WASTE-TO-ENERGY CLIMATE ROADMAP

TECHNICAL ANNEX (TA)

MAIN ASSUMPTIONS & METHODOLOGY

The CEWEP climate roadmap intends to illustrate in a simplified way the current and future climate balance of the European Waste-to-Energy (WtE) sector.

It takes inspiration from the latest scientific works and technical references in literature to offer a vision around this topic adopting a Life Cycle Thinking. The work can serve as indication on a general level, but due to the many specificities and complexities involved, it cannot offer a detailed Life Cycle Assessment.

The bibliography listed at the end is recommended for more information.

INDEX

Section I. WtE direct CO_2 emissions

In a conventional WtE installation, carbon contained in residual waste is almost completely transformed (more than 99%) into CO_2. This generates at the stack, depending on the waste composition, an emission close to one tonne of CO_2 per tonne of waste treated. This simple but consolidated ratio [1] can be then applied as an average on EU level for conventional WtE facilities that treat mixed non-recyclable waste coming from municipal activities together with similar residual waste from commercial and industrial activities.

The total CO_2 generated by WtE depends on the composition of residual waste and can be differentiated in two categories according to its origin:

1. **biogenic CO_2**, coming from the biodegradable fraction of different waste streams, such as residual paper and cardboard, wood, leather, kitchen waste and green residues, not suitable for separate collection systems and recycling;

2. **fossil CO_2**, coming mainly from fossil-based waste such as residual plastics, textiles of fossil origin, etc.

By the determination of one of the two fractions, the other can be found by difference.

Ia. BIOGENIC CO_2 emissions

There are essentially two ways for the determination of biogenic CO_2 emissions: experimental (via radiocarbon dating - 14C analysis of carbon dioxide sampled from the flue gas) or modelling (via software through mass and energy balance calculations using the balance method).

On average, **the share of biogenic CO_2 emissions monitored at European level by WtE plants is around 60%, while the remaining 40% is fossil.** These values have been recorded by CEWEP WtE plants operators across Europe (Sweden, Denmark, Germany, Italy, etc.) and also confirmed in the scientific literature.

For example, Larsen et al. (2013) compared the biogenic carbon content determined via different methods and found that typically two-thirds of the CO_2 is biogenic and one third is fossil in flue gas produced by Danish incinerators. [2]

These results are also aligned with an investigation conducted by Fuglsang et. al (2014) comparing different sampling and measurement methodologies, data variation and uncertainty. [3]

More technical information on methodologies and standards can also be found on the Swedish investigation by Avfall Sverige on the determination of the fossil carbon content in combustible municipal solid waste in Sweden. [4]

More recently (November 2020), a French study on the determination of the biogenic and fossil content in waste found that the average **biogenic part of the CO_2 emissions emitted by the WtE plants analysed resulted in 58%,** which corresponds to an average 67% biomass content of the total residual waste treated and an average 55% renewables share in energy production by WtE plants. The results vary a lot depending where the plant is located, hence on the composition of waste and how effectively plastic waste (and biowaste) collection is implemented. The project “UIOM 14C” has been developed by Cabinet Merlin and ENVEA in collaboration with the French Environment Agency ADEME and FNADE, representing the private waste management industry in France. In the study, 148 representative samples of more than 2 million tonnes of waste incinerated in 10 French WtE plants have been collected through a monthly measurement campaign, applying the "MassBio2" method.

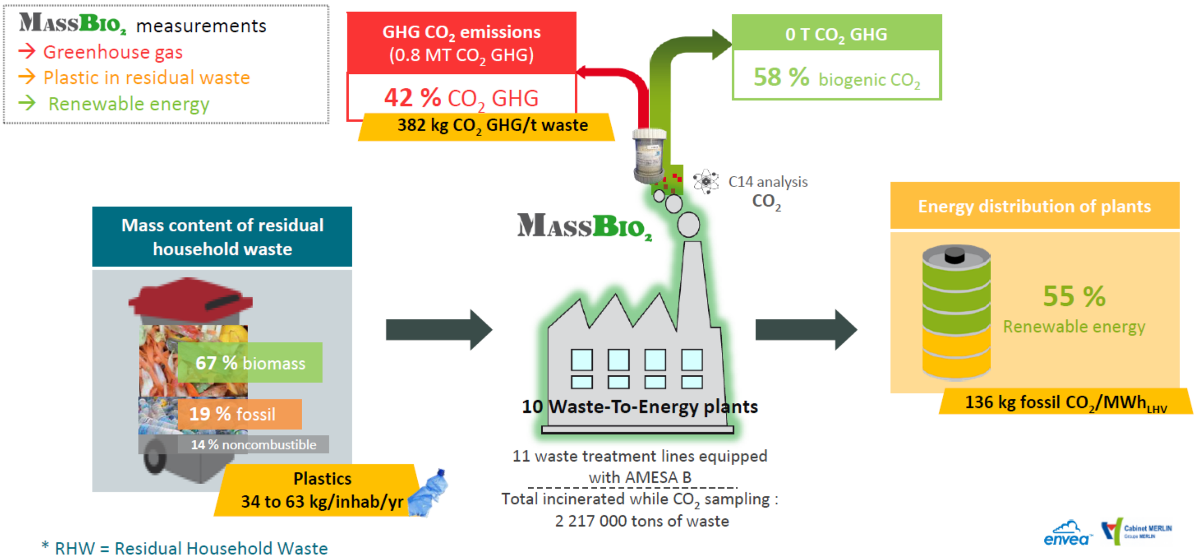


Figure1: Summary Slide of The French "UIOM 14C" project and the "MassBio2" method, November 2020

The full study is available online (in French) at this link. [5] At this Youtube link, a nice animation by ENVEA shortly explains how this study worked.

