACT programme with a budget of circa €2.5M. It started in September 2019 with the University of Edinburgh, the University of Sheffield, and industrial partner Carbon Clean based in the UK, SINTEF Energy Research AS in Norway, TNO in the Netherlands and the University of Stuttgart in Germany.

The innovation focus is on progressing three capture technologies for WtE to Technology Readiness Levels (TRLs) five to eight, with a combination of pilot-scale testing and modelling:

- Solvent-based post-combustion capture and, in particular, the management of combustion impurities typical of WtE plants;
- Oxy-fired circulating fluidised beds using Solid Recovered Fuels, i.e. fuels made of selected waste and by-products to increase calorific value;
- Membrane based CO_2 separation, and hybrid methods using partial flue gas recirculation and oxygen enrichment.

A comparative technology assessment will provide, in the second phase of the project, key metrics for the waste sector, policymakers, regulators and technology developers. Combined with Life Cycle Analysis, a market assessment and scenario-based analysis will quantify the contribution of the waste sector to Negative Emissions at the city, regional and national level.

3. Can conventional CCS technologies be used in Waste-to-Energy plants?

Municipal Solid Waste is typically incinerated in grate-fired boilers, a type of industrial combustion systems used for solid fuels. Although waste is a challenging fuel, heterogeneous in composition and containing a range of organic and inorganic contaminants, conventional, solvent-based, post-combustion CO_2 capture technologies are well suited to the resulting combustion gases. It is, however, critical to the deployment of CCS in the waste sector to understand fully the fate and the impact of any trace contaminants entering the CO_2 capture process, via the combustion flue gas of grate-fired boilers. Lessons learned on solvent degradation and emissions to air from commercial CCS projects burning coal, another heterogeneous solid fuel, are starting to be applied to the waste sector.
There are four waste incineration plants coupled with a carbon capture system of various scales, at the time of writing [4]. This includes a pilot facility in Norway, at the Fortum Oslo Varme (FOV) WtE plant in Klemetsrud, Oslo, and three commercial facilities with CO_2 utilisation. One is in Saga, Japan and two in the Netherlands operated by Twence and AVR. In each of these plants, carbon dioxide is scrubbed from the flue gas stream with a solvent-based technology,

3.1 Solvent degradation

Degradation of amine solvents, possibly caused by interaction with oxygen and flue gas contaminants, is a known issue in commercial scale, coal-fired, CCS power plants. If uncontrolled, solvent degradation can lead to large solvent inventory replacement costs and to a significant contribution to non-variable operating costs.
The CCS Knowledge Centre, based on commercial experience at coal-fired power plant Boundary Dam 3, states that "*……. the research currently available on post-combustion amine-based carbon capture is insufficient for adequately understanding interactions between amines and flue gases" [5]*. They report that accelerated solvent degradation occurred at Boundary Dam 3 after the typical period of operation of pilot test campaigning: *"Long-term testing of amines was quite often limited in duration around the time that BD3 was built. The data we have on the behaviour of the amine used on this particular facility does not reflect the accelerated degradation that occurred closer to 3,000 or 4,000 hours of run time."* They conclude that the *"Degradation products and operational challenges are unique to each of the different amines in combination with various flue gas streams"*.
The CCS Knowledge Centre highlights the importance of demonstrating long-term satisfactory operation of CO_2 capture solvents to achieve commercial confidence of CO_2 capture in the Waste-to-Energy sector.

3.2 Pilot-scale testing with waste flue gas

Fagerlund et al (2021) recently present the results of the first pilot plant test campaign of CO_2 capture solvent operating with waste flue gas. It includes data on solvent degradation from a circa 3 tonne CO_2/day amine-scrubbing pilot plant taking a slipstream of combustion flue gas from the FOV Waste-to-Energy facility at Klemetsrud in Oslo, Norway [6].

