D5.4 Techno-economic analysis of the potential market for waste-to-energy with CCUS technologies

Waste Not, Want Not: Europe's untapped potential to generate valuable negative emissions from waste-to-energy (WtE) using carbon capture technology

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Note that this study is also available on the Oxford Institute for Energy Studies (OIES) website.

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Executive Summary

Waste-to-energy (WtE) is a waste treatment process that incinerates waste to produce energy in the form of electricity and/or heat. WtE is considered one of the most environmentally-friendly methods of dealing with residual waste. The alternative to this process is waste dumping or landfilling, both of which lead to long-term adverse impacts on the environment. The capture of CO_2 from WtE plants has received increasing attention over the past decade. Particularly, waste contains a substantial amount of biogenic carbon content, i.e., carbon which is part of the natural carbon cycle, the capture and permanent removal of which effectively removes CO_2 from the atmosphere, leading to 'negative emissions'. Considering the important role of carbon-negative solutions in achieving ambitious decarbonisation goals, retrofitting WtE plants with CCS will be a major starting point. This study assesses the potential for generating negative emissions from WtE + CCS with focus on the European waste sector as a case study.

This analysis focuses on the current European WtE fleet and its total capacity (circa 100 Mt/year processing capacity across 500 WtE plants), and further assumes a set of criteria to determine whether and which WtE facilities are retrofittable with CCS. These factors include i) an acceptable distance for CO2 transport between plants and CCS clusters, hubs and CO_2 storage sites, ii) availability of on-site space for CCS retrofit and iii) an appropriate plant size to ensure that CO2 capture is economically viable. Specifically, a top- down approach consisting of three stages is adopted and is delineated in the following sections.

In a first stage, proximity of WtE plants to a CCS cluster or hub via pipeline was assessed, assuming an appropriate/acceptable distance for pipeline transport. Plants which do not meet this criterion but are coastally-located are also retained in the analysis, assuming CO_2 transport via ships as a more feasible option. For plants which do not meet either of the two criteria, proximity to a storage site was instead investigated (with a 100km assumed range). In a second stage, all plants which were retained based on the distance criterion were analysed for availability of enough on-site space for CCS retrofit: those with little-to-no space for deploying a capture facility in their vicinity were excluded from the analysis. In the third and final stage, the remaining plants were analysed for their emissions footprint, with plants producing more than 100,000 tCO_2 per year considered likely, economically-speaking, to be retrofitted with CCS.

This study shows that if the entire existing European WtE fleet (i.e. 100.9 Mt of installed capacity) was retrofitted with CCS, negative emissions in the range of -50.5 to - 70.6 $MtCO_2$/y would be generated per year, assuming a capture rate close to 100%. In its 2019 sustainability roadmap, CEWEP anticipates a total of 142Mt of residual waste generated in 2035 when meeting the thresholds for recycling (minimum of 65%) and landfilling (maximum of 10%) in accordance with the EU Circular Economy Package. It may admittedly not be possible to bridge the current ~30Mt gap in WtE capacity needed to treat the remainder of this residual waste, as some existing WtE plants come to the end of their life and others are newly commissioned. Yet, in theory, if enough WtE capacity where to be built and is retrofittable with CO_2 capture, a range of -71 to -99.4 $MtCO_2$/y of negative emissions can be achieved. When CCS limitations are considered, these ranges are naturally reduced, with a range between -20 to -30 $MtCO_2$/y achievable when all CCS considerations are taken into account.

Abbreviations

ADEME	French Environment Agency
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation and Storage
CDR	Carbon Dioxide Removal
CEWEP	Confederation of European Waste-to-Energy Plants
CH_4	Methane Gas
CO_2	Carbon Dioxide
CO2StoP	CO_2 Storage Potential in Europe Project
EGDI	European Geological Data Infrastructure
EU	European Commission
FID	Final Investment Decision
GCCSI	Global CCS Institute
GDP	Gross Domestic Product
GWP	Global Warming Potential
ICW	Industrial and Commercial Waste
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LHV	Low Heating Value
MEA	Monoethanolamine
MSW	Municipal Solid Waste
Mt	Mega Tonne
NbS	Nature-based Solutions
NCCC	National Carbon Capture Centre
NETs	Negative Emission Technologies
tCO_2	Tonnes of CO_2
tCO_2e	Tonnes of CO_2-equivalent
TCM	Technology Centre Mongstad
tMSW	Tonnes of Municipal Solid Waste
WtE	Waste-to-Energy
ZEP	Zero Emissions Platform

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1 Introduction

In its 2021 Climate Change report, the Intergovernmental Panel on Climate Change (IPCC) put forth a number of scenarios for the deployment of climate mitigation solutions that will be needed to keep global temperature rise within 1.5°C relative to pre-industrial levels (IPCC, 2021). Future trajectories of greenhouse gas (GHG) emissions will depend on the choice, scale and impact of solutions deployment; however, one thing was made clear: a 1.5°C world will require large-scale deployment of negative emission technologies (NETs).

NETs – often interchangeably referred to as carbon dioxide removal (CDR) technologies – are solutions that physically remove CO_2 from the atmosphere, reducing the overall stock of legacy emissions that have been emitted since the industrial revolution, but also countering the current flow of anthropogenic emissions which are projected to rise drastically over the next decades (Gidden et al., 2019; Pires et al., 2019; Haszeldine et al., 2018). CDR solutions come in a number of different forms ranging from nature-based solutions (NbS) – some of which have been mainstream practice for as long as humans have been around such as planting trees –, to deploying breakthrough geoengineered solutions for the specific purpose of addressing global warming (Keith, 2000).Geoengineered solutions can include radical processes such as fertilizing the oceans with iron to enhance phytoplankton bloom (Williamson et al., 2012), enhancing the natural process of minerals weathering which would otherwise take millennia to occur (the 'enhanced weathering' method) (Hartmann et al., 2013), or capturing CO_2 from point sources (e.g., bioenergy with carbon capture and storage (BECCS)), or directly from the atmosphere (direct air capture with carbon storage (DACCS)) (Vaughan and Lenton, 2011). One promising solution to reducing both fossil and biogenic CO_2 emissions involves capturing emissions from the conversion of waste to energy (waste-to-energy).

Waste-to-energy (WtE) is a waste treatment process that incinerates residual waste after re-use, recycling and composting to produce energy in the form of electricity and/or heat (Kumar and Samadder, 2017; Brunner and Rechberger, 2015; Kothari et al., 2010). WtE is considered a more environmentally-friendly method of dealing with residual waste (CEWEP, 2022a) than its alternative: waste dumping or landfilling. Waste dumping and landfilling lead to long-term adverse impacts on the environment: these include the use of large spaces of land and the release of highly detrimental pollutants as the waste decomposes over time, particularly as the carbon embedded in waste converts into methane gas with a much higher global warming potential [GWP] than CO_2 (Krautwurst et al., 2017).

WtE plays a key role in mitigating such impacts and produces valuable by-products (i.e. heat and electricity); however, if not retrofitted with carbon capture technology, the practice also leads to CO_2

emissions itself – albeit at an even faster rate than dumping or landfilling. For this reason, the capture of CO_2 from WtE plants has received increasing attention over the past decade. Particularly, waste contains a substantial amount of biogenic carbon content, i.e. carbon which is part of the natural carbon cycle, the capture and permanent storage of which effectively removes CO_2 from the atmosphere, leading to 'carbon-negative emissions'. This is the case when more CO_2 is captured and permanently removed from the system than what would have been emitted from the waste's non-biogenic content (Lomax et al., 2015). Waste-to-energy also addresses other issues created by population growth, including the rise in energy demand and mounting pressures to reduce landfilling around major cities (Grazhdani, 2016).

Considering the important role of carbon-negative solutions in achieving ambitious decarbonisation goals, retrofitting WtE plants with CCS will be a major starting point (IPCC, 2022). This report assesses the potential for generating negative emissions from WtE+CCS with focus on the European waste sector as a case study. Section 2 provides an overview of relevant existing literature. Section 3 details a novel methodology developed by the authors to assess overall negative emissions from the sector, taking into account three overarching factors which may enable or prohibit carbon capture retrofit at the WtE plant level: i) viability of carbon capture retrofit based on plant proximity to CCS clusters, hubs or storage sites, ii) viability of capture retrofit based on space availability at the plant site, and iii) economic viability of carbon capture based on emissions intensity of plants. Section 4 presents and discusses results while Section 5 concludes.

2 Background

In 2022, around 2,600 WtE plants were operational globally (Ecoprog, 2023). Of these, around 500 plants, processing a total of 100Mt of residual waste, were operating in Europe (CEWEP, 2022a). Eurostat (2022) reports that 2,153 million tonnes of waste (4,813 kg per capita) were generated by all economic activities and households in Europe in 2020, while 1,971 million tonnes were treated the same year.[1] Of the total waste treated in the EU, more than half was treated in recovery operations (59.1%) including recycling (39.9%), backfilling (12.7%) and energy recovery (6.5%). The remaining waste was either landfilled (32.2%), incinerated without energy recovery (0.5%) or disposed of (8.2%) (Eurostat, 2022).

Calling for higher resource efficiency, the EU Waste Framework Directive (European Commission, n.d.) aims to prevent and reduce the adverse impacts caused by waste generation. The Directive's five-step

[1] Note that the waste treatment figure includes waste imported from outside the EU, so not comparable with the reported waste generated.

waste hierarchy makes clear that preventing waste generation, where possible, is a preferred option while waste disposal, especially landfilling, comes as a last resort (Figure 1). The EU's Circular Economy Package (2018) also sets recycling targets on municipal solid waste (MSW) generated by EU Member States where, by 2035, a minimum of 65% by waste weight shall be prepared for re-use and recycling and a maximum of 10% can be landfilled (EC, n.d.). This target directly affects the scale of development of the waste-to-energy sector, as it is waste that is not recyclable that will be eventually used for energy recovery.

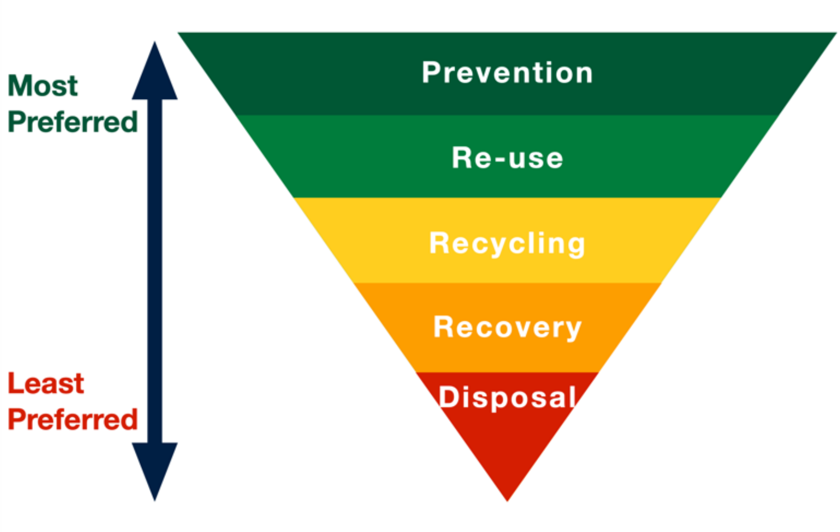

Figure 1: The waste hierarchy

Note that no equivalent recycling targets currently exist for commercial and industrial waste (ICW). Using these targets in its 2019 Sustainability Roadmap, the Confederation of European Waste-to-Energy Plants (CEWEP) estimates the amount of residual waste which would be diverted to WtE facilities in 2035, after separation of waste at source and sorting and pre-treatment before recycling: this is reported for MSW, but also for ICW under the assumption that recycling and landfilling targets similar to those of MSW would be implemented. Respecting the waste hierarchy, CEWEP (2019) approximates that 142Mt of residual waste would be generated annually in Europe by 2035 (Figure 2).