According to the IPCC guidelines [6], the biogenic CO_2 is considered carbon neutral and, as conventionally adopted in Life Cycle Assessment modelling, its climate burden is equal to zero. Christensen et al. (2009) for example discussed the principles applied to CO_2 accounting in waste management, concluding that releases of biogenic CO_2 into the air should not be counted as contributing to climate change. [7]

Ib. FOSSIL CO_2 emissions

As said before, once the biogenic fraction is determined via 14C analysis or software modelling, the fossil CO_2 fraction can be found by difference. Hence, in this case, the fossil CO_2 fraction is considered on average 40% of the total CO_2 at the stack.

As reported in the Figure above, the French study estimated an average fossil CO2 emission factor of 382 kg CO_2/tonne of waste treated. Bisnella et al. [1] considers a fossil carbon content in waste emitted into the atmosphere of 370 kg CO_2/tonne of waste treated.

Taking into account:

1. the variability of the waste composition, hence the fossil-biogenic CO_2 share at the stack;
2. the modest fossil CO_2 emissions of the auxiliary fuel used during start-up/shutdown or for operational purposes (diesel oil or natural gas, which could account 0.8%-1% of the total CO_2 emissions – Astrup et al. also concluded that combustion of auxiliary fuels only appears to have a marginal contribution of about a few percent of the direct emissions [18])
3. the upstream and downstream fossil emissions of the WtE process (material and chemicals use), adopting a Life Cycle Approach
   - ➔ the total fossil CO_2 emission factor can be rounded up to **400 kg CO_2eq per tonne of waste treated**, as average for the WtE sector in Europe.

Ic. (Other direct GHG emissions from WtE plants - N_2O)

Nitrous oxide (N_2O) is formed in the flue gas from nitrogen present in the air and in the waste input. Depending on the flue gas cleaning system, nitrous oxides may also be emitted from a WtE facility. Generally, the amounts are very small compared with CO_2 emissions; however, as N_2O is a more potent greenhouse gas than CO_2 these emissions should be also assessed.

In 2009, the work by Astrup et al. "*Incineration and co-combustion of waste: accounting of greenhouse gases and global warming contributions*" found that the main greenhouse gas (GHG) emissions (in terms of kg CO_2eq/t residual waste treated) directly emitted by WtE from the combustion processes is related to the fossil carbon contained in the waste, while N_2O emissions appeared to contribute by less than 2%. Astrup et al. concluded that N_2O emissions are insignificant and may be neglected when estimating global warming contributions for incineration and co-incineration of waste. [18]

Considering finally the latest technological developments in flue gas cleaning systems, N_2O concentrations at the stack of a modern WtE plant can be also considered irrelevant today.

Hence, N_2O emissions do not represent a significant impact on the climate balance of a WtE facility and were not represented in the simplified figures of this Roadmap.

Section II. Energy Substitution

Energy Substitution IIa. Benchmarks

A WtE plant generates power and/or heat which avoids generation of heat and electricity from conventional sources. Depending on what source substituted is considered, different CO_2eq emissions savings can be achieved.

In this work the power and/or heat generated by WtE installations were benchmarked with the **European electricity and heat grid mix** respectively. Additionally, the CO_2eq benefits of energy substitution by WtE include the expected changes to the electricity and heat mix in the future.

Benchmarks [kgCO_2/kWh]	**Today Scenario**	**Future Scenario**
Electricity Grid Mix	0.415	0.15
Heat Grid Mix	0.215	0.162

The values for the average European electricity and heat mix have been adopted from the recent study "***CO_2 reduction potential in European waste management***", by Prognos and CE Delft (January 2022, available at this link). [8]

While the electricity grid will see a higher penetration of renewables, i.e. a significantly lower emission factors in the future, the **heat sector is much more difficult to decarbonize** due to the high share of fossil fuel sources that are still present.

Considering the greater decarbonization challenges of the heat sector and an assessment of the European Commission showing slight variations in the heat mix [9], the study by Prognos and CE Delft assumed a stable CO_2 emission factor for the heat mix in the future.

Adopting a more conservative approach, in this work a lower emission factor for the European heat grid mix was considered for the future scenario, assuming that the most CO_2 intensive sources – oil, coal and lignite – will be completely phased out for heat production and supply.

Based on the supplementary material of the work by Bisnella et al. [1], an average mix of natural gas and biomass has been assumed for heat production in the future:

Natural Gas - Heat	*0.07 [kgCO_2/MJ]*
Biomass - Heat	*0.02 [kgCO_2/MJ]*
Average future Heat Mix	*0.045 [kgCO_2/MJ]*
Average future Heat Mix	***0.162 [kgCO_2/kWh]***

A different approach could have also been used for assessing the energy substitution benefits by WtE: instead of considering the European electricity and heat grid mix as a benchmark, it can be assumed that the energy generated at WtE plants avoids the most carbon intensive conventional power generation technologies, i.e. fossil fuel sources.

Adopting this approach, the energy substitution benefits by WtE would have resulted higher.

For the sake of simplicity and more conservatively, the energy generated by WtE installations in Europe was assumed to replace the average energy mix of the grid. This is the approach always considered as baseline for the two scenarios of this work (“status quo” and “future”).

As further improvement of this work, multiple energy scenarios could be chosen in order to span from fossil fuel-based energy sources to non-fossil based energy sources for assessing the CO_2eq savings by WtE energy substitution.

For reference, a comprehensive sensitivity analysis on the variations of the energy substitution by WtE (with and without the integration of carbon capture technologies) under different energy scenarios was developed by Bisinella et al. [1]

This analysis showed how the emission factors of the energy system chosen as benchmark can significantly change the climate change impact of WtE plants and how the largest savings are obtained when the energy system considered is based on fossil fuels.

Similarly, a sensitive analysis on the CO_2eq savings of the Amager Bakke WtE plant in Copenhagen integrated with CCS was conducted by Bisinella et al. under different energy system scenarios (from natural gas only to higher penetration of renewables such as wind, solar and biomass in accordance with the energy forecast in the Denmark). [10]

Energy Substitution IIb. Average Net Electrical and Thermal Efficiency of European WtE Plants

The references values are based on an extensive data collection done internally within CEWEP members (April 2021).