They report that solvent degradation, with Shell's CANSOLV capture technology using solvent DC-103, initially increases linearly for the first 5,000 hrs from 0 %wt to ~4.25 %wt, at a rate of $0.85 \cdot 10^{-3}$ %wt/hr of solvent degradation. It is, then, followed by a sharp acceleration of solvent degradation in the last 250 hrs of the test campaign. The concentration of degradation products increases from ~4.25 %wt to 5.75% wt over 250 hrs – a seven-fold increase equivalent to a gradient $0.6 \cdot 10^{-3}$ %wt/hr potentially exposing an exponential growth rate. Fagerlund et al [6] attribute this to "*upset conditions at the pilot plant as well as the Waste-to-Energy plant*", where "upset conditions" refer to "transient" or "abnormal" conditions.

In the absence of further data after 5,250 hrs of operation, and with the insight from the CCS Knowledge Centre of accelerated degradation of solvent DC-103 at Boundary Dam 3 after 4,000 hours, it is not clear at the time of writing whether long-term satisfactory operation of the solvent used at Klemetsrud has been achieved. Noting that no Thermal Reclaiming Unit† is currently installed at the Klemetsrud pilot plant, further testing is an important step to demonstrate the capacity to maintain degradation in a linear regime beyond 5,250 hrs, when uncontrolled contamination caused by unplanned upsets, i.e. transient or abnormal conditions, of the Waste-to-Energy plant occurs. This could be achieved with conventional, commercially available methods of solvent management such as filtering, solvent reclaiming or makeup.

3.3 Emissions to air

Pilot testing of amine scrubbing technologies shows that coal fly ash, dust (coarse particles) and aerosols (submicron particles), if unmitigated, can cause entrainment of solvent into the air [5]. Fagerlund et al [6] successfully report that, with the use of an 'amine emission mitigation device' consisting of special filter candles for sub-micron mist elimination, average emissions of solvent to the atmosphere remained well below a target concentration of 0.4 ppmv, including during periods - of the order of hours - of high concentration of dust in the flue gas (<8 mg/Nm3).

4. CO_2 capture solvent research in NEWEST-CCUS

Fagerlund et al. [6] show the importance of understanding the effects of gaseous trace contaminants and aerosols in the combustion gas of Waste-to-Energy plants. At present, the experience with industrial pilot testing is limited to Shell's proprietary technology. In the NEWEST-CCUS project, CO_2 capture solvent activities aim to bridge the gap between bench scale R&D and large scale industrial pilot trials to further understand the challenges posed by impurities in the flue gas from waste incinerators.

4.1 Pilot scale testing at 1 tonne CO_2/day - Contaminants from contaminated biomass and bio-waste fuels - University of Sheffield

The Translational Energy Research Centre, the national R&D centre for low carbon conventional and renewable energy, including carbon capture and storage/utilisation, at the University of Sheffield is developing new capabilities in the project with a 240 kWth grate-fired boiler integrated with a 1 tCO_2/day capture plant and analytical instruments measuring particle concentration/sizes, entrained aerosols and trace metal release from combustion of waste wood. The experimental setup is shown in **Fig. 2** below whilst the new experimental capabilities are described in details in a project technology bulletin available in [7].

The grate-fired biomass boiler is retrofitted specifically with an array of ports in the combustion chamber and overpass sections for characterising in-furnace temperatures, pressure, gas composition, deposition and corrosion. In-built cyclones and a new electrostatic precipitator are employed to control particulate emissions in the flue gas to the capture plant. The boiler is modified to introduce a flue gas recycle mechanism to enhance fuel variation capability. The boiler can be employed to combust a wide range of chipped and pelletised biomass and bio-waste fuels. Metal release characterisation is achieved via a state of the art Inductively Coupled Plasma Optical Emissions Spectrometer (ICP-OES), with the focus being on metal contaminants of interest to CO_2 capture, such as transition elements that initiate or catalyse solvent degradation Cu, Ni, Fe, V, in addition to K and Na. These contaminants can cause operational issues, such as slagging, fouling and corrosion, or toxic trace metals such as Hg, Cr, Cd and Pb.