A large proportion of this residual waste is currently treated in WtE plants (90Mt fleet capacity in 2017, currently at around 100Mt), so retrofitting plants with CCS will be crucial to negate the respective emissions. In fact, many European WtE operators are already retrofitting plants with CCS (GCCSI, 2019): notable examples include the Hafslund Oslo Celsio plant in Norway (CCS Norway, n.d.), the Twence plant in the Netherlands (Aker Carbon Capture, 2021), the Amager Bakke plant in Denmark

(Bisinella et al., 2022) and the Cory WtE plant in the UK (Cory, 2022). Note that only the first of these had reached a final investment decision (FID) as of the time of writing.

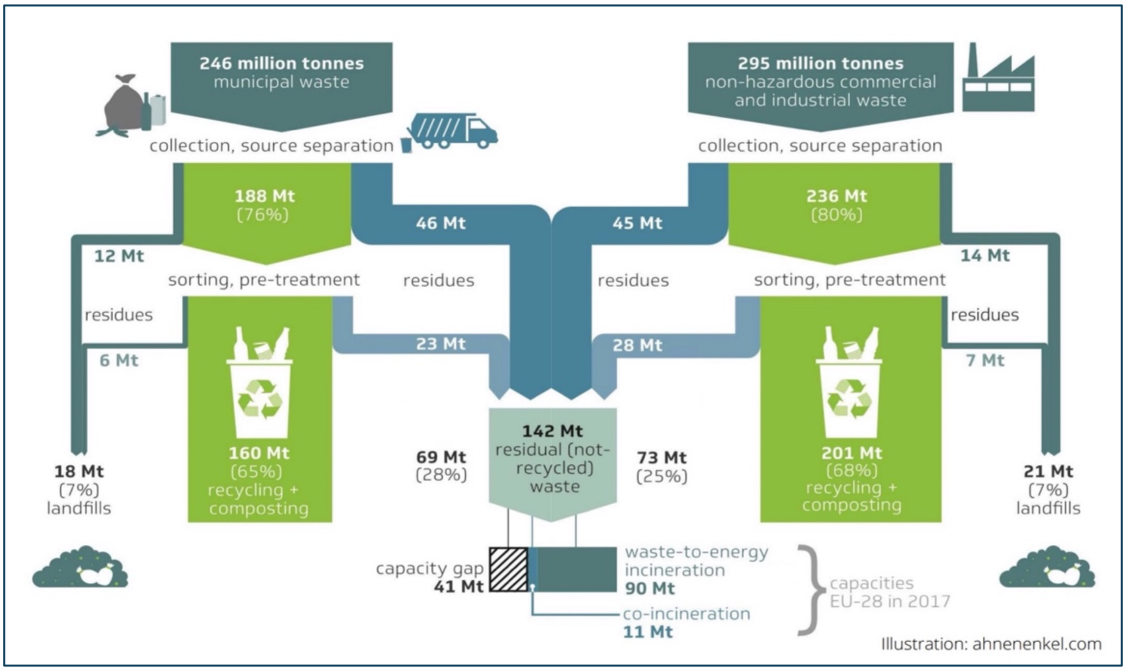

Figure 2: Destination of different waste streams in Europe

Source: CEWEP's 2019 Sustainability Roadmap.

As CCS will be a major technology to decarbonize this sector, CEWEP's recent Climate Roadmap (CEWEP, 2022a) evaluated the climate benefits which can be captured with CCUS[2] retrofit: these include the direct capture and removal of CO_2, but also indirect benefits such as avoiding emissions due to landfill diversion, energy substitution in the grid and bottom ash material recovery. In its analysis, CEWEP (2022a) assumed that one tonne of waste treated emits one tonne of CO_2-equivalent (CO_2e). It also undertook different sensitivity analyses using different capture rates (50% and 90%) and integration levels (i.e., overall fleet capacity to which CCUS is retrofitted, also assumed 50% and 90% levels). Results show a range between -20 $MtCO_2$/year (for 50% capture, 50% integration) and -75 $MtCO_2$/year (for 90% capture, 90% integration) (CEWEP, 2022a). These calculations were based on hypothetical assumptions without considering specific factors which may limit CC(U)S applications in WtE, such as plant size, plant location and availability of a CO_2 transport network and storage opportunities.

This study builds on existing research to investigate the possible range of negative emissions achievable from European WtE+CCS, through a detailed and comprehensive plant-by-plant analysis.

[2] Note that CEWEP's study focused on CCUS rather than only CCS, assuming CO_2 utilisation with a permanent storage component. This study only focusses on geological storage rather than other possible utilization routes, as discussed later.

Results are reported both for present and future fleet capacities as the waste resource and its management evolve over time. This implicitly assumes that enough WtE capacity will exist to treat all residual waste generated in Europe, including from municipal, commercial and industrial wastes, yet this may not be realistically feasible. CEWEP's 2022 Climate Roadmap shows that this has not historically been the case, where a capacity gap of 41Mt existed in 2017 (Figure 2) and may well not be the case in the future (discussed below). As such, the total negative emissions which can be captured from all European residual waste remains a mere theoretical maximum and is here only reported for representative purposes, while a more in-depth assessment of the negative emissions which can be realistically achieved is undertaken.

3 Methodology

This analysis focuses on the current European WtE fleet and its total capacity, and further assumes a set of criteria to determine whether and which WtE facilities can be retrofitted with CCS. These factors include i) an acceptable distance for CO_2 transport between plants and CCS clusters, hubs[3] and geological CO_2 storage sites, ii) availability of on-site space for CCS retrofit and iii) an appropriate plant capacity to ensure that CO_2 capture is economically viable. Specifically, a top-down approach consisting of three stages is adopted and is delineated in the following sections.

In a first stage, proximity of WtE plants to a CCS cluster or hub via pipeline is assessed, assuming an appropriate/acceptable distance for pipeline transport (an acceptable distance is assumed to be 300km, see Section 3.3). Plants not meeting this criterion but are coastally-located are retained in the analysis, assuming CO_2 transport via ships is a site-specific feasible option. For plants not meeting either of the two criteria, proximity to a geological storage site is instead investigated (with a 100km assumed range).

In a second stage, all plants retained are analysed based on capacity, the footprint of a post-combustion CO_2 capture facility and the availability of land in the proximity of the plant to accommodate space for a CO_2 capture retrofit: plants with limited space in their vicinity for the footprint of a capture facility are excluded from the analysis. In the third and final stage, the remaining plants are analysed on the basis of their yearly total emissions, with WtE plants producing more than 100,000 tCO_2 per year considered more likely to be retrofitted with CCS. Figure 3 depicts this stepwise elimination process.

[3] A CCS hub collects CO_2 from different emission sources and transport and stores it using common infrastructure, while a cluster represents the different sources from which CO_2 are collected, usually in close geological proximity to one another.

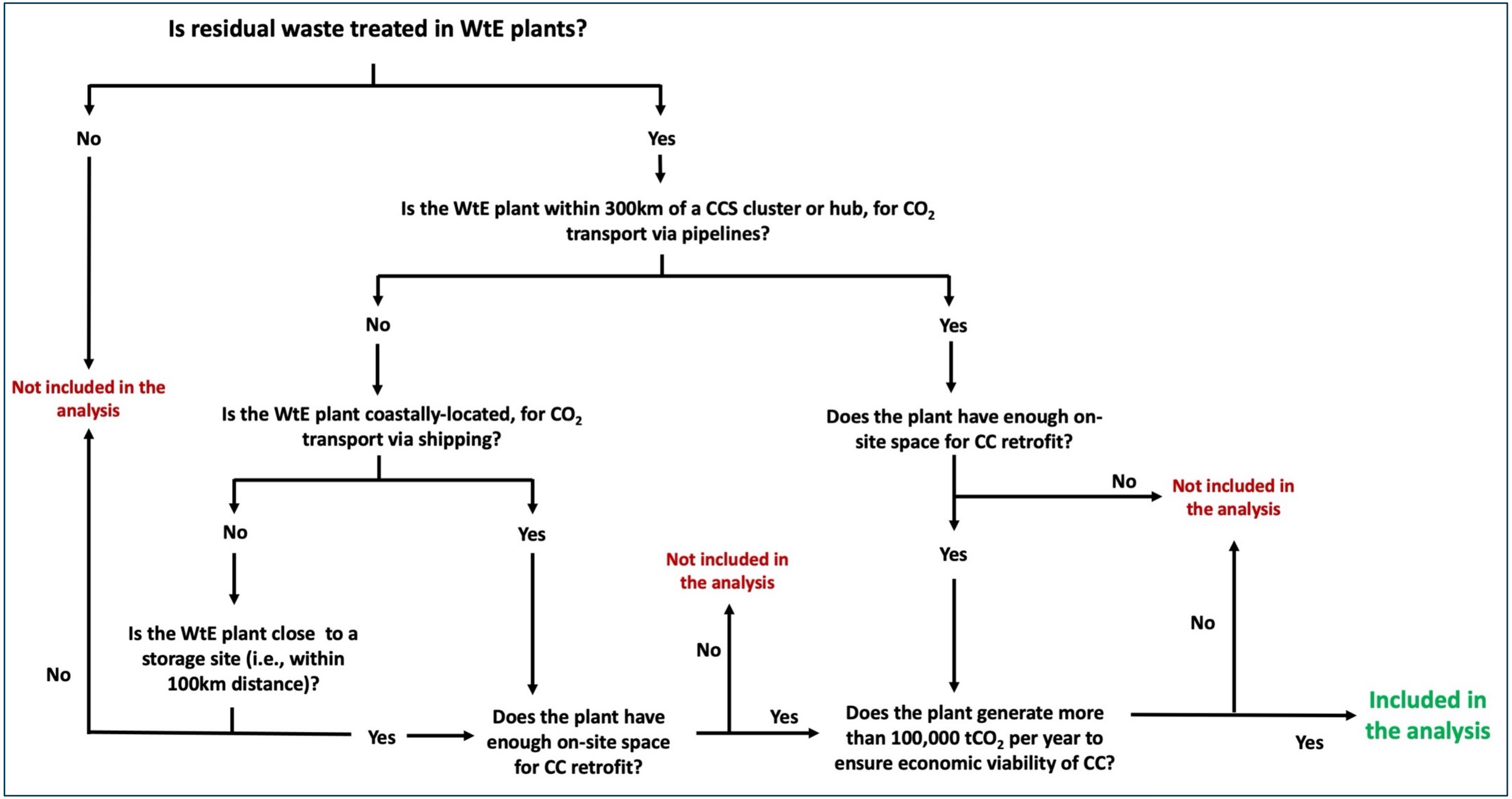

Figure 3: Stepwise approach to identify EU WtE plants that are likely to be retrofittable with CCS

3.1 Waste resource, composition and climate impact

3.1.1 Waste resource

Waste generation and its composition are widely regarded a function of income levels, population growth, and evolving recycling rates (World Bank, 2018). These factors are naturally bound to change over time: as a rule of thumb, the higher the GDP per capita of a country, the higher the consumption and hence waste generated, and the lower its biogenic content as recycling rates are expected to increase over time (IEAGHG, 2020).