The average efficiency values are expressed as weighted averages on the plants’ treatment capacities and plants’ type: **Electricity-Only, Combined Heat&Power (CHP), Heat-Only** (see *NOTE 4*).

With this regard, the average net efficiencies do not represent a specific WtE plant, but they are representative of the **overall European WtE fleet**:

WtE Efficiency [%]	Today Scenario	Future Scenario
Net Electricity Export	15%	20.4%
Net Heat Export	32%	43.3%

WtE Production rate [MWh/tonne]	Today Scenario	Future Scenario
Net Electricity Export	0.4	0.58
Net Heat Export	0.9	1.23

NOTES:

NOTE 1 – Values are representative of the effective conditions of the European WtE fleet:
The numbers reported above are yearly averages including shut down periods, maintenance stops, etc., i.e representing on average the actual operating status of WtE plants in Europe. Energy efficiency values based on the plant's nominal power capacity or based on design conditions would be higher.

NOTE2 – PLANT AGE:
The numbers reported are a representative sample of the whole European WtE fleet which includes plants also very diverse in terms of years of service. Net energy efficiency values for newer plants are typically higher than existing ones.

NOTE3 – SIZE:
The numbers are expressed as weighted averages on the plants' treatment capacities. Plant size affects energy performances too.

NOTE4 – PLANT TYPES:
The reported Net Export Efficiency and Net Production Rate for Electricity and Heat are overall weighted averages on the plants' treatment capacities and plants' type but it's important to make a distinction between plants producing electricity only, combined heat and power generation (CHP) and heat only. From a thermodynamic point of view, this distinction is also fundamental to consider when assessing the energy substituted by WtE and the relative CO_2 savings for the equivalent production of electricity and heat.

While WtE plants' performances in electricity only mode could be considered very similar, on average in Europe, the same does not apply for CHP plants. Other than size and age, another factor that significantly affects the numbers of the table above for CHP is the power-to-heat ratio. Cogeneration plants use a single process to generate both electricity and usable heat (or cooling), but have the flexibility to select, depending on various factors, which one to prioritise.

WtE CHP plants' performances vary significantly from the seasonality and the location, in other words they directly depend on the local set-up for the electricity and heat supply. CHP located in colder countries (Northern-Central Europe) are typically more oriented towards heat production and therefore prioritise generating heat rather than electricity (higher thermal production rates), whereas warmer countries (Southern Europe) are typically more oriented towards electricity production (higher electrical production rates) and are perfectly able to operate in electricity-only mode during warmer seasons. This is why for CHP plants rather than referring to an energy efficiency range (such as for electricity only plants), it is more appropriate to talk about working ranges, as Net Electricity Export Efficiency and Net Heat Export Efficiency for CHP plants are directly correlated.

The majority of WtE plants in Europe are CHP both in terms of number of plants and in terms of capacity (size).

According to CEWEP latest data analysis, the European distribution of the WtE fleet is:

	CHP	**Electricity Only**	**Heat Only**
Size (capacity)	**69%**	**25.5%**	**5.5%**
Number of plants:	**67.6%**	**22.1%**	**10.3%**

CHP plants are more than double both in terms of capacity and in terms of number of plants than electricity only ones. Heat only plants represent instead a minor part of the total, and in general are smaller plants. The predominance of CHP WtE plants in the European fleet is also in line with the previous CEWEP Energy Efficiency report [11] and with an overview for the WtE sector done by the JRC "Status and Opportunities for Energy Recovery from Municipal Solid Waste in Europe" [12] (work published in 2018, European WtE data for 2015 as reference year).

NOTE5 – Correlation between the efficiency and the production rate:
Average LHV (from CEWEP data analysis) results ca. **10 MJ/kg on European level**

NOTE6 – FUTURE:
for this work, CEWEP also provided an outlook of the overall European WtE fleet performances in the future.

Higher net efficiencies for both heat and power recovery are predicted, based on the assumption that some older plants will be substituted by more efficient facilities, typically as CHP plants that will gradually also become more present in Europe in the future.

This also reflects a higher commitment of the WtE sector towards a continuous improvement.

Energy Substitution IIc. Integration of Carbon Capture units in WtE installations

As described in the previous section, it is assumed that in a future scenario the overall European WtE fleet efficiency will increase, due to increased performances and a higher presence of CHP facilities.

However, with the application of CCUS technologies, the significant energy penalty of the CO_2 capturing process must be accounted.

It is assumed that when CCUS technologies will be integrated into WtE plants, flue gas condensation will be essential to help compensating the significant energy penalty of the CO_2 capturing process.

Heat pumps will also require electricity, but on the contrary more heat will be recovered from the flue gas and made available for heat supply in the district heating and/or cooling network.

Also, the heat generated in the CO_2 capturing process can be partly recovered when coupled to the steam/heat cycle of the WtE plant.

Overall, it is estimated that the integration of carbon capture technologies in combination with heat pumps will severely reduce the net electricity production by half (approximately -50%) while the heat production will be increased by 20%.

These values were adopted from the investigation by Bisinella et al. [1] [10].

Similarly, the IEAGHG report on the application of carbon capture technologies in the WtE sector showed that on a district heating scheme through the integration of a heat pump, it is possible to recover enough energy from the WtE process to cover the needs of the CO_2 capture system. [13]

The combination of all these effects leads to new values for the net Electricity&Heat export by WtE plants to be considered in the future scenario with CCUS:

WtE Production rate [MWh/tonne]	**Today Scenario**	**Future Scenario**	**CCUS Energy Penalty**	**Future Scenario including CCUS penalty**
Net Electricity Export	0.4	0.58	**-50%**	**0.29**
Net Heat Export	0.9	1.23	**+20%**	**1.476**

NOTE: the energy penalty of CCUS is mostly associated with the use of steam in the CO_2 capturing process itself that reduces the amount of steam sent to the turbine and thus introduces the main penalty reflected on the net electricity generated by the WtE facility.

The extra energy requirements for CO_2 compression and transport should be also considered. For simplicity, their impact on the total climate balance is already incorporated to the overall CCUS penalty considered above.