† A conventional method of separating solvent from its degradation products by distillation,

The test campaigns taking place in the second phase of the project will be carried out with two solvents, a generic 30%wt MEA amine solvent and Carbon Clean's proprietary solvent technology. They will aim to

- Assess the types and levels of trace metals in the grate boiler and determine their release profiles as entrained aerosols, as contained in the combustion flue gases
- Measure emissions of particulate matter, specifically sub-micron particles (PM1, i.e. aerosols), from combustion, in terms of particle size distribution and particle concentration
- Determine and quantify the impacts of the fuel and therefore the flue gas composition (contaminants) on the operational performance of a pilot-scale post-combustion CO_2 capture plant based on key performance indicators, including solvent degradation and reboiler duty

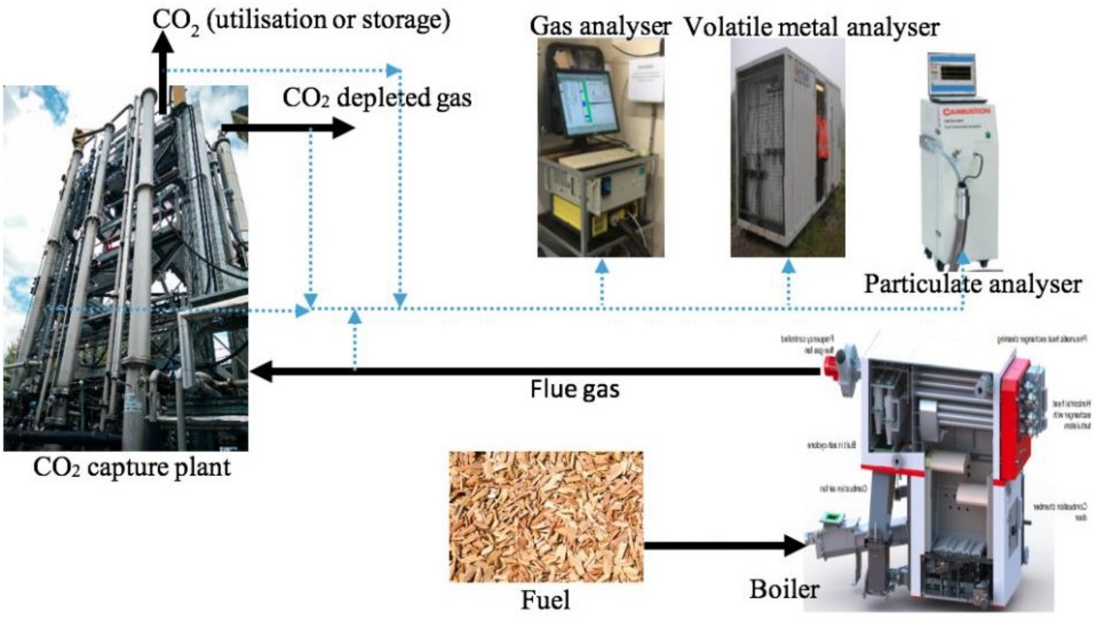

Fig. 2. Experimental setup of TERC facilities in the NEWEST-CCUS project

4.2 Industrial pilot testing at 10 tonne CO_2/ day of Carbon Clean's technology at Twence WtE plant – TNO and Carbon Clean

Twence, a WtE company in Hengelo (NL), has upgraded, with project partner TNO, its CO_2 capture plant into a multi-solvent test facility with a capacity of ca 10 tonne CO_2/day. The plant currently treats a slipstream of one of the waste incinerator furnaces. The captured CO_2 is partially used in-house, to produce sodium bicarbonate, and the remainder is purified to food-grade, liquified, and transported by truck to greenhouses to enhance enhance plant growth.
Carbon Clean's proprietary solvent will be tested during the second phase of the project, with a focus on validating energy requirements and the operational performance of the solvent and to develop a solvent management strategy between TNO and Carbon Clean. This strategy will take into account:

- Monitoring of emissions to air at the top of the water wash (amine and ammonia emissions),
- Continuous monitoring of the solvent quality
- Characterisation and mitigation of possible aerosol-based emissions

4.3 Demonstration of a new solvent system – TNO

Project partner TNO is focusing on developing a novel solvent system, focusing on achieving high pressure CO_2 desorption. The minimum target for the desorption pressure is set at 6 bar. This would lower the CAPEX and OPEX associated with CO_2 compression. Within the NEWEST-CCUS project, TNO will demonstrate the performance of that solvent using a lab test facility. TNO's lab scale CO_2 capture plant allows for cyclic (absorption-desorption) continuous operation, and will be used to evaluate aspects such as solvent degradation and emissions over time. The plant will operate on synthetic flue gas, with an inlet flowrate of ca. 3 Nm^3/h, and has the possibility to desorb CO_2 at pressures up to 10 bar.