However, as reported by CEWEP (2022b), the amount of waste to be treated in WtE facilities in the future is difficult to predict or model. Despite expected increases in waste generation due to population and GDP growth, and the diversion of waste away from landfilling, the evolution of waste prevention policies, enhanced eco-design, increased environmental awareness and environmentally friendly consumption patterns are expected to offset to a certain extent the increase in waste generation. Moreover, analysing the future fate of the proportion of waste currently not incinerated in WtE plants is also important, as part of or all waste in some EU countries is currently landfilled and may be diverted to waste incinerators in the future.

Shown in Figure 2, CEWEP's (2019) analysis is based on Eurostat data on the amounts of waste in individual European Member States: Municipal Solid Waste (MSW) calculations in the 28 EU States involved summing up the municipal waste streams in each country (bottom-up approach), while aggregated data on commercial and industrial waste at the EU-28 level is used to estimate European Industrial and Commercial Waste (ICW) (top-down approach). CEWEP's study was peer-reviewed by Prognos (2019) who acknowledged that the assumptions made, i.e. higher recycling and waste prevention and lower landfilling rates, are admittedly optimistic and the figure for residual, non-recycled waste treatment capacity in 2035 could be higher than what is presented in Figure 2.

Note here that this estimate was based on 2017 EU waste data and is therefore outdated: for instance, in 2017, 246 million tonnes of MSW was generated in Europe; a figure which had risen to around 300Mt in 2021 (Eurostat, 2021). As noted earlier, this projection was based on a number of assumptions, namely that waste generation rates in Europe would remain constant over that period and that a similar 2035 recycling target would be implemented by the EU for ICW (assumed target of 68%) as the 2035 recycling target which currently exists for MSW (65%).

Based on these assumptions and on 2017 WtE fleet capacity, CEWEP (2019) estimated that 41Mt of residual waste remains untreated in 2035 in either WtE plants or co-incinerated in cement kilns. As noted earlier, the WtE fleet capacity has grown to around 101Mt so, assuming the overall capacity for cement kiln co-incinerators has not changed (i.e. 11Mt)[4], a total of around 30Mt of yearly residual waste would remain untreated by 2035.

3.1.2 Waste composition

Based on data collected from the literature, the composition of European waste is investigated with the objective of assessing its biogenic content, which would ultimately lead to negative emissions with CO_2 capture and permanent storage. However, despite an existing Eurostat database on the waste streams that constitute MSW (Eurostat, 2021), the database has missing data and is therefore not fit for purpose in this analysis. Moreover, detailed MSW data is not available for all European countries, and where available, data from different countries is reported differently due to variance in measurement methods and the waste stream categories reported. Similarly, ICW data on a country-by-country basis is not available. Due to this limitation, estimates from real-life data reported by a 2020 study by the French Environment Agency (ADEME) are instead adopted here.

Through measurements of the ratio of Carbon 14 to Carbon 12 in flue gas streams (called the Carbon-14 method), ADEME (2020) investigated the composition of waste streams from 10 WtE plants in France using 148 samples, covering around 2 million tonnes of waste. These plants were equipped with CO_2 samplers and, over a one-year period, monthly CO_2 samples were collected and analysed to determine the percentage of biogenic and fossil CO_2 in the exhaust flow gas. The results were later used by CEWEP in its 2022 Climate Roadmap to approximate the proportion of biogenic content of waste across Europe. These are shown in Figure 4.

The analysed samples show a minimum biogenic content of 53% and maximum of 63%, with an assumed average of 60% on a European level, which is consistent with data from other sources in the literature and findings of other studies of the NEWEST-CCUS project (Herraiz et al., 2022). For specific countries, this average may be lower, such as in the Netherlands where it has been reported to be in the range of 50% (Palstra & Stoffregen, 2010), or higher, such as in Denmark (68%) (Astrup et al., 2009). To accommodate these values, and as a conservative measure, this study undertakes a sensitivity analysis assuming a wider range of 50-70% biogenic content on a European level.

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[4] Up-to-date data on cement kiln co-incinerator capacities is lacking.

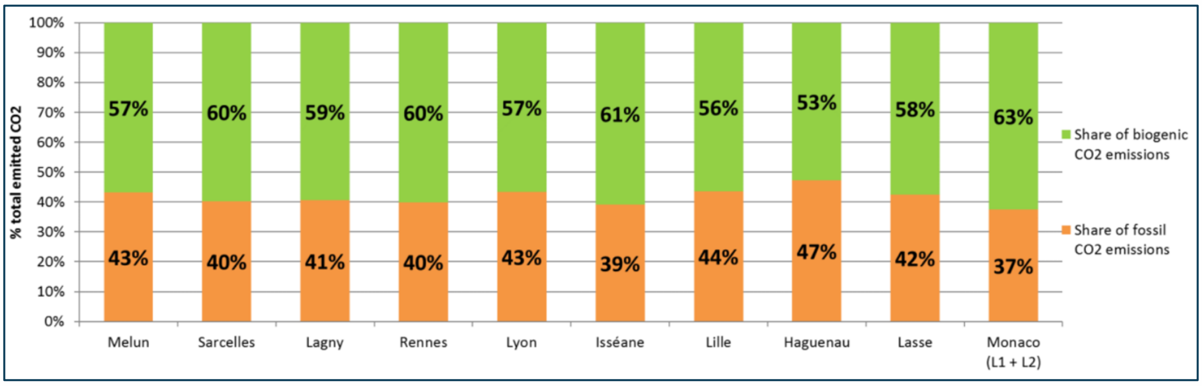

Figure 4: Percentage biogenic content in 10 WtE plants in France

Source: ADEME (2020)

3.1.3 From waste to climate impact

Based on the different destinations of waste streams, the fate of waste from its generation to its eventual impact on the climate (i.e. contribution to greenhouse gas emissions in the atmosphere) is presented in Figure 5. As far as this study is concerned, the climate impacts of waste specifically treated in WtE plants are of particular interest. Here, two overarching factors affect the type of climate impact: 1) whether WtE is retrofitted with carbon capture, and if so, whether the resulting CO_2 is destined for long-term storage or is temporarily utilised, and 2) whether it is the biogenic or non-biogenic (fossil) content of waste that is in question. The analysis of these different WtE-based scenarios yields 6 different combinations, which lead to different climate impacts:

1) WtE with carbon capture and long-term storage (whether in geological storage sites or another form of permanent utilisation, such as in long-lived construction materials):

    a. For the non-biogenic content, the resulting climate impact is ***emissions reduction***, as man-made fossil carbon content present in waste (e.g. plastics) would have ended up in the atmosphere otherwise.

    b. For the biogenic content, the resulting climate impact is the generation of ***negative emissions***, as CO_2 which is already in the biosphere is eliminated and locked out of the system. **The investigation of this scenario is the objective of this study.**

2) WtE with carbon capture and short-term storage or non-permanent utilisation (such as in the production of food, beverages, fuels or agricultural products):

    a. For the non-biogenic content, the resulting climate impact is the generation of ***direct emissions*** into the atmosphere, as man-made carbon content is released to the atmosphere.

    b. For the biogenic content, the resulting climate impact is ***'zero-flow emissions'***, i.e. emissions which would have resulted from the biogenic content of waste anyway, leading to a neutral impact (no net negative or positive) on the atmosphere.

3) WtE without carbon capture and storage:

a. For the non-biogenic content, the resulting climate impact is the generation of ***direct emissions*** into the atmosphere, as in scenario 2a.

b. For the biogenic content, the resulting climate impact is ***zero-flow emissions***, as in scenario 2b.

Similarly, there are climate impacts for other scenarios not involving waste-to-energy. For instance, some of the residual waste remains untreated and ends up being dumped or landfilled. As in scenarios 2a and 3a, the non-biogenic carbon content of dumped waste leads to direct emissions into the atmosphere, while the biogenic content of dumped waste leads to zero-flow emissions (e.g. in 2b and 3b). For landfilled waste, assessing climate impacts is more complicated. Specifically, landfilled carbon may be converted to methane gas in time, creating higher direct emissions to the atmosphere; this is even the case for the biogenic proportion of waste which would have otherwise resulted in zero-flow emissions if incinerated. However, the analysis of these scenarios remains beyond the scope of this study.

