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Unleashing the power in waste

Comparison of Greenhouse gas and other Performance Indicators for Waste-to-Energy concepts and Landfilling

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Abstract

A CO_2-evaluation is made for landfill and Waste-to-Energy (WtE) concepts.
Different concepts are identified and compared for their performance on energy and materials recovery. ***Performance indicators for WtE*** *are compared; like energy efficiency, EXergy efficiency, the R1-D10 formula from the EU Waste Framework directive, and CO_2-emission and avoidance.*

It is shown that, due to the biomass content and the avoidance effect due to the recovery of energy and materials, conventional WtE has a near zero CO_2-emission per ton of waste. Optimised WtE can have a significant ***negative overall emission*** *of 200-300 $kgCO_2$/ton of waste. This means an absolute net avoidance of CO_2 by WtE. The reduction relative to land filling is as much as 500-1200 $kgCO_2$/ton of waste. The potential for optimisation of the energy recovery as well as the material recovery of the WtE infrastructure is demonstrated.*

If WtE is evaluated as a power plant, an optimised plant can have an emission of only 0,336 $kgCO_2$/kWh, lower than a gas fired electrical power plant, and this absolute figure does not include the avoided landfill emissions. With CHP this can be reduced even further.

The actual potential of electricity production from WtE for the EU-15 is calculated to be over 7,5% of total electricity production. Additionally heat and the metal recoveries could be doubled.

1 Introduction

Waste is mainly dealt with as a problem of hygiene and other health related risks. The potential of waste as a resource is seldom taken as the starting point for waste management regulations. Until recently WtE was principally designed around the paradigm *“design to be clean”,* designed to minimize the quantity and the (negative) effect of its emissions. There is however a new and strong tendency to develop a new generation of WtE that are *“designed for output”,* maximising the recovery of energy and materials. This requires new evaluations of the effects of the outputs of WtE.

In this study the calculations for the Green House Gas (GHG) evaluation are) compared with some other performance indicators. Eight cases are defined and evaluated with all performance indicators.

The study is focussing on the residual Municipal Solid Waste (MSW) and similar commercial waste, difficult streams that remain after all other possibilities of the waste hierarchy are exhausted. For this waste, the normal choices are landfilling or combustion (incineration) in Waste-to-Energy (WtE) plants. Of course incineration should only be considered as the alternative for landfilling. Only an effective outlet for the difficult material will allow breaking the impossible competition of Reuse, Recovery and Recycling (RRR) with low landfilling prices. This is so, because of the relative high price, WtE is never a competitor to RRR. But by avoiding the cheap outlet to landfilling it is an effective stimulus for RRR. This is also shown by the data of countries in EU where a high RRR is corresponds perfectly with the installed waste-to-energy capacities [1] [2].

The many variations in mechanical sorting of residual MSW are not dealt with in this note. They can be considered as combinations of partial landfilling, partial WtE (e.g. in the form of RDF), and some other processes like biological drying, composting or digestion (biological materials) and reuse of specific fractions (e.g. iron, aluminium, plastics). Their performance on energy recovery and on CO_2-emissions varies and is dominated by the amounts that are landfilled and incinerated. Generally speaking their performance can be considered as in-between the optimal landfilling and conventional WtE variants of this study.

The study focuses on **distinguishing the differences within variants of landfilling and variants of WtE**. These show great variations in environmental performance. Up to now the general approach has not focussed on maximization of the output of recovered energy and materials. Lack of appropriate performance indicators obscures these differences between the variants. Use of appropriate performance indicators can be a driver in improving environmental performance. The aim of this study is to provide an overview of different performance indicators with their results for relevant variants of landfilling and WtE. The CO_2-greenhouse gas evaluation is compared with other performance indicators in this paper [3].

The cases used throughout this study are:
1) Landfill:
    a) Simple dumpsite
    b) Sanitary landfill with optimised collection of landfill gases and biogas engines
2) Waste-to-Energy:
    c) Average Dutch WtE plant
    d) Conventional WtE with state of the art electricity production
    e) Optimized WtE with maximum electricity production and recovery of metals
    f) Conventional WtE with CHP
    g) Optimized WtE with CHP
    h) Conventional WtE with only heat production

For all variants of WtE, Best Available Technology (BAT/BREF) [4] is taken as a starting point. This is taken as "conventional" (3rd-generation) WtE which has *"design to be clean"* as a starting point, guaranteeing that the process and stack emissions are fulfilling all modern standards.
For the "optimised" (4th-generation) installations, additionally, the ***optimization of the recovery of energy and materials*** is added to the starting point: *"design for output".* For the recovery of energy and materials the BAT/BREF for WtE [5] provides up to now limited reference, so new performance indicators are needed.

The following graph gives an overview of the results of the calculations for the Green House Gas (GHG) effect as a performance indicator. The structured approach with well-established references (IPCC and for LCA studies ISO 14040 series) allows for a reliable overall comparison of performances.

WtE can actually have a negative CO_2-emission as will be explained later in the detailed graph. This is mainly due to the large amount of biomass in waste that provides energy without a net CO2-emission and the effect of substitution by the recovery of energy and materials.

The CO_2-balance of current average of Dutch WtE-plants shows a small positive GHG-effect. This effect however is small compared to an optimally designed and operated landfill, the alternative for residual MSW. A classical dumpsite has a dramatically higher greenhouse effect than the optimal landfill, using biogas collection and biogas engines for electricity production.

A WtE plant as it is currently built, with conventional but state-of-the-art technology, has a near zero GHG-effect. The new generation of plants optimised for electricity production however show a strong negative GHG-balance (is a high avoidance), which is also the case for WtE designed for heat delivery and even more so for those with Combined-Heat-and-Power (CHP). This GHG-evaluation calculates the direct emissions of CO_2 and CH_4, and the effects of recovered energy and material by substitution of normal production processes.