As carbon capture technologies will improve and as new configurations will be developed for their optimal integration into WtE plants, the overall energy penalties and auxiliaries' requirements for CCUS processes will be also reduced in the future.

NOTE: conservatively, a full-scale CO_2 capturing system (**85% capturing rate)** has been taken as a reference for assessing the energy penalties of CCUS by default in this work [1]. However, a partial CO_2 capture (**50% capturing rate**) has been considered as baseline for the main figures developed in the Roadmap. A lower amount of CO_2 captured per tonne of waste treated would hence imply less energy requirements by the capturing installations accordingly.

NOTE: it is out of scope of this work to provide a full LCA of the different paths that the captured CO_2 could have beyond the boundaries of WtE installations. For a further assessment, the work *"Climate Change impacts of introducing carbon capture and utilisation (CCU) in waste incineration"* by Christensen et. all (2021) is suggested. [14]

Section III. Landfill Modelling

Other than the possible CO_2eq emission savings of energy substitution, a second important contribution of GHG savings from WtE comes from landfill diversion. WtE avoids residual waste going to landfills which can emit significant amounts of methane, depending on their technological level and other variables to be accounted.

In this Roadmap, an emission factor of **600 kg CO_2eq/t residual waste treated** has been considered for landfills as European average, hence for considering the CO_2eq savings of landfill diversion through WtE.

The value is adopted from the recent study "***CO_2 reduction potential in European waste management***", by Prognos and CE Delft (January 2022, available **at this link**). [8]

The study considered an emission factor of **617 kg CO_2eq/t residual waste treated**, based on the Ecoinvent inventories of materials 'to sanitary landfill', with an average **methane recovery rate of 53%**.

Prognos and CE Delft compared also the numbers extracted from the Ecoinvent database with the work by Wang et. al [15]. This study shows a range in CO_2 emission factors for three methane capturing techniques (passive venting, flaring and energy recovery) and for different methane decay rates, with an average value of **608.5 kg CO_2eq/t residual waste treated**.

The CO_2 factors chosen in the study by Prognos and CE Delft felt within the range for the flaring technique as reported by Wang et al. [15], as on a 20-year as on 100-year time horizon. The passive venting has a (much) higher CO_2 factor whereas the energy recovery has a lower CO_2 factor. The Ecoinvent models were, therefore, considered by Prognos and CE Delft to be representative for landfilling on average in Europe.

Hence the value of **600 kg CO_2eq/t residual waste treated**, representative on average of conventional landfill with flaring, can be considered the technological level in the middle between landfills without flaring and any type of energy recovery at all on one end and highly engineered landfills with methane capture and energy recovery on the other.

However, it can be very complex to simplify landfill modelling with just one numerical average for all Europe as multiple factors should be accounted. As said, the main type of landfills can be classified under 3 categories: open dumps or landfills without flaring, conventional with flaring, engineered with energy recovery. Additionally, the scientific literature suggests wider sensitivities analysis that, other than the technological level of landfills, consider the possibility of considering carbon credits, different decay rates for methane, a static vs. a dynamic approach, etc. [15]

Due to the high variations associated with landfill modelling, this Roadmap also investigated how the final balance of WtE would change even if the important benefits associated with landfill diversion would be excluded.

The climate benefits of landfill diversion are left as an indication and the scenarios without landfill diversion were considered as the reference scenarios when estimating the total reduction potentials of the WtE sector equipped with CCUS.

More precise considerations on landfill diversion are also addressed later in *Section VII. Comments to the Peer-Review and Integrations.*

Section IV. IBA Recovery

The CO_2eq savings achievable in WtE plants through the recovery of ferrous and non-ferrous metals from incineration bottom ash (IBA) are considered in the order of **-60 kg CO_2eq per tonne of waste treated.**

This value is adopted and rounded from the work of Bisinella et. al [1], (**-63 kg CO_2eq per tonne of waste treated**), which is also in line with the one used in the estimations by IEAGHG. [13]

As expressed in the CEWEP bottom ash fact sheet, the CO_2eq savings through ferrous and non-ferrous metals recovery from IBA can be indicated in an equivalent way as 2000 kg CO_2eq/ton metals recovered.

OTHER CO_2eq SAVINGS

The recovery of the inert fraction could lead to further CO_2eq savings but this depends on the final use and application of the mineral fraction of the IBA. Due to the complexities of considering a full LCA analysis, such benefits would result beyond the scope of this work and are not considered.

Similarly, some considerations could be done on the **IBA Carbonation effect** that removes CO_2 from air, hence delivering further CO_2eq benefits. The natural carbonation process of IBA, which involves a reaction between carbon dioxide in the ambient air and calcium in the material, is initiated when the IBA reaches contact with air:

$$\begin{gathered}\mathrm{CO_2 + H_2O \leftrightarrow H_2CO_3}\\ \mathrm{CaO + 2H_2O \leftrightarrow Ca(OH)_2 + 2H^+}\\ \mathrm{H_2CO_3 + Ca(OH)_2 \rightarrow CaCO_3 + 2H_2O}\end{gathered}$$

The carbonation binds carbon dioxide to the IBA, which also decreases the pH. Normally the IBA is stored during six months to lower the pH from circa 12 to a pH of 8.5-9. The carbonation process that occurs during this time is affected by how much air the IBA is exposed to, the chemical composition, the grain size and the moisture content of the material. Preliminary estimations on the amount of carbon dioxide that could be captured by IBA carbonation can be found in the investigation "*Slag - a carbon dioxide sink? A study of carbonation in slag from combustion of household and industrial waste*" [16] and other available investigations in the technical literature. [17]

A precise accounting of the additional CO_2eq savings achievable with the carbonation process of IBA goes beyond the scope of this work and it is left as a reflection for future considerations.