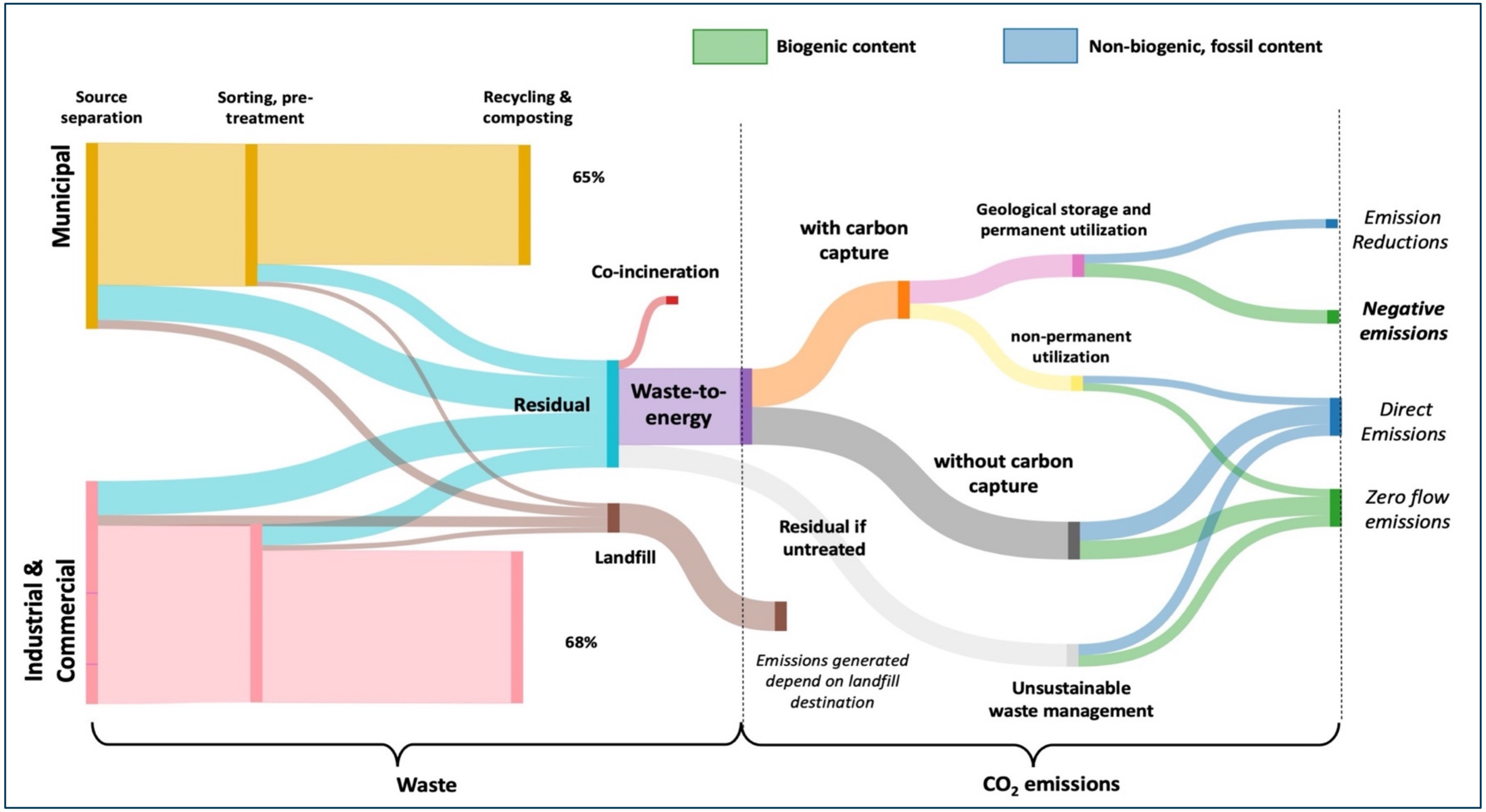

Figure 5: An illustrative Sankey diagram showing the projected fate of municipal, industrial and commercial waste in Europe in 2035

Source: Developed by the authors, based on 2017 waste data by CEWEP (2019), where 65% of municipal solid waste is assumed to be recycled and a maximum of 10% landfilled. Note that original waste data was reported in Mt per year and that the weighing of arrows corresponding to each waste stream (i.e. recycling & composting, residual and landfill) are proportionate to the data reported by CEWEP. Weighing of arrows corresponding to CO_2 emissions are not based on actual data and are for illustration only.

3.1.4 CO_2 capture rates

For post-combustion CO_2 capture, amine-based technology remains the most widely adopted and economically-feasible option and has been applied in large-scale commercial use since 2014 (e.g. at SaskPower's coal fired power plant in Boundary Dam, Canada) (Stéphenne, 2014). Monoethanolamine (MEA) aqueous solvents are suitable for atmospheric CO_2 containing gases over a wide range of CO_2 concentrations (Husebye et al., 2012) and are being developed commercially as an open art technology by some vendors. As such, post-combustion CO_2 capture with MEA is the technology assumed in this study to be used for capture from WtE plants.

There is a growing body of evidence suggesting that ultra-high capture rates, typically defined as CO_2 capture rates equal to or higher than 99%, can be technically and economical feasible. Feron et al. (2019) finds that increasing CO_2 capture rate from 90% to zero-direct emissions with an amine-based system leads to a 1.5 percentage point reduction in thermal efficiency for an ultra-supercritical coal-fired power plant (34.5% to 33% LHV) and a 2.2 percentage point reduction in thermal efficiency of a gas-fired combined cycle (48.6% to 46.4 LHV). Danaci et al. (2021) also reports that increasing the capture rate from 90% to 99% for three different flue gas flow rates of 4%, 10% and 20%vol CO_2 concentrations leads to an increase in overall capture costs of 7%, 10% and 13%, respectively. Similarly, pilot testing at the National Carbon Capture Centre (NCCC) showed that increasing the CO_2 capture rate from 90% to 99% in a coal-fired power plant results in an increase in specific reboiler duty of lower than 5% (Gao et al., 2019), while Mitsubishi Heavy Industries Engineering Ltd tested with 99.5% CO_2 capture on a reference coal-fired power plant and reported that near zero emissions could be achieved with a 3% increase in the total annualised cost of CO_2 capture ($/t$CO_2$).

Su et al (2023) uses operating data from literature and operating data from an unspecified WtE UK plant to examine configurations '*representative of the WtE facilities in operation in Europe'.* They report power and heat output for a power-only WtE plant and CHP WtE plant before and after the retrofit of open art 35%wt MEA CO_2 capture system. Two capture rates are examined: a 95% capture rate and a 99.7% capture, corresponding to 100% capture of fuel CO_2. They find that 100% capture of fuel CO_2 in a WtE plant requires an additional 6m of packing height in the CO_2 absorber column (18m at 95% capture) and increases the electricity output penalty in the power-only configuration by 7 kWh_e/tCO_2 (from 297 kWh_e/tCO_2 at 95% capture). For the CHP plant, the power and heat output are 4.9MW_e and 31.4MW_{th}, respectively, and 5MW_e and 32.2MW_{th} at 95% capture.

In addition to the aforementioned studies, UK Government's guidance on best available amine-based technologies for post-combustion carbon capture, published in July 2021, states that an operator should aim to achieve a design CO_2 capture rate of at least 95%, although operationally this can vary up or down (UK Government, 2021). Although this guidance only applies to gas-fired and biomass power plants at the time of writing, it is expected that similar expectations on capture rates will apply when specific guidance for waste-to-energy plants is released in the UK.

In this context, Su et al. (2022) conducted specific analysis for WtE plants on the impact of different capture rates – namely 90%, 95% and 100%[5] – on power consumption (i.e. total electricity output penalty) and the avoidance costs of CO_2. They show that there is limited variation in both metrics with capture rates rising from 90 to 100% (Figure 6).

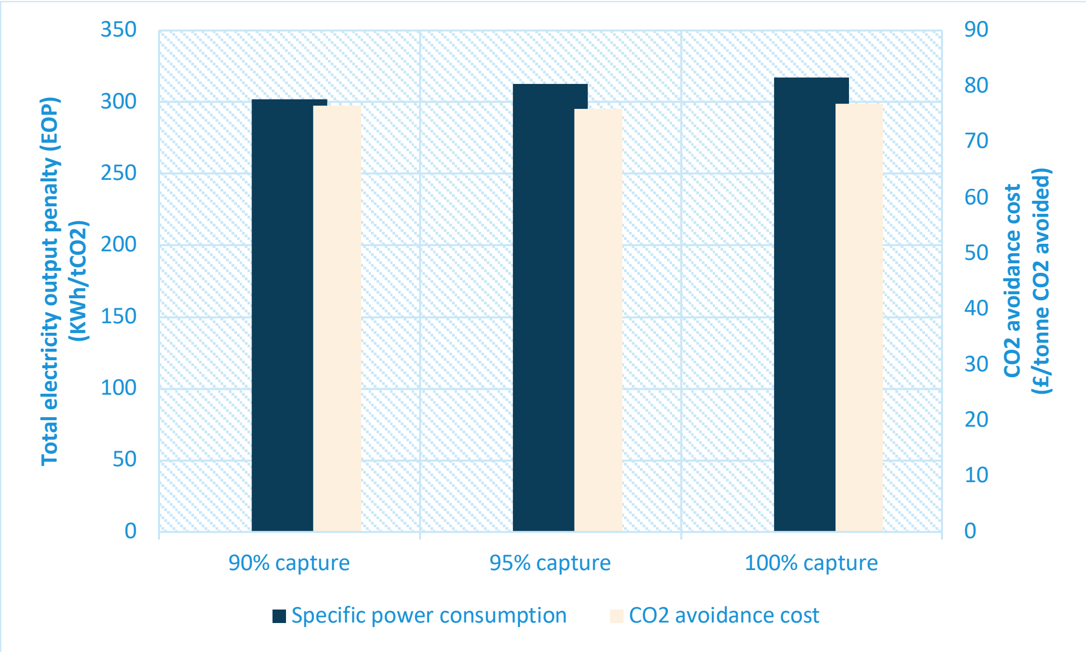

Figure 6: Variation in power consumption and CO_2 avoidance costs with different capture rates

Source: Su et al. (2022).

3.2 Identification of WtE facilities and CCS clusters

To assess whether WtE plants can be retrofitted with CCS, existing WtE plants in Europe are first identified through personal communications with CEWEP, including coordinates and installed capacities (2021 data). Second, future CCS clusters and hubs are identified from a number of industrial reports, recent government policy reports, academic publications, and CC(U)S-specific projects and webinars, including GCCSI (2016), ALIGN CCUS project (2017), REALISE CCUS project (2020), and International Association of Oil & Gas Producers (2021). The coordinates of each cluster/hub are then

[5] It is important to note that the 100% capture rate reported in Su et al (2022, 2023) applies to CO_2 originating from the combustion of waste. When accounting for combustion air, the equivalent capture rate is 99.7%.

collated using Google Earth, with the exact location corresponding to a central reference point within each cluster.[6] Overall, a total of 22 clusters were identified and are listed in Table 1.

The focus on a WtE plant's proximity to a CCS cluster or hub is justified by the fact that a CCS cluster/hub will already have a storage outlet in place, including an existing or planned transport infrastructure (whether through pipelines or ships). That said, it is important to note that the inaccessibility of a WtE plant to a CCS cluster does not eliminate the possibility of capturing CO_2 from that facility, as it could still have direct access to a geological storage site, granted it has its own transport routes, as discussed below. Similarly, coastal WtE facilities which are not close to a CCS cluster/hub can capture CO_2 for transport via ships and are thus retained for further analysis.

It is also noteworthy that, if a WtE plant is not located near a CCS cluster/hub or a geological storage site, it may be close to large industrial users of CO_2 where the captured CO_2 can be utilised. However, generating negative emissions involves the storage of the captured CO_2 away from the atmosphere for timescales consistent with climate change mitigation, i.e. in excess of 1,000 years. Examples of permanent CO_2 utilisation applications are mineralization in long-lived materials, e.g. in concrete or in construction aggregates. As these industries are not yet developed at scale, and the likely areas of production cannot be accurately located, these utilisation routes are currently not included in the scope of this study. The authors recognise that they may directly contribute to negative emissions in the future.

Table 1: List of 22 European CCS clusters and hubs included in the analysis

Country	Cluster/hub
France	Le Havre (COCATE)
	Marseille (VASCO)
	Pycasso
	Dartagnan
UK	Teesside
	Yorkshire & Humber
	Merseyside
	Firth of Forth
Norway	Klemestrud/Northern
	Skagerrak/Kattegat

[6] Coordinates and identified central points provided as supplementary material.