The ***reference case*** for the waste input is in this study the case in which the waste is not produced, but remains in use (or reuse). This case can be seen as a theoretical absolute reference: prevention of the generation of waste generation by keeping it in stock in the society without any CO_2-emissions, energy or material recovery.
The reference case on the output side is for the substituted electricity production the actual mix of power plants in Germany. Germany is chosen because it is a large country with a wide variety of energy sources for its electricity production, being representative for the average European situation. It is also a relative conservative assumption as using actual CO_2-emissions solely from fossil fired power plants as a reference would give much higher values for the GHG-reduction by WtE.

The performance indicators considered are:
- Primary resource
- Diversion rate
- Energy efficiency
- R1/D10-formula from EU Waste Framework directive
- Exergy efficiency
- GHG from waste: kg-CO_2 / ton of waste
- GHG on electricity from waste: gram CO_2 / kWh

All of these performance indicators have their specific fields of application. It could however be useful to make more use of the higher-level evaluations to stimulate real optimisation of the full potential in waste.
Better standardisation of the calculation methods, definitions of the input data and the way they are measured are required. This would ease the use of higher-level evaluations and increase their validity for comparisons and decision-making.

In a last chapter the potential of optimisation of final treatment of MSW is shown.

Adapting regulations for WtE, from a limitation of negative effects, into regulations pushing for more recovery of energy and materials, could unleash a large potential from waste.

In a separate article the costs of achieving higher efficiency will be analysed [6] and translated into costs per avoided ton CO_2 in a partial Life Cycle Cost analysis [7].

2 LCA evaluation on CO_2

2.1 The evaluation method

The study focuses on residual Municipal Solid Waste (MSW) and similar wastes. The residual waste considered is processed in either a landfill or Waste-to-Energy installation.

The better waste classes (e.g. source separated streams) that have a potential for direct Reuse, Recycling or Recovery (RRR) these options are of course considered to be favourites. But, different from what is sometimes suggested, even a fully elaborated waste management system will have a stream of residual materials. Simply put: as long as mankind takes materials from nature, the law of mass-conservation implies that in the long run exactly the same “output” will result as that is taken as natural “input” into our society. So the ever increasing amounts taken from nature, and the increasing variations in types of materials, will make the residual waste an ever more complex material.

Along with clean and hygienic treatment of waste the fundamental aim of waste management should be to recover as much materials and energy as possible. This leads to substitution of materials that would otherwise have to be mined from nature. By this reduction of input into our society in the long run the amount of waste of our society is also reduced. The resource efficiency of WtE can be expressed by the amount of avoided primary materials that are replaced by the recovered energy and materials. This means that the evaluation of resource efficiency encompasses not only the plant or process under investigation, but also effects of conventional production, substituted by the recovered energy and materials.

The system boundaries are defined by the moment in which the waste enters the plant and that when the energy and materials leave the plant as products, emissions or residues. The CO_2-effect of the products from the recovery of energy and materials is evaluated by using data from literature for the CO_2-effect of the substituted primary products.

The following table gives basic parameters used for the waste input material:

Waste (input)		
MSW amount	500	kton / year (=Ggram/yr)
Carbon content	23,5%	on the basis of elementary analyses, spec. WFPP
Biological fraction MASS	55%	based on carbon content [kg-$_{biol}$/kg-$_{waste}$]
Biological fraction ENERGY	47%	based on ENERGY content (MJ_{biol}/MJ_{waste}), Dutch official value for MEP
Carbon of biological origin =	65	kton C/ year
Biological origin CO_2 =	237	kton CO_2/ year
Fossil origin CO_2 =	194	kton CO_2/ year
Calorific value	10	MJ / kg
Energy content =	5000	TJ-prim / year
Iron content	28	kg Fe / ton waste
Aluminium content	3	kg Al / ton waste
Copper content	1	kg Cu / ton waste
Non-Ferro metal content	2	kg NF-Metals / ton waste
Inert residue	220,	kg/ton waste

The amount represents a large-scale WtE plant or equivalent landfill. The calorific value is an average value for untreated residual MSW. The biological fraction of carbon is taken at 55% which is relatively low as there is also data that suggests higher values up to 63%. The metal content is an estimate based on some preliminary data from analysis from Amsterdam bottom ash. These values are however very specific and can vary greatly among different origins of the waste, depending on social and economical conditions for the area, separation at the source and the way that coarse waste is dealt with.

The sum of materials used in the WtE plant (chemicals for flue gas cleaning, maintenance and fuels) is set at a fixed value for all WtE-cases: 1,5% of waste input with an estimated average CO_2-equivalent of 1 kg CO_2/ton. As this has only a small impact variations are not studied, but in real plant design there could also be some optimization on this point.

Construction of the WtE plant or land fill is not considered as a specific CO_2-source because the amount of material for construction (mainly concrete and steel) is less than 10% of the waste throughput in the first year. Even with a high specific CO_2-emission of the construction of the plant it would be relevant only for roughly the first year of operation, making it negligible over a plant lifetime of 30-40 years.

The outputs considered are:
1) Energy:
  a) Electricity
  b) Heat

2) Materials:
   c) CO_2-emitted
   d) Methane and N_2O
   e) Iron
   f) Aluminium
   g) Copper
   h) Other Non-Ferro metals (Stainless, Zn, Pb, Sn, Ni, Cr, Mo, Ag, Au)
   i) Inert materials: bottom ash is taken as washed product streams separated in sand and granulate for application in building materials. It consists mainly of sand, stones, glass, pottery, china, ceramics and similar materials contained in the waste.
   j) Residues: Fly ash and residue from the flue gas cleaning that have an even smaller CO_2-impact and amounts. These streams are not dealt with separately, but included implicitly in the figures for inert materials.