5. Oxy-fuel combustion research in NEWEST-CCUS

Oxy-fuel combustion is expected to be an effective method for controlling combustion with heterogeneous waste fuels in the industrial furnaces of WtE plants. In these oxy-fuel furnaces, oxygen is supplied as a single gas stream and oxygen distribution in the furnace can be adjusted to allow real-time control of local combustion properties. It is particularly well-suited to Municipal Solid Waste, with a wider inhomogeneity in composition and feedstock than coal. In addition, flue gas recirculation for furnace temperature control, necessary in Oxy-fuel combustion, is a common strategy in grate-fired boilers used in WtE plants.

5.1 Oxy-fuel grate boiler – fundamental properties of Municipal Solid Waste under oxy-combustion – SINTEF Energy Research

Although demonstrated in industrial environment for coal fired power generation, oxy-fuel combustion capture has yet to be demonstrated in grate-fired boilers with MSW as fuel. Basic data of the fundamental combustion properties of MSW under oxy-fuel conditions are necessary for the proper design of grate-fired furnaces, which are particular in that the full combustion process is staged over a moving bed. This type of furnace allows to take full advantage of the freedom given by oxy-fuel combustion to inject oxygen at different concentration levels at different stations along the bed. Complete knowledge of the combustion properties in all types of O_2-CO_2 atmospheres is therefore paramount. For that purpose, SINTEF Energy Research is conducting fundamental research to measure and compare the influence of oxygen in oxidizer systems CO_2/O_2 and N_2/O_2 in a dedicated Vertical Tube Furnace, extending the programme of work in the nationally funded project CapeWaste (Research Council of Norway Grant #281869). Development of CFD capabilities for upscaling industrial design with a validation program based on the pilot results at the University of Stuttgart (see next section).

5.2 Oxygen fired circulating fluidised bed – 200 kW pilot scale testing – University of Stuttgart

Improvements in automatic waste sorting technology are allowing operators to divide waste into high quality higher calorific value Solid Recovered Fuel (SRF) and low quality waste. The latter can be incinerated in a grate-fired boiler, and the former allows for the use of fluidized bed boilers to maximise the energetic value of SRF. Fluidised bed combustion is an industrially available technique for hard coal.
In NEWEST-CCUS, pilot scale testing at the Institute of Combustion and Power Plant Technology (IFK) at the University of Stuttgart will explore how specific mechanical and chemical properties of SRF affect design and operation, including factors such as fuel dosing, bed agglomeration, fuel conversion and corrosion.

Table 1: Characteristics of the IFK's experimental facilities in NEWEST-CCUS

	20 kW_{th} facility	200 kW_{th} facility
Fluidisation regime	Bubbling	Circulating
Temperature	Up to 950ºC	850-950 ºC
Height	3.5 m	10 m
Thermal input	Up to 20 kW_{th}	100-330 kW_{th}

Pre-testing of fuels of SRF are carried out in a 20 kWth electrically heated bubbling fluidised bed (BFB) facility to support the pilot-scale experiments in a 200 kWth pilot scale test rig of a circulating fluidised bed (CFB) oxy-fuel combustion. The characteristics of the facilities are shown in Table 1 and the reader is referred to a NEWEST-CCUS project technology bulletin for a full description of the facilities [8]. **Fig. 3** shows a schematic of the installation for the 200 kW_{th} pilot scale testing for process validation in industrially relevant conditions.