Sweden	Skagerrak/Kattegat
Denmark	Skagerrak/Kattegat
	C4 Carbon Capture
	Greenport
Netherlands	Porthos
	Rotterdam
Germany	Duisburg
	Hamburg
Belgium	Antwerp
Ireland	Ervia Cork
Italy	Ravenna CCS Hub
Poland	EU CCS Interconnector

3.3 Distance between WtE facilities and CCS clusters/hubs

Subsequently, distances between WtE plants and CCS clusters/hubs are calculated using their coordinates. In this analysis, transport via straight-line pipelines is assumed, which may admittedly not be possible in certain cases (e.g. mountainous topology, crossing cities or rivers, etc.) but remains a best approximation and a subject for further investigation at the facility level. The distances were determined using the equation:

$$D = 6371 * acos(cos(radians(90-Lat1)) * cos(radians(90-Lat2)) + sin(radians(90-Lat1)) * sin(radians(90-Lat2)) * cos(radians(Lon2 - Lon1))$$

where Lat 1 refers to the latitude of a WtE facility and Lon 1 to its longitude, while Lat 2 refers to the latitude of a CCS cluster/hub and Lon 2 to its longitude.

Here, distance from a cluster or hub is assumed to be more relevant for CO_2 transport via pipelines than through shipping, where costs of pipeline transport are more sensitive to pipeline length as CAPEX constitutes more than 90% of overall transport costs; this is less so the case for shipping of CO_2 where costs are mainly operational (ZEP, 2019). As such, and as far as transport via pipelines is concerned, cumulative capacity of the European WtE fleet is reported as a function of distance from CCS clusters/hubs. It is also assumed that facilities falling within 300km from a cluster would likely transport CO_2 via onshore or offshore pipelines while those falling outside this range may either 1) be coastal and hence likely to transport CO_2 via ships, 2) be closer to a CO_2 storage site than the cluster/hub itself, or 3) be considered 'stranded' for geological storage if neither of the former two options apply. As previously discussed, plants stranded for geological storage may be able to prevent CO_2 from the atmosphere and create negative emissions, via some forms of CO_2 utilisation compatible with climate change mitigation.

Ultimately, WtE plants are categorised into four groups: 1) plants located within an acceptable distance range to CCS cluster/hubs, 2) coastal plants not within an acceptable distance to a CCS cluster/hub, 3) plants not within an acceptable distance to a cluster/hub nor coastally located, but within range to a geological storage site, and 4) plants without any identified means of geological CO_2 disposal. Mapping of geological storage sites is based on data provided by the CO2StoP (CO_2 Storage Potential in Europe) project and is publicly available through the European Geological Data Infrastructure (EGDI) database (Figure 7).[7]

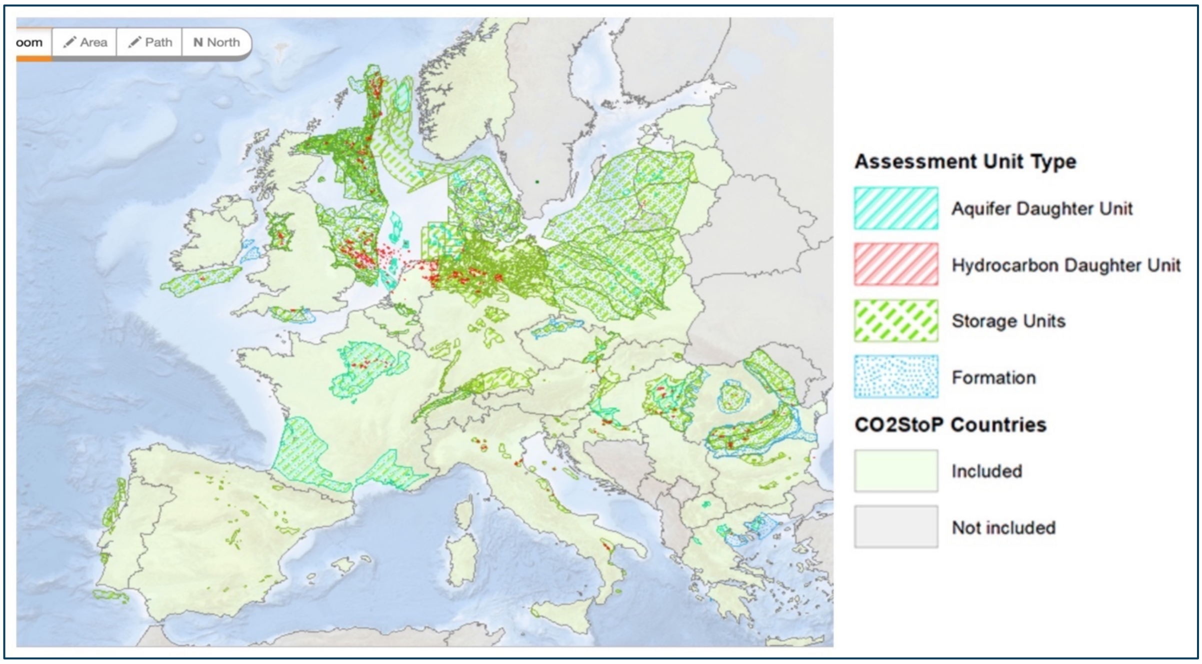

Figure 7: Map of Europe's geological storage sites

Source: CO2StoP project.

[7] Note that state participants to the CO2StoP project did not include Sweden and Finland and so analysis for corresponding WtE plants in these regions is not included in this study, except when they are closer to storage sites located outside both countries.

3.4 Availability of space for CO_2 capture retrofit

For all plants, the potential for a CO_2 capture retrofit is assessed based on availability of land to accommodate the footprint of a capture facility. In this stage, the geographical attributes of the area surrounding the identified plants are explored using satellite imagery (e.g. Google Earth): as a rule of thumb, the larger a WtE plant, the larger the land footprint of the corresponding capture facility needed. In its Climate Roadmap, CEWEP (2022a) reports that a tonne of MSW treated has an emission intensity of one tonne of CO_2e. However, this estimate varies between countries and different plants within each country: for instance, the UK Environment Agency (2020) reports a range of 0.7-1.7 tCO_2 per tonne of waste treated. To provide higher certainty to this analysis, a sensitivity analysis is conducted, assuming CEWEP's average emissions intensity (i.e. 1 tCO_2/t) as a lower end, and the UK environment Agency's maximum of 1.7 tCO_2/t as an upper end: more space will be required when assuming the latter. This allowed the identification of i) WtE plants with no space limitation (i.e., where enough space is available when assuming 1.7 tCO_2/t), ii) WtE plants stranded for space (i.e., space not available with the assumption of 1 tCO_2/t) and 3) WtE plants where further site-specific assessment would be required (i.e. space available with the assumption of 1 tCO_2/t, but not 1.7 tCO_2/t).

The footprint of 7 amine-based post-combustion CO_2 capture facilities from public domain studies or Google Earth imaging is used to estimate space requirements for a CO_2 capture retrofit (US Department of Energy, 2020; AECOM, 2020; Gassnova, 2019; International CCS Knowledge Centre, 2018; World Bank 2016), and then develop a correlation of footprint in m^2 as a function of CO_2 capture capacity (tonnes of CO_2 per year), as shown in Figure 8.[8]

As noted, this work assumed the use of amine technology for CO_2 capture which is technically capable of achieving ultra-high capture rates of CO_2 of 100% of CO_2 from waste combustion. Further details on the design and operation of the post-combustion CO_2 capture process are available in Su et al (2023). Figure 9 shows examples of two WtE plants, one with enough on-site space for CO_2 capture retrofit (the AVG KG Tornesch WtE plant in Germany) and another without space (Berlin City Cleaning WtE plant).

[8] Note that the capture facility at AVR Netherlands WtE plant has an area of around 2400m^2 but does not contain a compression component. The total area needed for a full capture facility at the plant including compression was assumed to be 1.5x larger than without compression (i.e. 3600m^2), based on the land footprint ratio of the compression component to total capture facility size at a reference plant, the Shand power station in Saskatchewan, Canada.

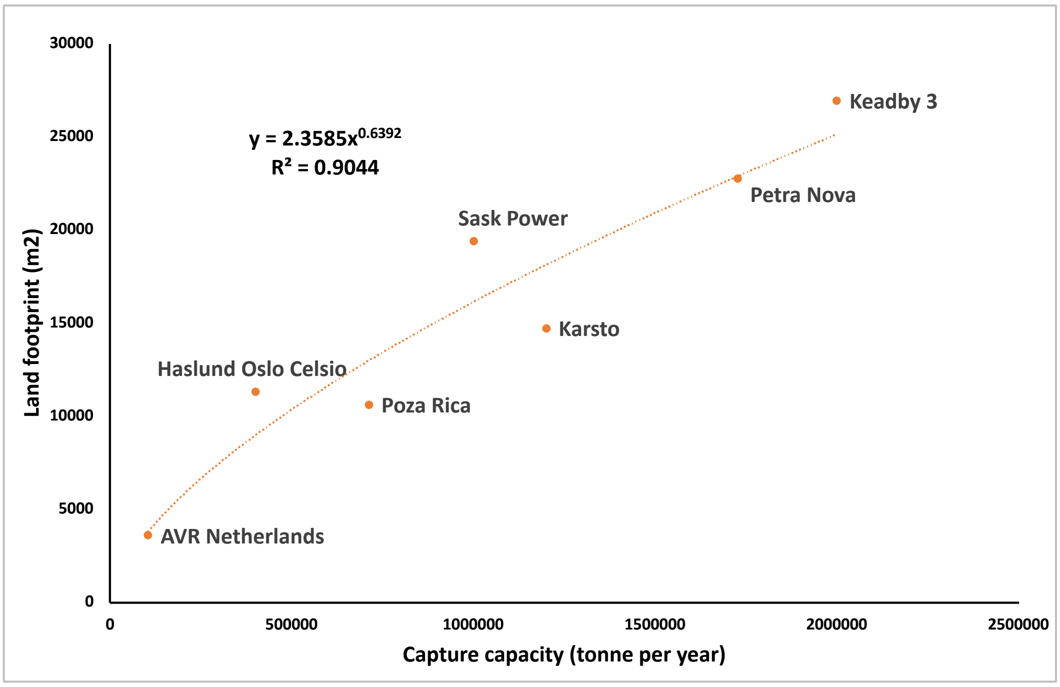

Figure 8: Land footprint as a function of capture capacity of existing capture facilities globally

Figure 9: Examples of a WtE plant with no space limitation for CO_2 capture retrofit (AVG KG Tornesch plant in Germany, left) and a plant with insufficient space for retrofit (Berlin City Cleaning WtE plant, right)

3.5 Economic feasibility of CO_2 retrofit based on capture capacity

The majority of commercial CCS projects currently have a capture capacity higher than 100,000 tCO_2/year. Small scale WtE emitters could possibly be retrofitted with CCS, under the right conditions. This analysis reports potential negative emissions by distinguishing between plants based on CO_2 capacity, with the assumed cut-off capacity being 100,000 tCO_2/year. This is equivalent to a waste processing capacity of around 58,800 tonnes, if the higher end of the UK Environment Agency's emissions intensity estimate of 1.7 tCO_2/tonne is assumed, or a waste processing capacity of 100,000 tCO_2/year, if CEWEP's average estimate of 1 tCO_2/t is adopted.