The evaluation is adding the CO_2-equivalents of all inputs and outputs [8]. The waste input is the same for all cases. The properties of the landfill or WtE plants are varied per case. All the outputs are calculated on basis of the given input and the properties of the process in landfill or WtE plant. As products are the outputs of a recovery operation, they are evaluated via substitution of equivalent products that are produced from raw materials. This conform standard LCA practice as in ISO 14040.
For the relation between the output produced and the equivalent CO_2 values the following parameters are used:

LCA-parameters[9]		
ELECTRICITY	-0,594	kg CO_2 / KWh-Electr (German mix of all sources)
HEAT	-0,256	kg CO_2 / KWh-heat (gas fired boiler)
Avoided CO_2 at Iron production	-2,40	kg CO_2 / kg Fe [Corradini/Köhler 1999], [Rentz et al.1996],[GEMIS Version 4.1]
Avoided CO_2 at Aluminium production	-10,06	kg CO_2 / kg Al [Boustead 2000]
Avoided CO_2 at Copper production	-5,53	kg CO_2 / kg Cu [ECOINVENT 2000]
Avoided CO_2 at Non-Ferro metals prod.	-5,0	kg CO_2 / kg NF-metal (MvB: estimated average for Stainless, Zn, Pb, Sn, Ni, Cr, Mo, Ag, Au)
Avoided CO_2 at inert materials	-0,0039	kg CO_2 / kg inert

The CO_2-equivalent figures for electricity and heat have a strong impact on the overall GHG-effect. This makes it important as to what reference is chosen for the alternative primary source of primary energy that is being replaced. The literature reference for the mix of all sources in Germany is taken because of its large and differentiated use of fuels for electricity production. Due to the inclusion of nuclear, hydro and biomass power this is a relative low value, nearly equivalent to gas fired power plants (0,551 kg CO_2 / kWh) and lower than for example the Dutch electricity production (0,698 kg CO_2 / kWh) [10]. The fossil-only mix of Germany (1,037 kg CO_2 / kWh) [11] is however more likely to be the relevant electricity to be substituted by electricity from WtE.

These higher values that are applicable for many countries would give a much stronger differentiation in the resulting CO_2-avoidance of WtE. As WtE installations are operated as base load plants they could even be considered to replace mainly coal fired power plants which have a CO_2 emission of 1,20 kg CO_2 / kWh.

2.2 Installations being considered

In many studies LCA evaluations have been done for many different materials, following them from cradle to grave, eg [12][13]. In these studies however a fixed value is taken for the parameters of WtE. And generally the parameters used are the average of the existing WtE plants thereby neglecting the important differences between the performances of the existing installations. They are also using the average of the complete range of actual installations, many of which are 20 to 30 years old and have never been designed for effective recovery of energy and materials. This makes the LCA's parameters for WtE too conservative for installations currently built and even more for policymaking based on future WtE installations.

This study is specifically differentiating between the properties of WtE plants, keeping the properties for waste identical for all cases.
The variants compared are:
1) Landfill:
   a) Simple dumpsite: classical variant that is generally used and which has no specific provisions for preventing the escape of landfill gases formed by the digestion processes.
   b) Sanitary landfill with optimised collection of landfill gases and biogas engines: uses best available technology and operating procedures to cover the waste with plastic foils and collect as much landfill gas as possible for use in biogas engines to produce electricity.
2) Waste-to-Energy:
   c) Average Dutch WtE plant: the installed base of existing WtE plants that have been build in the Netherlands in the last 30 years in The Netherlands. It has a relatively low electrical conversion efficiency of 14,5% [14].
   d) Conventional WtE with state of the art electricity production: a plant which is nowadays state of the art with a net-electrical-efficiency of 20% [15]. New installations tend to have net-electrical-efficiencies of 18% to 24% mainly depending on their size, steam parameters and air/water cooled condenser.
   e) Optimized WtE with maximum electricity production and recovery of metals: is chosen with a 30% net electrical efficiency. This is the maximum feasible to date with a 530.000

ton/year reference installation in operation since spring 2007 in Amsterdam[16].

f) Conventional WtE with CHP: same as d) but with Combined Heat and Power (CHP) for an assumed 50% of the yearly available heat at 140°C that can be used in district heating or in industry. This is based on the common mismatch between available heat and heat-demand due to daily and seasonal variations. Generally also the heating need does not match available heat. In most countries the common situation is that electricity production is the base load, and heat is distributed as the varying demand needs.

g) Optimized WtE with CHP: same as e) with the CHP equal to f).

h) Conventional WtE with only heat production: same as d) but no electricity generation and a complete use of the available heat is taken, assuming a relative small WtE installation and a much larger demand that is partially met with specific heat production from other sources to cover the variations in the demand

For all WtE-cases own consumption of electricity (parasitic load) is taken as 3,5% of the energy input from the waste is taken. So there is no differentiation in the choice of technology for flue gas cleaning, which could lead to a variation ranging from 2 to 4%.