Section V. Flue gas condensation

From scientific literature [1] and model simulations [13], flue gas condensation is recommended when applying carbon capture technologies in WtE plants for 4 main reasons:

1. Process Temperature: it cools down flue gases and helps the absorption process that must occur at low temperature (differently than the stripping process at high temperature);

2. Reduces the flue gas volume thereby increasing the CO_2 vapour pressure;

3. Delivers a further abatement of pollutants in the flu gas that:
    a. protect the solvent from degradation and poisoning
    b. improve the quality of the captured CO_2

4. **Ensure Heat recovery (most important):** partially counterbalance the significant energy penalty of the CO_2 capture unit. Higher auxiliary requirements for the heat pumps are also envisaged, but more thermal energy is available at high temperature for heat recovery and supply.

As said in *Section IIc*, the IEAGHG report on the application of carbon capture technologies in the WtE sector showed that on a district heating scheme through the integration of a heat pump, it is possible to recover enough energy from the WtE process to cover the needs of the CO_2 capture system. [13]

Section VI. Waste Generation

It is assumed that the total amount of the residual waste treated by WtE and its composition will remain constant (ca. **100 million tonnes of residual waste per year**).

In the first place, keeping residual waste treated by WtE facilities constant at current levels is a necessary assumption to allow a clear comparison between the CO_2eq reduction potentials of the different scenarios (Status Quo, Future with CCUS, CCUS+ and CCUS++).

Secondly, waste prevention, eco-design and more virtuous consumption patterns will favour a decrease in waste generation in the next years. On the other hand, population and GDP growth, demographic change, among others could increase waste generation. The decrease of residual waste going to landfills, in accordance with the landfill directive, will also increase the amount of residual waste that will need final treatment. These dynamics and the combination of these aspects are hard to predict and model, but they should be kept in mind.

Finally, in line with the findings of the 2019 WtE Sustainability Roadmap by CEWEP, residual waste will not disappear in the next decades even if the higher Circular Economy targets of waste prevention and recycling are reached by 2035.

More recently this was also confirmed by the study "***CO_2 reduction potential in European waste management***", by Prognos and CE Delft (January 2022, available **at this link**). [8]

A sensitivity analysis on the variations of the CO_2eq reduction potential under different amounts of residual waste treated by WtE yearly is out of scope in this work. This assessment could be further explored in future investigations.

Section VII. Comments to the Peer-Review and Integrations

The work was peer-reviewed by Thomas Højlund Christensen, Professor at the Technical University of Denmark (DTU) in May 2022.

The main conclusion of the peer-review was that “***The roadmap presents a logic and data-supported overview of the climate change aspects W-t-E*** *as it looks today and as it may develop with the introduction of carbon capture including storage or utilization*. *The only shortcomings to be mentioned are the comparison with landfilling and the unspecified use of the term CCUS as a combination of CCS and CCU*.”

Section VII.a - Comments to the Peer-Review: Landfill modelling

The first shortcoming addressed is related to landfill modelling. The peer review suggests that *“the data used on the climate change impacts of landfilling are likely overestimating the impacts of the landfill beyond what modern landfilling technology causes.”*

In this Roadmap, an emission factor of 600 kg CO_2eq/t residual waste treated has been considered for landfills as European average. This value is adopted from the recent study “*CO_2 reduction potential in European waste management*”, by Prognos and CE Delft. [8]

As explained in *Section III. Landfill Modelling*, Prognos and CE Delft considered a value of 617 kg CO2eq/t waste, based on the Ecoinvent inventories of materials 'to sanitary landfill’, with an average methane recovery rate of 53%.

Prognos and CE Delft compared the numbers extracted from the Ecoinvent database with the work by Wang et. al [15] and found that Ecoinvent data falls within the range by Wang et al. (‘flare gas control’ for landfills, characterization factors of the 5th assessment report - AR5, neutral CO_2b).

As reported by Prognos and CE Delft, in the supporting information by Wang et. al [15], available at this link, table S6 (extract below) summarizes the GWP estimates:

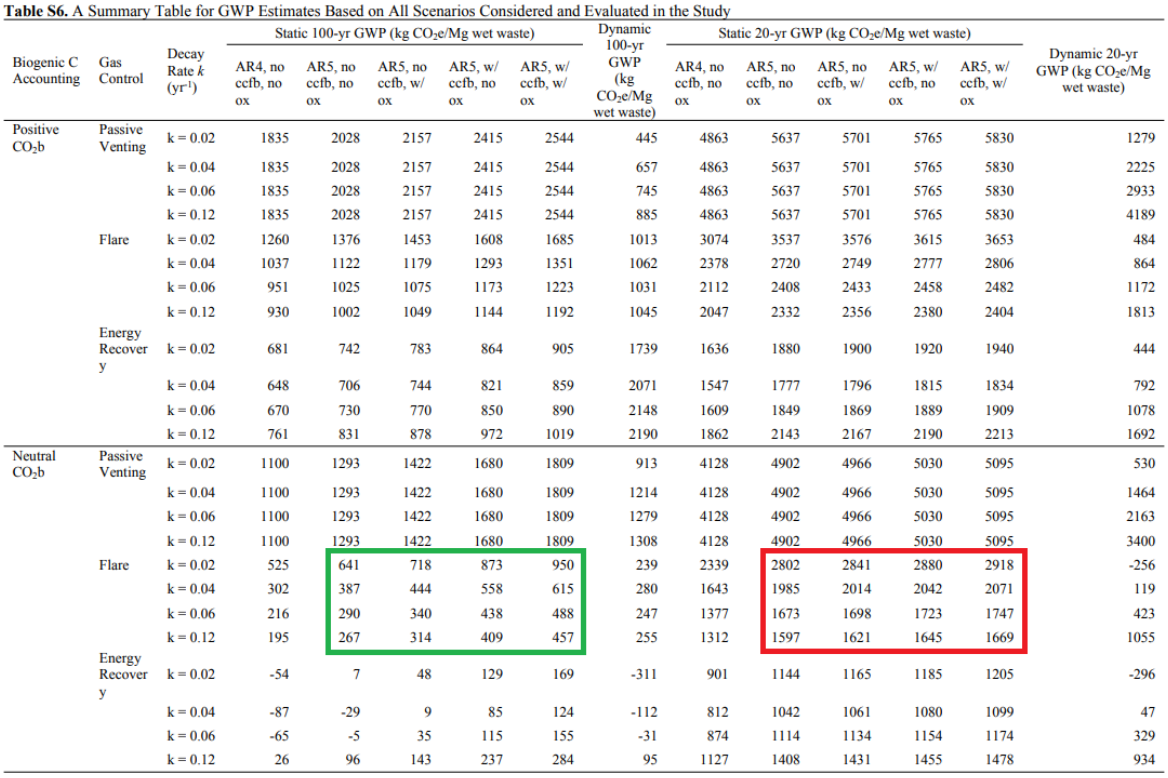


Table S6. A Summary Table for GWP Estimates Based on All Scenarios Considered and Evaluated in the Study