Overall, this methodology yields different selections of WtE plants from which negative emissions can be generated, based on three main factors: 1) distance from CCS clusters/hubs and from storage sites, 2) on-site space for capture retrofit and 3) plant emissions capacity (Table 2). Total negative emissions under each scenario are then evaluated by multiplying the overall WtE capacity of the plants included in that scenario by a biogenic content range of 50-70%, as discussed earlier in Section 3.1.2.

Table 2: Scenarios for assessing retrofit potential of existing plants, assuming a number of limiting factors

Country	Cluster/hub		
Scenarios	**Limiting factor(s)**	**Condition(s)**	**WtE plants included**
Scenario 1	No restriction to deploying CCS	N/A	All existing WtE plants (but excluding any new capacity)
Scenario 2	Transport	Access to geological storage via proximity to a CCS clusters/hubs, or via shipping	WtE facilities falling within a 300km distance from a CCS cluster/hub, in addition to coastally-located ones
Scenario 3	Transport	Access to geological storage	As Scenario 2, with the addition of WtE facilities located within 100km of CO_2 storage capacity

Scenario 4	Capture	Space availability for retrofit	WtE facilities with space availability for CCS retrofit according to the relationship between land footprint and capture capacity presented in Figure 8. Analysis includes two sets of WtE plants: those with enough space if assuming 1 tCO_2/t of waste combusted and those with enough space if assuming 1.7 tCO_2/t (i.e. more conservative)
Scenario 5	Capture and plant size	Plant size large enough for the economic viability of carbon capture	WtE facilities producing more than 100,000 tCO_2/year and with enough on-site space for capture retrofit
Scenario 6	Transport,	All of the above	

4 Results & Discussion

4.1 Distribution of European WtE facilities and CCS clusters

Using 2021 CEWEP database, data was collected for 498 WtE facilities from 23 European countries. With a total overall fleet installed capacity of 100.9Mt of waste per year, the average processing capacity of a WtE plant across Europe is around 200,000 tonne of waste per year. Figure 10 shows the geographical distribution and installed capacities of these facilities.

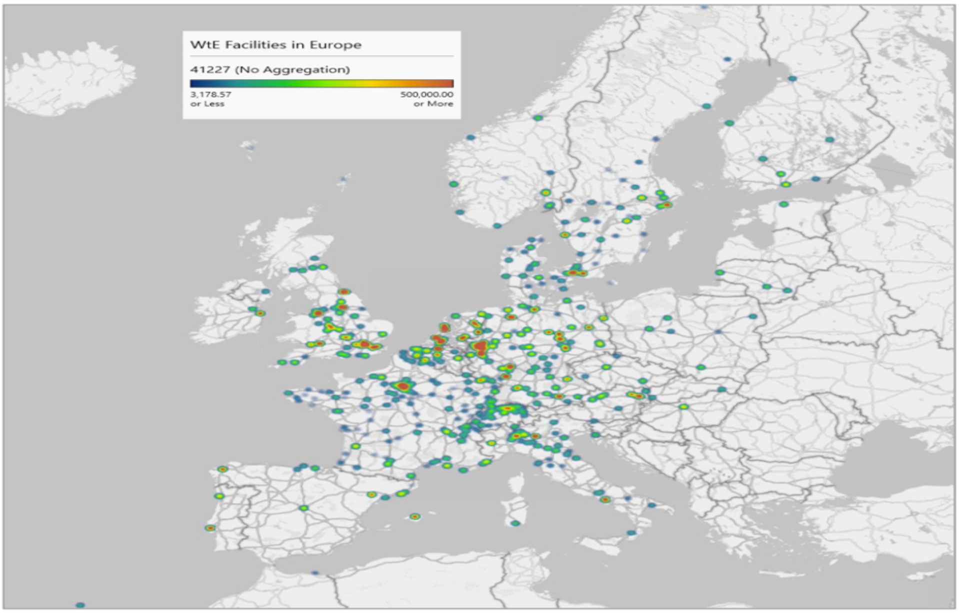

Figure 10: Location and installed capacities of European WtE facilities
Source: CEWEP (2021)

Germany is the country with the highest WtE installed capacity, processing around 24.7Mt of waste (2018 figures) in 85 facilities, followed by France and the UK, both with installed capacities of around 15.8Mt each, processed in 132 and 52 WtE facilities respectively. Using a number of data sources, 22 CCS clusters and hubs in construction or planning in Europe are identified from the literature and plotted in Figure 11.

Figure 11: Map of European CCS clusters and hubs[9]

Investigating the closest CCS cluster or hub to a WtE plant, the analysis shows that around a third of overall installed capacity (32.9 Mt waste/year, 118 plants) falls within a 100km range, while more than half (57.9 Mt/year, 241 plants) falls within 200km, and more than two-thirds (76.4 Mt/year, 351 plants) within a 300km range (Figures 12 and 13).

[9] This and all subsequent maps have been produced using the online mapping tool Map Maker (available at http://maps.co) for which a license has been acquired.

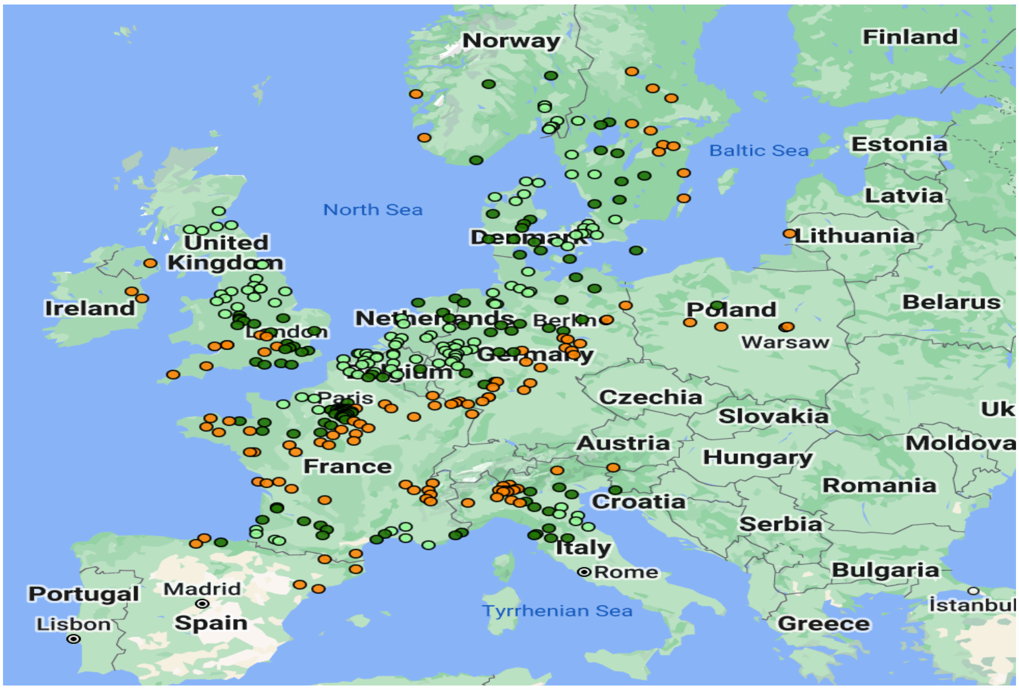

Figure 12: WtE plants falling within 100km (light green), 200km (dark green) and 300km (orange) from a CCS cluster or hub

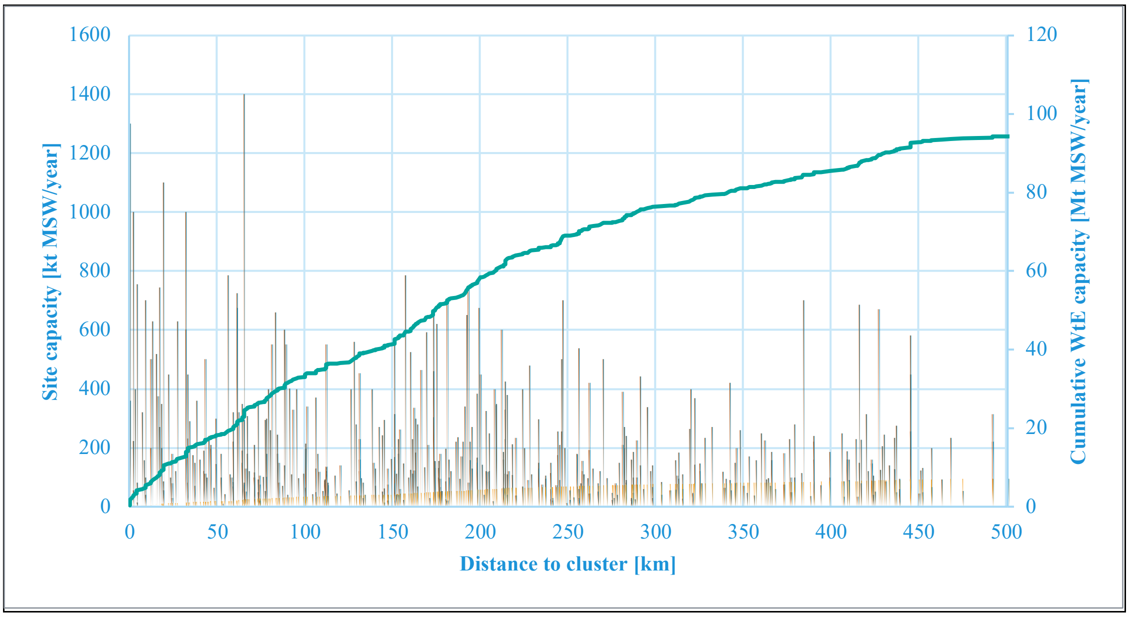

Figure 13: Cumulative installed WtE capacity as a function of distance from a CCS cluster/hub

For plants falling outside this predetermined range, transport via ships is considered. Here, 61 WtE facilities with an overall installed capacity of 11.3 Mt/year are found to be located along a coast and from which CO_2 could be potentially captured and shipped. These plants are identified in Figure 14.