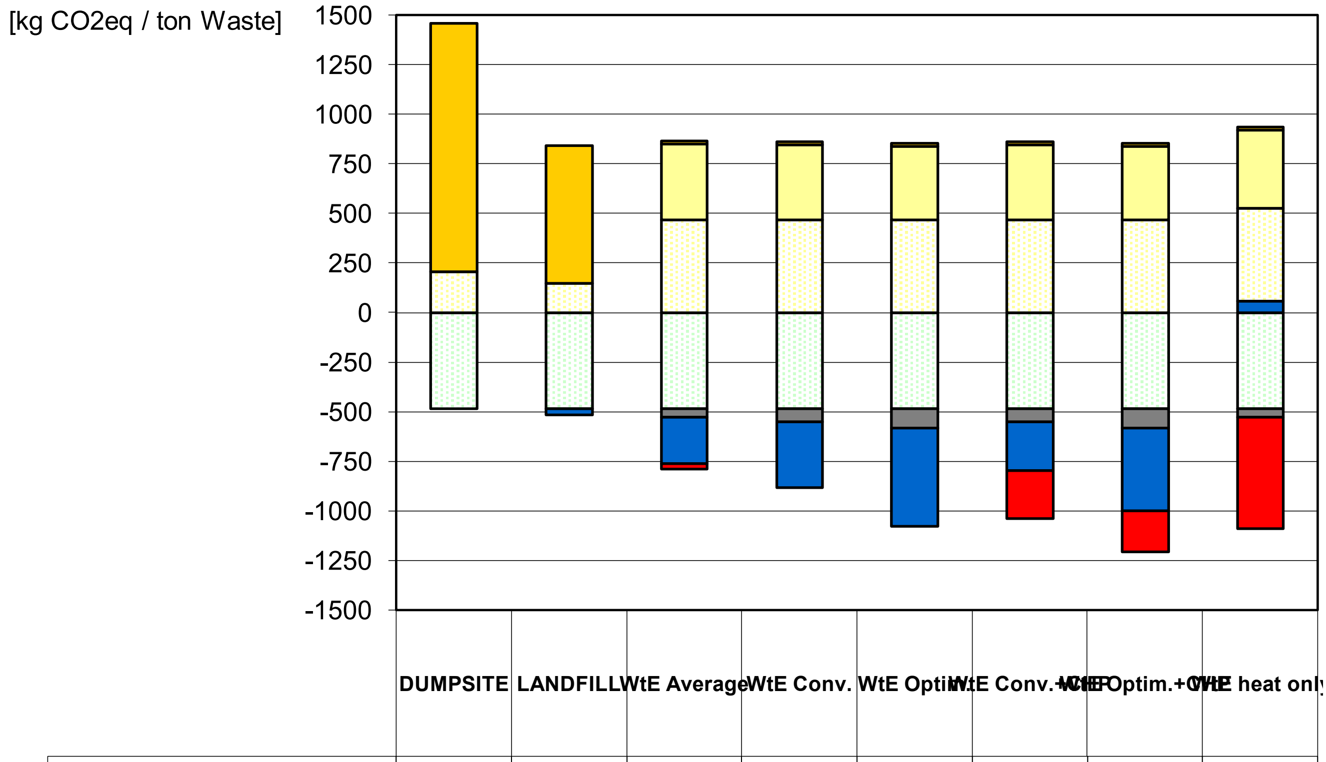
It is important to consider that heat delivery is an option that is relatively simple to implement in any WtE plant. The practical limitations are the investment in the distribution net, which accounts for investments of the same order of magnitude as the WtE plant. The extra performance of heat delivery is not the merit of the technology of the WtE-plant, but of the distribution net and the avoidance of inefficiency at the consumer of the heat. A WtE plant located near energy consuming industry or sufficiently large district heating net permits the WtE with to deliver heat and enables CHP process. In this respect it is important to consider that steam is used for the production of electricity and heat in a WtE-plant just the same as from any other power plant. Regulations for the use of heat have great potential, but should have their own reasoning and justification, irrespective of the original source of energy. This is also needed to create a level playing field between the different sources, to enable the huge potential of the use of heat in combination with power production in general.

2.3 Calculations of CO_2-emissions

The CO_2-evaluation is made as an input/output analysis where all in- and outputs have been converted to their equivalent CO_2-emissions. The data for the equivalent CO_2-emissions are taken from literature for the reference case [17, 18]. For sensitivity analysis some alternative equivalence figures have also been calculated based on different assumptions.

The ***reference case*** for the waste input is in this study the case in which the waste is not produced, but remains in use (or reuse). This case can be seen as a theoretical absolute reference: prevention of the generation of waste generation by keeping it in stock in the society without any CO_2-emissions, energy or material recovery.
The reference case on the output side is for the substituted electricity production the actual mix of power plants in Germany. This is a relative conservative assumption as using actual CO_2-emissions solely from fossil fired power plants as a reference would give much higher values for the GHG-reduction by WtE.
The judgment of processes is only possible in a *relative comparison*. There are no good or bad processes, only better or worse ones [19]. For the waste input in this study we chose a ***reference assuming the waste is not produced***. So for the reference the material is not set free from its source, but remains there in use. This can be seen as a theoretical absolute reference: prevention of the generation of waste generation by keeping it in stock in the society (either prevention or “store it on the attic”) without any CO_2-emissions, energy or material recovery. This reference assigns “absolute” values of emissions for the different options of final treatment of waste. When judging or choosing between different waste management options always the difference between the respective CO_2-emissions should be taken.

The cases are calculated for their direct effects (CO_2 and methane emissions) and the indirect effects from the other outputs. The CO_2 that is stored in the biomass part of the waste is calculated separately and offsets part of the total direct CO_2 emission that is calculated. The recovery of energy and materials is evaluated using the CO_2-equivalents of substituted processes.