			Static 100-yr GWP (kg CO_2e/Mg wet waste)					Dynamic 100-yr GWP (kg CO_2e/Mg wet waste)	Static 20-yr GWP (kg CO_2e/Mg wet waste)					Dynamic 20-yr GWP (kg CO_2e/Mg wet waste)
Biogenic C Accounting	Gas Control	Decay Rate *k* (yr^{-1})	AR4, no ccfb, no ox	AR5, no ccfb, no ox	AR5, no ccfb, w/ ox	AR5, w/ ccfb, no ox	AR5, w/ ccfb, w/ ox		AR4, no ccfb, no ox	AR5, no ccfb, no ox	AR5, no ccfb, w/ ox	AR5, w/ ccfb, no ox	AR5, w/ ccfb, w/ ox	
Positive CO_2b	Passive Venting	k = 0.02	1835	2028	2157	2415	2544	445	4863	5637	5701	5765	5830	1279
		k = 0.04	1835	2028	2157	2415	2544	657	4863	5637	5701	5765	5830	2225
		k = 0.06	1835	2028	2157	2415	2544	745	4863	5637	5701	5765	5830	2933
		k = 0.12	1835	2028	2157	2415	2544	885	4863	5637	5701	5765	5830	4189
	Flare	k = 0.02	1260	1376	1453	1608	1685	1013	3074	3537	3576	3615	3653	484
		k = 0.04	1037	1122	1179	1293	1351	1062	2378	2720	2749	2777	2806	864
		k = 0.06	951	1025	1075	1173	1223	1031	2112	2408	2433	2458	2482	1172
		k = 0.12	930	1002	1049	1144	1192	1045	2047	2332	2356	2380	2404	1813
	Energy Recovery	k = 0.02	681	742	783	864	905	1739	1636	1880	1900	1920	1940	444
		k = 0.04	648	706	744	821	859	2071	1547	1777	1796	1815	1834	792
		k = 0.06	670	730	770	850	890	2148	1609	1849	1869	1889	1909	1078
		k = 0.12	761	831	878	972	1019	2190	1862	2143	2167	2190	2213	1692
Neutral CO_2b	Passive Venting	k = 0.02	1100	1293	1422	1680	1809	913	4128	4902	4966	5030	5095	530
		k = 0.04	1100	1293	1422	1680	1809	1214	4128	4902	4966	5030	5095	1464
		k = 0.06	1100	1293	1422	1680	1809	1279	4128	4902	4966	5030	5095	2163
		k = 0.12	1100	1293	1422	1680	1809	1308	4128	4902	4966	5030	5095	3400
	Flare	k = 0.02	525	641	718	873	950	239	2339	2802	2841	2880	2918	-256
		k = 0.04	302	387	444	558	615	280	1643	1985	2014	2042	2071	119
		k = 0.06	216	290	340	438	488	247	1377	1673	1698	1723	1747	423
		k = 0.12	195	267	314	409	457	255	1312	1597	1621	1645	1669	1055
	Energy Recovery	k = 0.02	-54	7	48	129	169	-311	901	1144	1165	1185	1205	-296
		k = 0.04	-87	-29	9	85	124	-112	812	1042	1061	1080	1099	47
		k = 0.06	-65	-5	35	115	155	-31	874	1114	1134	1154	1174	329
		k = 0.12	26	96	143	237	284	95	1127	1408	1431	1455	1478	934

- at GWP 100 years horizon values are between 267 and 950 kg CO_2 eq. (green box above) (Ecoinvent arrives at 617 kg CO_2 eq.)

- at GWP 20 years horizon values are between 1597 and 2918 kg CO_2 eq. (red box above) (Ecoinvent arrives at 1801 kg CO_2 eq.)

The CO_2 factors in the study by Prognos and CE Delft felt within the range for the flaring technique as reported by Wang et al. [15], on a 20-year as well as on a 100-year time horizon. The passive venting has a (much) higher CO_2 factor whereas the energy recovery has a lower CO_2 factor. The Ecoinvent models were, therefore, validated and considered by Prognos and CE Delft a good representation for landfilling on average.

Hence the value of 600 kg CO_2eq/t residual waste treated, representative on average of conventional landfill with flaring, can be considered in Europe the technological level in the middle between landfills without flaring and any type of energy recovery at all on the one hand and highly engineered landfills with methane capture and energy recovery on the other.

(As an approximation and for comparability reasons, this number was assumed constant in the status quo and in the future scenario.)