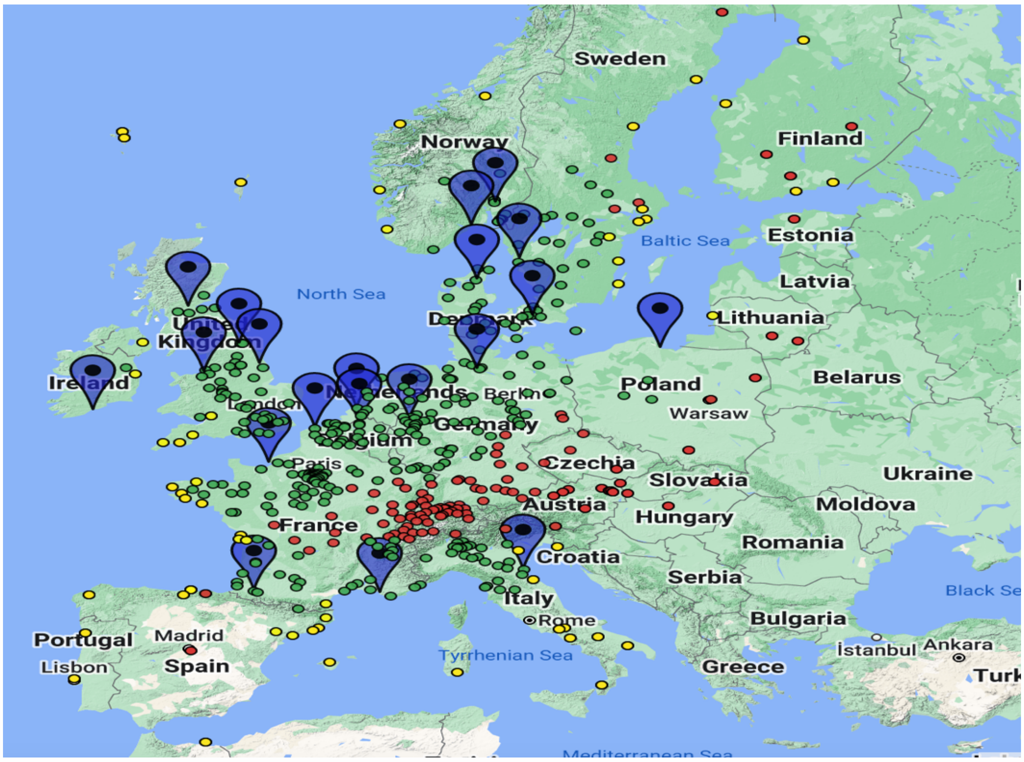

Figure 14: WtE plants within 300km (green) and outside the 300km range (red) of a CCS cluster or hub. Coastal WtE facilities for which transport by ships is possible are denoted in yellow

For plants that are further than 300km from a CCS cluster or hub and are not coastal, proximity to geological CO_2 storage sites was appraised. Of the 102 plants which did not satisfy either of the first two criteria, 97 were within 100km distance to a storage site (total capacity of 16.5 Mt/year) while only 5 plants did not satisfy any of the three criteria. These are identified in Figure 15.

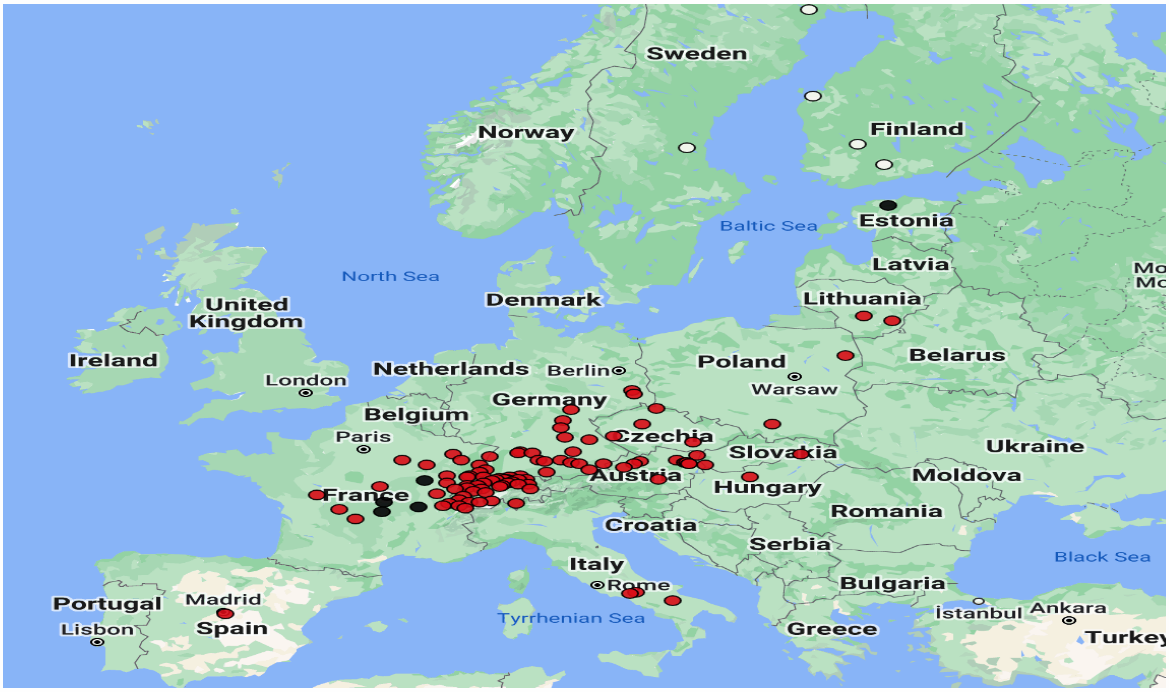

Figure 15: WtE plants which are outside a 300km range from a CCS cluster/hub and are not coastal. Plants in red are within 100km of a storage site, while those in black are further than 100km from a storage site. Plants in white are in Finland and Sweden, where storage data is not available

4.2 On-site space availability for CO_2 capture retrofit

For plants qualifying on the basis of distance to clusters, hub or storage sites or those that are coastally located, further analysis is conducted based on the emissions footprint at the plant level: plants which emit more than 100,000 tCO_2 per year are retained. However, as emissions intensity of the waste treated can vary, two different scenarios are assumed: plants emit 1.7 tCO_2/tonne of waste (conservative scenario, as larger space will be needed for a capture facility) or 1 tCO_2/tonne (average scenario):

- The first scenario limits capture retrofit to plants with a processing capacity of 58,800 tonnes of waste per year[10], and
- The second scenario includes WtE plants with a processing capacity of 100,000 tonnes of waste per year.

[10] 100,000 (tCO_2/y)/1.7 (tCO_2/t) ≈ 58,800 t/year

For plants included in the first scenario, no spatial restrictions exist for CO_2 capture retrofit: 333 plants with a total capacity of 58.6 Mt/year satisfy this condition. The second scenario includes plants for which there are possible spatial constraints for capture retrofit and further site-specific analyses are required: this applies to 27 plants with a total capacity of 8.5 Mt/year. For the remaining 132 plants with an overall capacity of 33.5 Mt/year, it is certain that even when assuming 1 tCO_2/tonne of waste, there is insufficient space for capture retrofit (Figures 16 and 17).

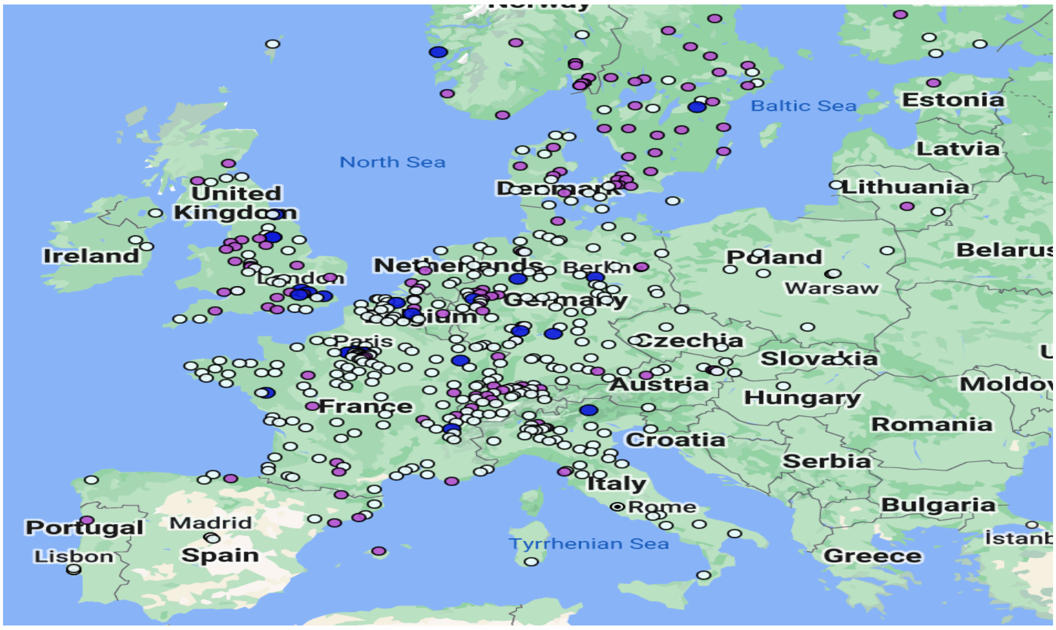

Figure 16: WtE plants with no space limitations (white), further site-specific analysis is required (blue) and insufficient space for CO_2 capture retrofit (purple)

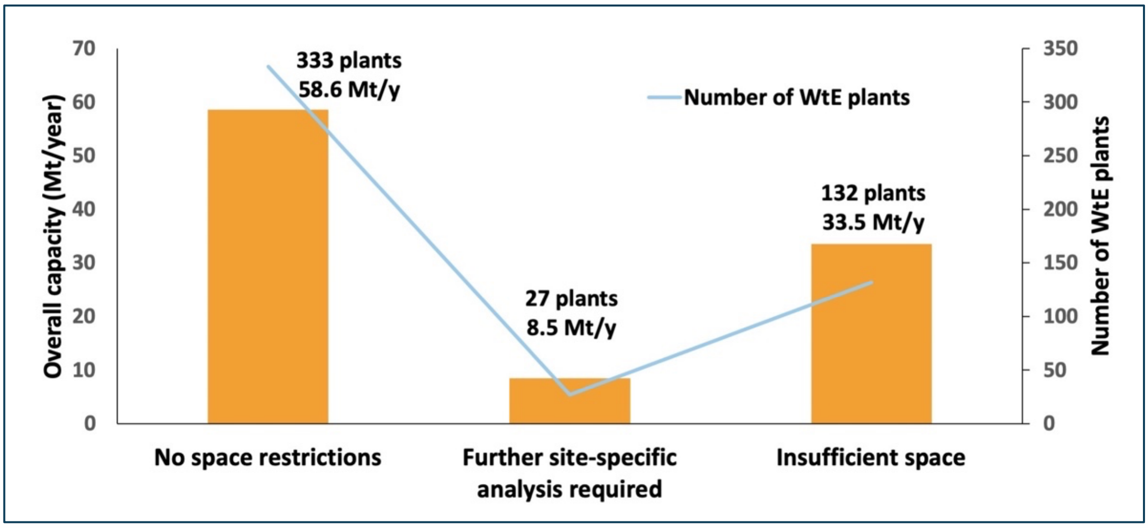

Figure 17: Distribution of WtE plants based on space availability for CO_2 capture retrofit

However, it is important to note here that the possibility of capturing CO_2 from WtE plants with space requirement limitations is not disregarded. This is because the analysis assumes the use of amine technology, while CO_2 capture process intensification – that is the introduction of capture technologies with much smaller footprints – is already underway in other sectors, such as oil refineries and offshore platforms and may become available in the WtE sector in the future (GCCSI, 2022).