	DUMPSITE	LANDFILL	WtE Average	WtE Conv.	WtE Opti	WtE Conv.+CHP	WtE Optim.+CHP	WtE heat onl
🟨 **Methane and N2O (CO2-equiv.)**	**1.251**	**693**	**15**	**15**	**15**	**15**	**15**	**15**
☐ **CO2 emission Fos.orig.**	**0**	**0**	**383**	**381**	**374**	**381**	**374**	**394**
☐ **CO2 emission Bio.orig.**	**208**	**151**	**468**	**468**	**468**	**468**	**468**	**468**
🟥 **Avoided CO2 by Heat delivery**	**0**	**0**	**-25**	**0**	**0**	**-241**	**-210**	**-563**
🟦 **Avoided CO2 by Electr. Prod.**	**0**	**-33**	**-234**	**-332**	**-495**	**-248**	**-416**	**59**
◼ **Avoided CO2 by metal recovery**	**0**	**0**	**-44**	**-65**	**-98**	**-65**	**-98**	**-44**
☐ **CO2 used for biomass**	**-483**	**-483**	**-483**	**-483**	**-483**	**-483**	**-483**	**-483**

Figure: analyses of contributions to CO_2-effect

Below the main effects visible in the graph are explained:

- The strong greenhouse effect of methane (factor 21 more than CO_2) accounts for the high value from a dumpsite. Even when the landfill gas is captured and used in a biogas engine this effect is still large since most of the landfill gas escapes before, during and after the period that the biogas engines can process the escaping gases[20]. N_2O-effect is, even with its high equivalence factor, limited to a few kg/ton of waste.

- The second largest effect is the direct CO_2-emission from land filling as well as from WtE. For landfill this CO_2 is formed together with the methane by the digestion of a part of the biological material in the landfill. For WtE all available carbon in the waste, fossil as well as biological, is converted to CO_2, which explains the high value of direct CO_2-emissions. The carbon used for the formation of the biomass is partially compensating these, and is of course equal for all alternatives.
  In effect MSW is a major source for energy from biomass. Because it uses waste as biomass source, it does not compete with other processes for the use of biomass, nor does it have the side effects of specific production of biomass.

- For landfill this is much lower than for WtE because only (part of the) carbon in the biological fraction is set free at the digestion process in the landfill.

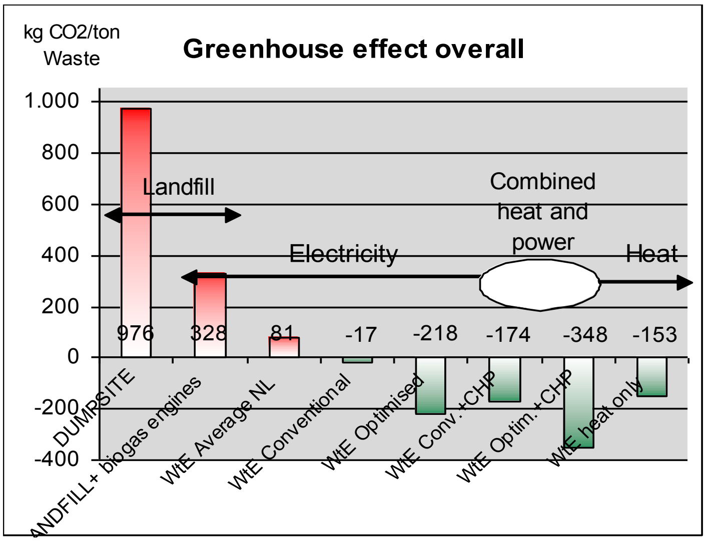
- Since WtE electricity production is reduces the use of other power plants, it has an avoidance effect. It is shown that the conversion efficiency to electricity has a high impact on the differences between the alternatives.

- The application efficiency (recovery rate) of the metals is generally a neglected value, but is shown to be an important contribution to the overall effect, even three times more than recovery of landfill gases. Inert materials however have a negligible impact on the CO_2-balance. Both metals and inert materials should however be evaluated separately with respect to the resource efficiency.

- The application of the heat reduces the use of primary energy for heating which results in a strong avoidance effect. Basically the application of heat is not a variant between the considered alternatives, because the amount of heat utilised is not depending on the WtE plant itself, but on the available infrastructure for distribution to possible users of heat. Choices for a location with a high potential to deliver heat, to industry as well as housing are a major influence on the CO_2-reduction potential. Because heat delivery has only a limited impact on the electrical efficiency, high usage of heat is an additional CO_2-reduction. This explains the good performance of installations with combined heat-and-power.

2.4 Comparison of overall CO_2-emissions

WtE can actually have a negative CO_2-emission. This is mainly due to the large amount of biomass in waste that provides energy without a net CO_2-emission. In effect WtE is one of the main sources of energy from biomass. Because it uses waste as the biomass source WtE doesn't interfere with other biomass processes.



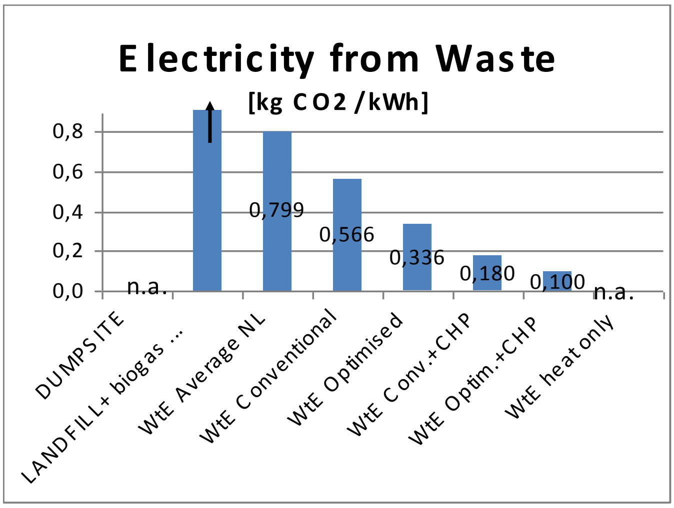
The CO_2-balance of conventional WtE-plants shows a small greenhouse effect. The alternative for this residual waste: landfilling has a dramatically higher greenhouse effect. So the ***relative effect of conventional WtE*** is still a great reduction if the alternative is landfilling.
For the optimised alternative even the "absolute" CO_2-emission (see 2.3 for reference definition) has a negative value, which is even improved for the CHP cases. This puts optimised WtE in the same position as energy produced from pure biomass, wind or solar energy.