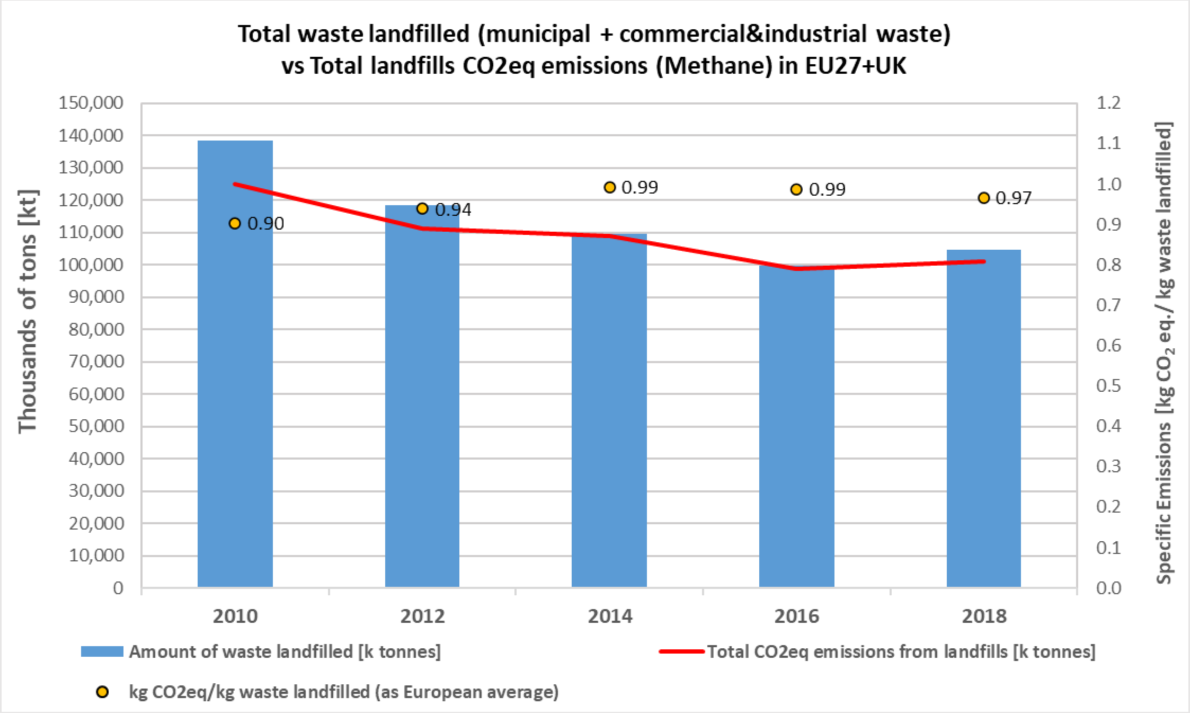
Additionally, this can be considered a first and conservative estimation of the heterogenous situation of landfills in Europe.

Looking at Eurostat data, Europe still landfills almost 60 million tonnes of municipal waste annually and significantly more when commercial and industrial waste is included (ca. **100 million tonnes of non-inert waste per year**).

Regarding greenhouse gas emissions accounting, data are sent by countries to United Nations Framework Convention on Climate Change (UNFCCC) and the EU GHG Monitoring Mechanism (EU

Member States). These are collected by the European Environmental Agency (EEA) and available at this link.

Analysing and merging accurately Eurostat data with the total CO_2eq emissions reported by the European Environmental Agency, a representation of the actual levels of methane emission (CO_2eq) from landfills in Europe can be estimated.



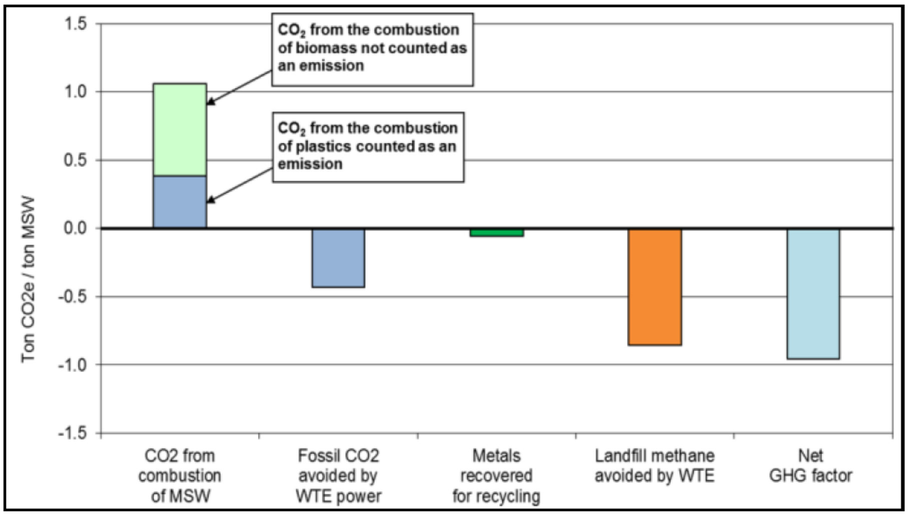
.

Figure2: CEWEP elaboration and analysis of total waste flows from landfills and relative methane emissions (CO_2eq) in Europe (EU27+UK)

Comparing the total amount of waste landfilled in Europe (EU27+UK) with the total amount of methane emissions recorded (CO_2eq), a value of around **970 kg CO_2eq/t residual waste treated** can be found for 2018, according to the latest and official data available. This means that 1 tonne of mixed residual waste sent to landfill in Europe currently releases ca. 1 tonne of CO_2eq, as an order of magnitude.

Similar estimations, adopting a comparable approach of this Roadmap, have been conducted by the Environmental Protection Agency (EPA) in the United States of America. On average, the U.S. EPA has determined that WtE facilities reduce GHG emissions by one tonne of CO_2eq for every ton of waste diverted from landfill and processed.

On average, the U.S. EPA has determined that WTE facilities reduce GHG emissions by one ton of CO2 equivalents (CO2e) for every ton of MSW diverted from landfill and processed.



More information and references at the U.S. EPA website at this link.

At any case, as described in *Section III* previously, it can be very complex to simplify landfill modelling with just one numerical average for all Europe as multiple factors should be accounted. As said, the main type of landfills can be classified under 3 categories: open dumps or landfills without flaring, conventional with flaring, engineered with energy recovery. Additionally, the scientific literature suggests wider sensitivities analysis that, other than the technological level of landfills, consider the possibility of considering carbon credits for landfills, different decay rates for methane, a static vs. a dynamic approach, etc. [15]

Acknowledging the complexities, variabilities, and the multiple parameters to be taken into account in landfill modelling, the CEWEP Climate Roadmap also investigated how the final balance of WtE would change even if the important benefits associated with landfill diversion would be excluded.