Examples include the use of rotating packed beds (Yu et al., 2012; Zhao et al., 2014; Xie et al., 2017) or technology using CO_2 liquefaction (e.g. Seo et al., 2016; Muhammad et al., 2020). Sites with limited footprint which are unsuitable for conventional amine technology retrofit may nonetheless be suitable for the addition of more compact CO_2 capture technology. Finally, other major barriers to CO_2 capture retrofit include access to water resources, access and suitability of the power cycle for steam extraction or a necessary corridor for CO_2 transport in the vicinity of the plant. The authors recognise that these barriers must be further examined on a case-by-case basis but remain beyond the scope of this work.

4.3 Assessment of negative emissions

This study shows that, if all of the existing European WtE fleet (i.e. 100.9 Mt of installed capacity) was retrofitted with CCS technology, negative emissions in the range of **-50.5 to -70.6 MtCO$_2$/y** would be generated per year, assuming a capture rate of 100% using recent evidence on ultra-high capture levels.

CEWEP (2019) anticipates a total of 142Mt of residual waste generated in 2035 when meeting the thresholds for recycling (minimum of 65%) and landfilling (maximum of 10%) in accordance with the EU Circular Economy Package. It may admittedly not be possible to bridge the current ~30Mt gap in WtE capacity needed to treat all this residual waste, as some existing WtE plants come to the end of their life and others are newly commissioned. Yet, in theory, if enough WtE capacity where to be built and is retrofittable with CO_2 capture, a range of **-71 to -99.4 MtCO$_2$/y** of negative emissions can be achieved.

When CCS limitations are considered, such as distance of WtE plants to CCS clusters/hubs and storage sites or space availability for retrofit, these ranges are naturally reduced. On distance, as presented earlier, 32.9 Mt of waste is treated yearly in WtE plants which fall within a 100km radius from a CCS cluster/hub, while 57.9 Mt/year is processed in plants within 200km and 76.4 Mt/year within 300km. In a scenario where all plants within these ranges are retrofitted with CCS (i.e. disregarding availability of on-site space for retrofit), negative emissions in the ranges of - 16.5 to -23 MtCO$_2$/year (corresponding to a 100km radius), -29 to -40.5 MtCO$_2$/year (200km) and -38.2 to -53.5 MtCO$_2$/year

(300km) can be generated. Moreover, additional negative emissions in the range of -5.6 to -7.9 $MtCO_2$/year could be generated from coastal WtE plants which are outside the 300km range (corresponding to total installed capacity of 11.3 Mt/year).

Table 3 summarises the results of this study, including an assessment of the overall number of plants and corresponding potential for negative emissions under each scenario. Figure 18 further depicts these results under two different assumptions: the generation of 1 tCO_2 and 1.7 tCO_2 per tonne of waste treated.

Table 3: Negative emissions assessment under different scenarios.

Scenarios	Limiting factor(s)	Condition	Number of plants (total processing	Potential for negative emissions
Negative emissions in all non-recycled residual waste (as in Figure 2). This includes waste going to the existing WtE fleet and residual waste currently going to landfill (the WtE capacity gap).				
N/A	No CCS restriction	N/A	Unknown in the future	-71 to -99.4
Analysis of the existing WtE fleet only				
Scenario 1	No CCS restriction	N/A	492	-50.5 to -70.6
Scenario 2	Transport (distance to CCS clusters/hubs)	within 100km	118 (32.9 Mt)	-16.5 to -23
		within 200km	241 (57.9 Mt)	-29 to -40.5
		within 300km	351 (76.4 Mt)	-38.2 to -53.5
Scenario 3	Capture (enough on-site space availability)	If 1.7tCO_2 emitted per tonne of waste	333 (58.6 Mt)	-29.2 to -40.9
		If 1.0tCO_2 emitted per tonne of waste	360 (67.1 Mt)	-33.4 to -46.8
Scenario 4	Capture and plant size (enough on-site space + plant size > 100,000 tCO_2/y)	If 1.7tCO_2 emitted per tonne of waste	274 (56.5 Mt)	-28.1 to -39.4
		If 1.0tCO_2 emitted per tonne of waste	207 (51 Mt)	-25.4 to -35.6
Scenario 5	Transport (including to storage sites) and capture	N/A	249 (46.1 Mt)	-23 to -32.1

Scenario 6	All of the above (transport, capture and plant size)	If 1.7tCO_2 emitted per tonne of waste If 1.0tCO_2 emitted per tonne of waste	203 (44.5 Mt) 154 (40.5 Mt)	-22.1 to -31 -20.1 to -28.2

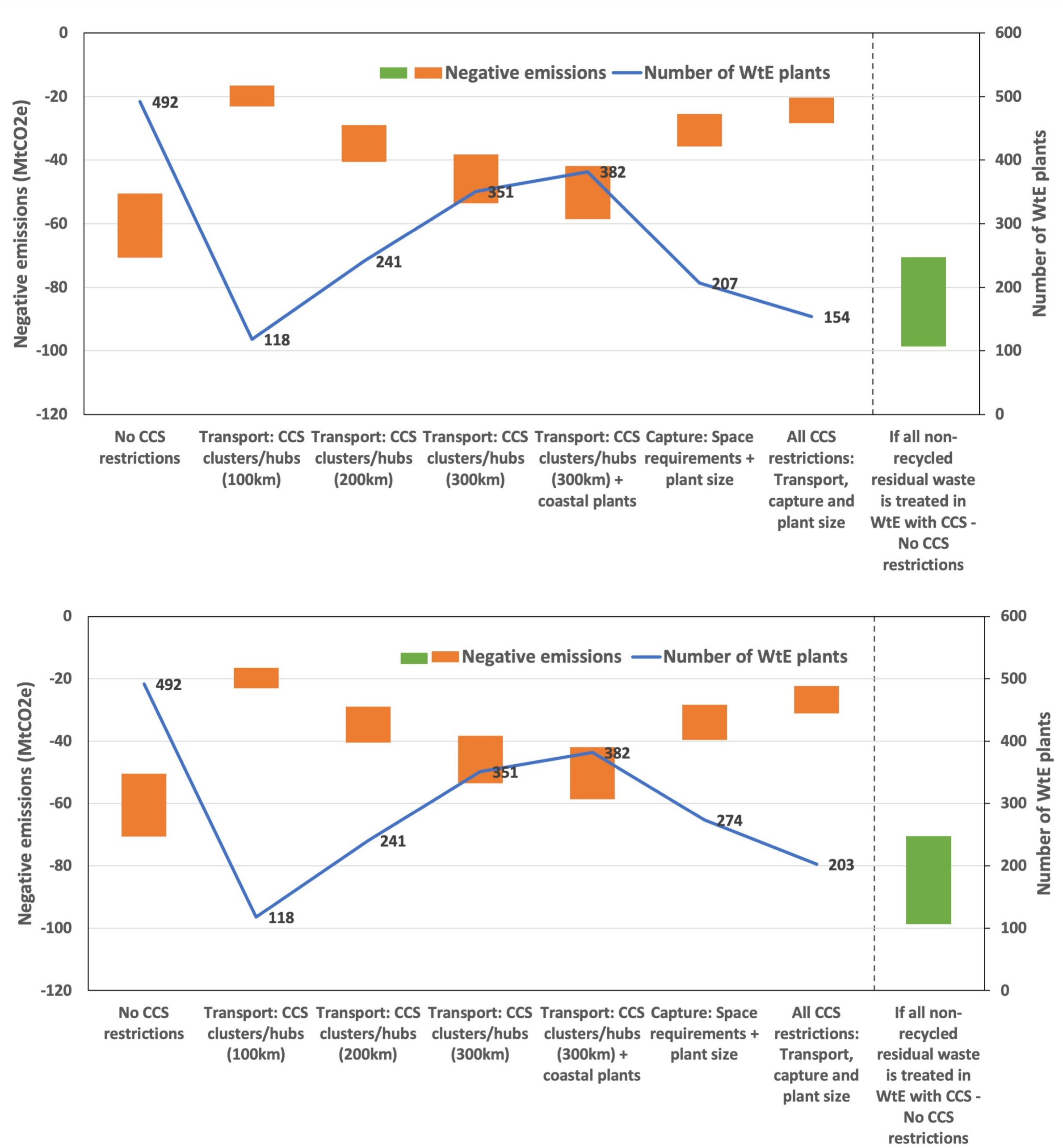

Figure 18: Assessment of the range of negative emissions under each scenario, assuming 1 tCO_2/t waste (above) and 1.7 tCO_2/t waste (below)

5 Limitations of this study

For waste-specific analyses, this study was limited by the uncertainty regarding the waste resource - both in magnitude and composition - and uncertainties regarding the evolution in future waste management policy, which in turn creates an uncertainty in the residual waste resource, again both in magnitude and composition. Limitations concerning the possibility for CCS retrofit were broadly encountered at three stages: i) when selecting WtE plants to be included in this analysis, and when conducting analyses on ii) distance and iii) space requirements. On the former, this study adopted a bottom-up approach that was limited to WtE grate-fired boilers (there are additional negative emissions which can be captured in the waste sector from landfill gas recovery, anaerobic digestion, etc., which are not included in this study that focused on WtE). It was also limited to the existing WtE fleet in Europe and did not account for negative emissions which can be generated from untreated residual waste, the estimation of which remains highly uncertain. Moreover, this work did not account for plant (un)availability, which could reduce the number of plants from which CO_2 capture is economically viable.

On distance, this work assumed CO_2 transport by straight-line pipelines from WtE plants to CCS clusters, hubs or storage sites, without regard to surrounding topology: in practice, it may not always be feasible to transport CO_2 by pipelines if rivers, cities or mountains need to be crossed. The analysis also did not assume CO_2 transport by barges along fluvial transport axes (e.g. Rhine, Danube, Rhone rivers), which may increase the number of plants from which CO_2 can be transported, especially from the innermost part of Europe. It is also worth noting that the calculation of distance from WtE plants to surrounding storage sites was approximated based on existing maps of storage sites (from the CO2StoP project), rather than by using specific coordinates. It is difficult to assign coordinates to large surface areas covering storage sites, so the distance was measured from WtE plants to the closest boundary of storage sites. Moreover, the CO2StoP project database does not include storage sites in Finland and Sweden, which were eventually missing from this analysis: it is worth noting however that all plants within or in proximity to both countries were close to clusters, hubs or storage sites in surrounding regions anyway, and were hence included in the ultimate analysis.

Lastly, on space requirements, this work assumed that WtE plant owners/operators can acquire the plant's surrounding land for CO_2 capture retrofit, which may not always be the case. The authors also only assumed the use of conventional post-combustion capture technology, whereas other less-intensive options may become commercially viable in the future (e.g. rotating packed beds and hot potassium carbonate), which would increase the number of plants which can be retrofitted with CO_2 capture technology, and hence increase the range of negative emissions achievable.

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