Using all possibilities to improve conversion-efficiency, resource as well as application efficiency, enables a great resource potential, directly available.

3 Efficiency Factors Considered

3.1 Electrical efficiency

The electrical efficiency is determined by the conversion efficiency of the plant.
Achieving higher efficiencies is difficult because of corrosion in the boiler which limits maximum steam temperatures. A higher electrical efficiency makes a WtE-plant more expensive.

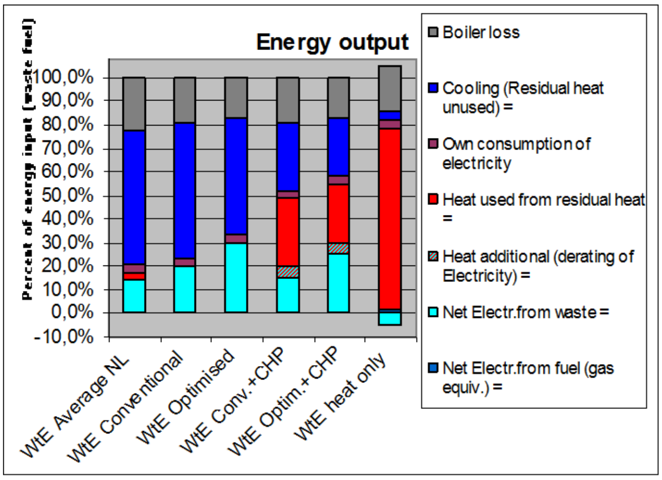


This is the reason why WtE plants are normally not built with a net electrical efficiency above 22%. With increasing electricity prices there is a tendency to achieve higher efficiencies. With traditional steam conditions (40 bars, 400°C) and good optimisation, up to 26% net electrical efficiency can be achieved. The maximum value now achieved is 30% net electrical efficiency at the new WFPP plant in Amsterdam, using all available technologies, including increased steam parameters (125 bar, 440-480°C)[21].

With rising electricity prices, installations with increased net electrical efficiency become economical. In a separate article the economical impact will be analysed.

3.2 *Heat delivery*

The delivery of heat is technically relatively easy to achieve in WtE-plants. It can be accomplished by a simple hot-water boiler for a heat-only WtE plant. More optimal Combined-Heat-and-Power (CHP) plants can be realized by steam extraction from the turbine in a WtE plant producing electricity. This however increases the investment cost of the WtE-plant because of a larger boiler and the steam-water-cycle with turbine, required for the electricity production.



It is the distribution network for the heat that determines the amount of heat that can be used. Steam can be used only within roughly a 1 km, and hot water within about a 10 km radius. Even with an optimal location of the WtE plant the cost for the piping network is generally the limiting factor for exploitation of the heat distribution. Also the heat demand for district heating has strong seasonal variations.
This makes heat-only WtE a low cost installation that only fits with a large district-heating network, which has an investment of at least the same order of magnitude as the WtE plant itself. The combination has a good performance on CO_2-avoidance due to the avoidance of the heat production with a gas fired boiler, which has a low exergy efficiency of only 10-18%.

3.3 *Material recovery*

Generally the iron is recovered from the bottom ash with magnets. The incineration breaks-down the structure of the waste and liberates the metals from other materials. This makes Sorting After Incineration (SAI) more efficient then removing iron directly from the untreated residual waste. Especially small particles can be retrieved to at a much higher level.
Also the other metals can be recovered from the bottom ashes with eddy-current separation (fast rotating magnets). This however is only efficient if the particle size is above about 6-10 mm.

For the optimised WtE we used figures from an improved process for the processing of the bottom ash, where more and different technologies are used. An example is described in [22]. In the table below an indication is given of the recovery of a good classical (dry) separation for the bottom ash, compared with the results from an optimised (wet) process. The values are estimates based on practical experience in a large scale pilot plant.

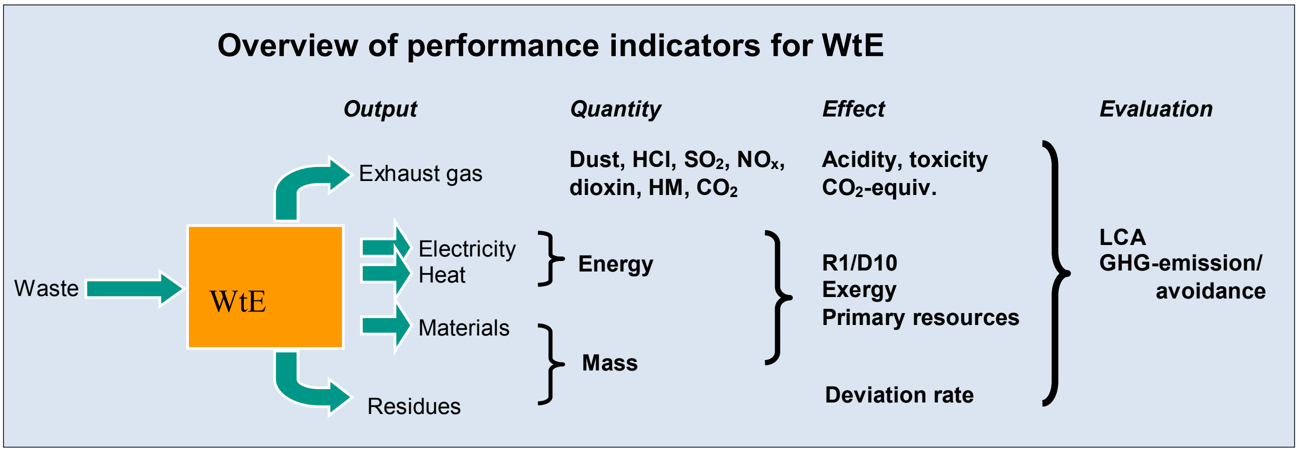
These values are used in the CO_2-evaluation of respectively the classical and optimised WtE. In the case of conventional WtE the inert residue is assumed to be used in road construction. In the case of optimised WtE the wet process is producing clean and high quality sand and granulate that have a reuse at a much higher quality level. This difference is not yet accounted for in the exergy and CO_2 calculations.