Taking a conservative approach, the scenario without accounting for landfill diversion was chosen as the default one when estimating the total reduction potentials of the WtE sector as absolute figures. Considering also landfill diversion the climate savings would be much higher but this was left as a qualitative consideration only. A precise accounting is offered as food for thoughts and for further estimations in the future.

Section VII.b - Comments to the Peer-Review: CCU

The second short-coming in this work addressed by the peer-review was related to CCU and *“the unspecified use of the term CCUS as a combination of CCS and CCU”.* More precisely, the peer review suggested that *“In order to ensure real savings in climate change impacts of introducing CCS and CCU, more care must be paid to the CCU options, while the CCS always provides net savings with respect to climate change.”*

Indeed, the CO_2eq savings delivered by CCU depends case-by-case on the final use of captured CO_2.

As explained before in the final note of *Section IIc*, it is out of scope of this work to provide a full LCA of the different paths that the captured CO_2 could have beyond the boundaries of WtE installations. As a first estimation, this work wants to focus on the benefits of capturing CO_2, independently from the final use or application that the captured CO_2 will have outside WtE facilities. For a further assessment, the work “*Climate Change impacts of introducing carbon capture and utilisation (CCU) in waste incineration*” is suggested [14]. This accurate LCA work assessed for example different possibilities for CO_2 use via Hydrogenation with the purpose of producing feedstock chemicals or fuels such as methane, methanol, dimethyl ether (DME) and formic acid. However, the comprehensive life cycle assessment showed how technology choices and the benefits of CCU applied to WtE depend on the energy system in which the WtE operates throughout its lifetime, and on the markets for the CCU products.

Direct utilisation of the captured CO_2 resulted beneficial only on a local basis when substituting fossil-based CO_2, obtaining similar benefits to CCS.

Using CO_2 in combination with H_2 is at its early developments and it’s complex to assess its relative benefits on a climate perspective in the near future. Keeping in mind the significant consumption of electricity for hydrogen production, the benefits associated with CCU applications will also depend on the surplus of renewable energy available. This does not mean that CCU in terms of producing hydrogenated chemicals and fuels cannot be beneficial, but it will depend on the energy context in which WtE plants will operate in the future.

One of the main findings by Christensen et. al [14] is that the use of CO_2 as feedstock chemicals provides more benefits than use as fuels, and CCU solutions focusing on methanol and DME are the most promising technologies.

In summary, for simplicity reasons and as commonly adopted, CCS and CCU have been considered in this Roadmap under the same macro category “CCUS”. This wants to mainly represent the rising opportunity for capturing CO_2 from WtE plants, as an extra tool towards negative emissions.

Building on this Roadmap, a more precise assessment on the different paths for CCU in combination with WtE is underpinned for future investigations.

TECHNICAL ANNEX BIBLIOGRAPHY

[1] Environmental assessment of carbon capture and storage (CCS) as a post-treatment technology in waste incineration, Bisinella et al., Waste Management, 2021

[2] Biogenic carbon in combustible waste: Waste composition, variability and measurement uncertainty, Larsen et al., 2013, Waste Manage. Res. 31, 56–66.

[3[Long-term sampling of CO_2 *from waste to- energy plants: 14C determination methodology, data variation and uncertainty, Fuglsang et. al., Waste Management & Research 2014, Vol. 32(2) 115– 123.*

[4] Determination of the fossil carbon content in combustible municipal solid waste in Sweden, RAPPORT U2012:05, Avfall Sverige, 2012.

[5] Détermination des contenus biogène et fossile des ordures ménagères résiduelles et d'un CSR, à partir d'une analyse 14c du CO_2 *des gaz de post-combustion, ADEME Library, November 2020.*

[6] Intergovernmental Panel on Climate Change (IPCC) 2006 Guidelines for National Greenhouse Gas Inventories, https://www.ipcc-nggip.iges.or.jp/public/2006gl/

[7] C balance, carbon dioxide emissions and climate change potentials in LCA-modeling of waste management systems, Christensen et al., Waste Manage. Res. 27, 707–715, 2009.

[8] CO_2 *reduction potential in European waste management, study by Prognos and CE Delft, January 2022.*

[9 Mapping and analyses of the current and future (2020 - 2030) heating-cooling fuel deployment (fossil-renewables), European Commission, 2016.

[10] Environmental assessment of amending the Amager Bakke incineration plant in Copenhagen with carbon capture and storage, Bisinella et al., Waste Management & Research, 2021.

[11] CEWEP Energy Report III (Status 2007-2010), Results of Specific Data for Energy, R1 Plant Efficiency Factor and NCV of 314 European Waste-to-Energy (WtE) Plants, 2012.

[12] Status and Opportunities for Energy Recovery from Municipal Solid Waste in Europe, Scarlat et al., Directorate for Energy, Transport and Climate, European Commission Joint Research Centre, Ispra, 2019.

[13] IEAGHG, "CCS on Waste to Energy", 2020-06, December 2020.

[14] Climate Change impacts of introducing carbon capture and utilisation (CCU) in waste incineration, Christensen et al., Waste Management, 2021.

[15] An Assessment of the Dynamic Global Warming Impact Associated with Long-Term Emissions from Landfills, Wang et al., Environ. Sci. Technol., 2020.

[16] "Slag - a carbon dioxide sink? A study of carbonation in slag from combustion of household and industrial waste", Josefin Johansson and Katarina Lönnebo Stagnell, LUND UNIVERSITY LIBRARIES, 2016.

[17] RMB's experience in bottom ash and slag from WtE treatment and recovery and sustainability balance in terms of CO_2*, proceedings of the Utilitalia webinar on IBA recovery, July 2021, available on-line.*

[18] Incineration and co-combustion of waste: accounting of greenhouse gases and global warming contributions, Astrup et al., Waste Management & Research, 2009.