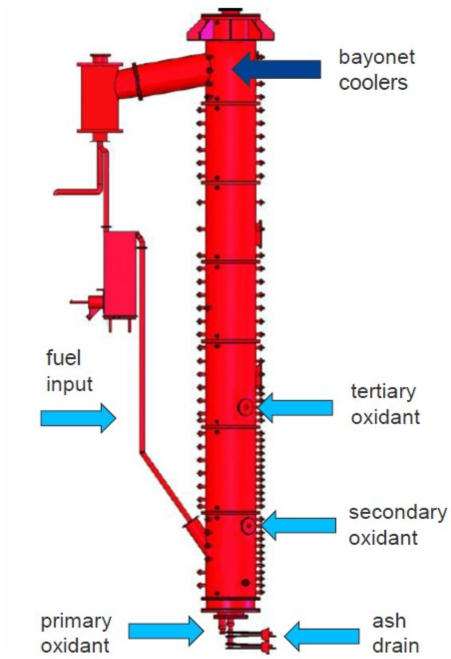

***Fig. 3**: Schematic of the 200 kWth CFB oxy-fuel reactor in the MAGNUS facility*

6. Hybrid separation by CO_2 membrane applied to WtE plants – SINTEF Energy Research

CO_2 separation membranes are competitive separation technologies proven at industrial scale in other applications such as cement. Earlier work on membrane-based CO_2 capture from various CO_2 concentrations show that this technology is not most suited to WtE flue gases with CO_2 concentrations of 10-12% [10]. However, membrane based hybrid process have a potential to be competitive compared to current mature technologies. Two membrane-based hybrid processes are considered in NEWEST.

6.1 Membrane-assisted liquefaction

The working principle and sequence of the hybrid membrane-low temperature process is shown in Fig. 4. Through this capture process, the CO_2 concentration in the flue gas from a WtE plant is first increased using a single-stage membrane process. The CO_2-rich permeate stream is fed to the low-temperature CO_2 processing unit (CPU). The stream is compressed to targeted separation pressure before it is cooled to separation temperature in a sequence of heat exchangers. A two-stage vapor compression cascade cycle with propane and ethane as refrigerants is assumed to provide the refrigeration duties in the CPU. After cooling to final separation temperature the CO_2-rich liquid phase is separated from the nitrogen-rich vapor phase, then flashed and purified in a secondary drum, and is subsequently conditioned to the specified transport state.

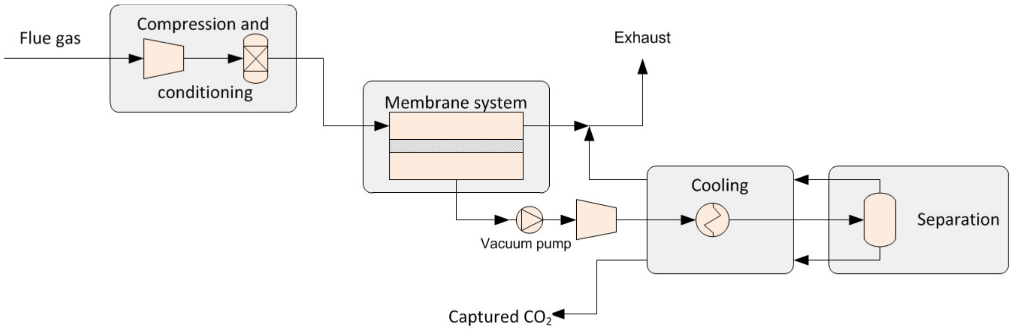

Fig. 4: *Process block diagram of the membrane-assisted liquefaction process [11]*

6.2 Exhaust air recirculation with enriched air combustion

An increase in CO_2 concentration in the flue gases is an interesting option to ensure a suitable driving force for separation and to minimize the cost of membrane systems. This can be done by recirculating a fraction of the flue gases (similarly as in the oxy-fuel concept) and can be combined with oxygen enrichment [12]. The latter brings a better performance and control of the incineration process with improved furnace zone temperature control. This concept is evaluated by SINTEF in order to define the range of optimal recirculation rate and oxygen enrichment. The technology chosen for oxygen production is both a cryogenic ASU and an oxygen membrane, since the purity of oxygen is not critical in this application.