TABLE					
Material recovery with SAI	Metal content	Conventional Recovery	Optimised Recovery	Process EXergy	Substituted GHG
	kg metal / ton waste			GJ / kg metal	kg CO_2 / kg metal
Iron	25,	70%	90%	22,2	-2,4
Aluminium	5,	30%	55%	98,6	-10,06
Copper	1,5	30%	80%	45,6	-5,53
Stainless steel	2,	40%	70%	30,	-3,
Non-Ferro metal	1,5	30%	80%	40,	-4,
Inert residue	220,	95%	85%	0,15	-0,0039

4 Other performance indicators for WtE potential

4.1 Output evaluation

The evaluation of the potential of WtE can be done in several ways. Until recently, WtE was only designed to minimize the quantity and the (negative) effect of its emissions: *"designed to be clean"*. There is however a new and strong tendency to develop a new generation of WtE that are *"designed for optimizing output"* of energy and materials. This requires new evaluations of the effects of the outputs of WtE.



In this study the calculations for the GreenHouse Gas (GHG) effect are compared with some other Performance indicators. For all performance indicators the same cases are used.
In the next paragraphs the following performance indicators are compared:

- Diversion rate
  This expresses the reduction of material disposed in landfills. [% of waste].
- Primary resources
  This expresses the reduction materials taken from nature by substitution with recovered materials and energy [e.g. TOE=ton oil equivalent].
- Energy efficiency
  This simply adds all heat and electricity produced [% of calorific value of waste].
- R1/D10 energy efficiency formula in EU waste management regulation
  This expresses all energy in units of heat-energy, whereby gross-electricity has a chosen conversion factor of 2,6316 [23] [factor with no dimension].
- Exergy approach
  This expresses all production in exergy (units of physical work) by using physical relations that express the heat delivery in equivalent amount of electricity depending on the temperature at which the heat is produced [% of calorific value of waste].
- Greenhouse effect
  - In absolute terms for a project [ton CO_2 per year]
  - Per ton of waste relative to land filling [ton CO_2 per ton waste]
  - Per ton of waste relative to average WtE-plant [ton CO_2 per ton waste].
  - Relative to electricity produced [gramCO_2/kWh].

All these approaches are set up as partial Life Cycle Analysis (LCA) in which only the greenhouse effect stages of dealing with MSW are compared on the major effects for the process [24]. These limited evaluations have the advantage of giving a real difference between different process options.

4.2 Primary materials

It is possible to convert all outputs to their equivalent use of primary materials, for example the tonnes of oil equivalents.
There is much similarity with the CO_2-evaluation as, for all fossil sources, there is a direct relation between the energy available in the material and the resulting CO_2-emission. The respective weighing factors however are different depending on the carbon-hydrogen ratio in the material. Expressing the outputs in tonnes-oil-equivalents gives a simple reference situation, avoiding the large differences in CO_2-emission of coal, natural gas (or even biomass or nuclear power). The GHG the methodology however has been worked out in great detail in last years which makes it a more generally accepted performance indicator.

For materials, and especially metals, the substitution by recovery is a performance indicator gaining importance. Metal prices are currently high compared to prices over last decade.
The price of a metal however is not a good reference for the scarcity of a material; it is only an indication of availability for current needs and current production costs. A future scarcity is not reflected in the current price. Conservation of resources and security of

supply are the main advantages for all energy and materials from waste.

4.3 Diversion rate

The diversion rate is a simple performance indicator showing the material-efficiency of the entire chain of waste management.

It is however not making a distinction between low grade reuse (for example road construction) and higher grade reuses (metals, reuse of plastics, concrete).

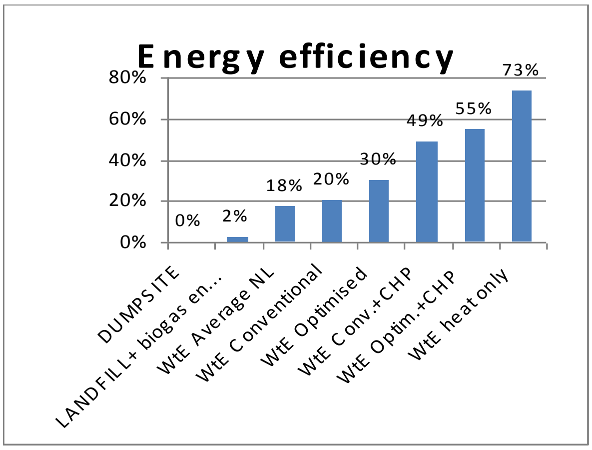
This makes it a good first step in promoting the amount of reused materials, but is not helping further development of reuse systems to types of reuse with a higher (environmental) quality. That is because these optimal material reuses have more specific and stringent requirements for the materials that should be reused and as a consequence the amounts of rejects are higher. That is why in the long run the diversion rate is not an optimal performance indicator and could even hamper optimisation to higher quality levels of reuse.