7. How much carbon dioxide can the waste sector remove from the atmosphere? – led by the University of Edinburgh

Pour et al [2] provide the best available estimate to date of the contribution of the Waste-to-Energy sector to negative emissions. They use environmental impact assessments to show that around 0.7 kg CO_2eq is removed per kg of wet Municipal Solid Waste incinerated. They estimate, for the first time, an upper limit of 2.8 billion tonnes CO_2 of negative emissions, if all the available 4 billion tonnes of MSW assumed to be generated worldwide by 2100 is utilised in waste incinerators with CCS. In practice, many factors will effectively determine the actual value of negative emissions created in the waste sector, and likely reduce the upper estimate in Pour et al.

7.1 Assessing net atmospheric CO_2 removal

Project Partner The University of Edinburgh leads activities on assessing the cumulative net atmospheric CO_2 removal of WtE with CCUS, at different national levels and at the European level.

In order to quantify with a greater level of accuracy of what is practically achievable in the sector, a comparative assessment of CO_2 capture technologies in the WtE sector, supported by a process modelling effort from all partners, feeds into a multi-criteria analysis taking into account

- A scenario-based analysis for the phasing out of landfilling via the deployment of waste incineration facilities in Europe, on the basis of the EU Landfill Directive
- A scenario-based techno-economic analysis of the implementation of CCUS across the sector
- An evaluation, at the plant level, of how many WtE plants can be retrofitted
- Environmental impact assessment
- Life cycle analysis techniques

7.2 Other important considerations for the sector

Waste is a local, domestic resource, and with the capacity of CCS to operate at 99% capture level, negative emissions from biogenic waste can be maximised to create a supply chain complementary of any national/regional BECCS supply chain. In a net-zero society, waste could become a strategic resource of negative emissions, without competing for land availability with biomass production.

It is important that governance at the local, regional and national levels factors in the value of negative emissions from waste, when planning new WtE facilities. Designing new plants to be carbon capture-ready will facilitate retrofitting new facilities with CCUS, at minimal cost and maximal value to society.

Business models specific to the Waste sector may be necessary as the characteristics of WtE plants with CCS are partially similar to BECCS power plants, heavy industries exposed to international competition, and district heating plants.

It is important that these dedicated business models recognise that waste can be exported via cross-border shipping. This could imply that WtE plants may require characteristics of industrial CCS contracts, in addition to contracts for the provision of zero carbon electricity and zero carbon heat. Business models must obviously recognise, as with any other form of BECCS, the fraction of biogenic carbon captured with CCS, typically around 50% and up to 80% for municipal waste.

For policymakers to formalise the latter, it is important that conventional life cycle analysis methods are made fit for purpose to account for negative emissions from waste. It is currently common practice to discount biogenic carbon emissions.

Finally, understanding of public acceptance must be improved. Public acceptance of waste incineration and public acceptance of CCUS may change when these two technologies are combined to advance a net-zero society. Since society and policymakers no longer accept the health and environmental effects to water, soil and localised air pollution of waste disposal, how much longer can they ignore the contribution of waste to climate change?

8. Conclusion

This paper has provided an overview of the programme of research of the NEWEST-CCUS programme. Overall, the programme progresses the understanding in a number of important areas for the effective development and deployment of CO_2 capture in the Waste-to-Energy Sector. The programme of research focuses on innovation in CO_2 capture technologies, with a dedicated strategy including technology validation in the lab, pilot scale testing, industrial scale testing, CFD and process modelling, and quantifying the contribution to negative emissions of the waste sector in Europe. Finally, important considerations on the value of waste to a net zero-society and research gaps are discussed.

Nomenclature

ASU	Air Separation Unit
BECCS	Bio-energy with Carbon Capture and Storage
BFB	Bubbling Fluidised Bed
CCS	Carbon Capture and Storage
CCUS	Carbon Capture and Utilisation
CFB	Circulating Fluidised Bed
CFD	Computational Fluid Dynamics
MSW	Municipal Solid Waste
NET	Negative Emissions Technology
SRF	Solid Refuse Fuel
TRL	Technology Readiness Level
WtE	Waste-to-Energy

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