For WtE the diversion rate mainly depends on the regulations for the application of bottom ash. When the bottom ash has to be landfilled diversion rate is limited to about 75%. In countries where bottom ash can be used in road construction the diversion rate of a typical WtE-plant can be as high as 98,5% (only fly ash and air pollution control residues). An improved bottom ash treatment recovering more metals and producing clean sand and granulate in this case does not show in the diversion rate.

4.4 Energy efficiency

Energy efficiency is the most used and simplest performance indicator for WtE installations:

$$Energy\ efficiency = \frac{\text{Heat} + \text{Electricity}}{\text{Input from waste}}$$



Many calculation methods have been proposed for energy efficiency, differing in details but giving incomparable results. Calculations differ for example in the use of gross electricity production of the generator or the use of net delivery to the grid. In a Dutch study alone, already 11 methods that are used in different legislation have been listed [25,pag14]. This is mainly due to different definitions, deviations from the laws of physics and the specific parameters and assumptions.

The energy efficiency for the different cases considered shows the low efficiency of the recovery of biogas production and recovery from a landfill. This is a combination of the low conversion rate and low biological efficiency in the landfill combined with limited efficiency of extraction.

The net-electrical efficiency for WtE in this study varies from 14,5% for the Dutch average (which also has some heat delivery), to 20% for state of the art conventional WtE and 30% for the most optimized case.

The three cases on the right hand side show the high contribution of heat delivery for increasing energy efficiencies.

The energy approach has some fundamental advantages:

- The method is “absolute”, no reference case is needed in the definition.

This approach has some disadvantages:

- The Energy efficiency is adding “apples and pears”: the low quality heat is added on an equal basis to the high quality electricity.
- Material/metal recycling is not taken into account.
- The offset from the biogenic content in the waste is not taken into account.

4.5 EU: R1/D10 formula

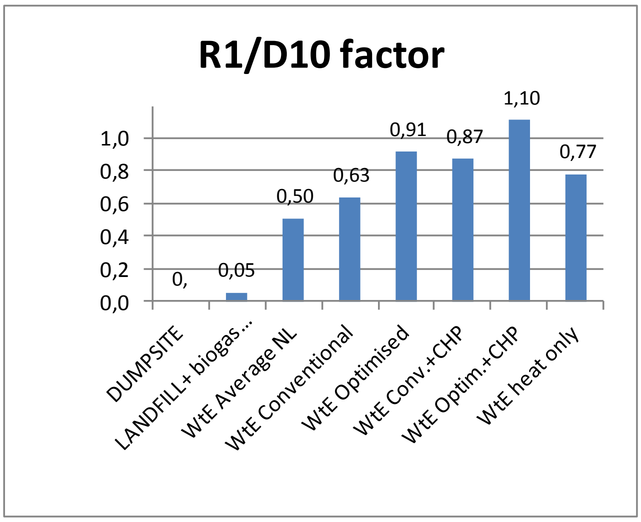
The R1/D10 formula in the EU Waste Framework directive is one of the energy efficiency formulas developed for WtE. In 2003 the EU-court made the distinction between recovery and disposal based on the sentence " ….the greater part…..". Later this sentence was transformed in a formula in the BREF that gives the ratio between the energy produced and the energy used [1]:

$$R1/D10\ efficiency = \frac{\mathrm{E_i} - (\mathrm{E_f} + \mathrm{E_i})}{0.97 \text{ x } (\mathrm{E_w} + \mathrm{E_f})}$$

This formula is now basis of a new EU ruling which determines the distinction between reuse (R1-status) and disposal (D10-status) on basis of this formula. For performance of WtE plants in EU see [26]. Thresholds of 0,6 for existing and 0,65 for new plants are being considered currently. For a stand-alone installation without imported energy or fuel use and the definition of the ratio between electricity and heat the formula simplifies to:

$$R1/D10efficiency = \frac{1{,}1 * \text{Heat} + 2{,}6 * \text{Gross. Electr}}{\text{Input from waste}}$$

The heat produced is the primary performance indicator, corrected with the total electricity production by the generator multiplied with an equivalence factor. This "Gross.Electr" is the net exported energy plus the energy "circulated" for internal consumption. This study used 3,5% own consumption for all cases.



As can be seen in the graph there is a correlation between this formula and the CO_2-emission, but it is not a clear relationship. This is mainly caused by the following factors:

- Material/metal recovery is not taken into account.
- The offset from the biogenic content in the waste is not taken into account.
- Ratio of the fixed "value" of heat and electricity differs from that explained by the respective CO_2-effects.

The EU R1/D10 formula for energy approach has some fundamental advantages:

- The method is "absolute", no reference case is needed in the definition.
- The biogenic content in the waste, which is impractical to measure, is not needed.
- Electrical efficiency for a plant can be measured by an established definition (ISO 1940).

This approach has some disadvantages:

- The Energy efficiency definition is a new political definition, setting WtE apart from electrical power production industry
- Material/metal recovery is not taken into account.
- The offset from the biogenic content in the waste is not taken into account.
- The equivalence factors (1.0989 for heat, 2,6316 for electricity and 0,97 to account for energy losses due to bottom ash and radiation) have no real physical background.[27]
- The equivalence factors don't take the temperature, and thereby enthalpy of the heat delivered, into account. This rewards (and stimulates) low-temperature district heating, but underestimates the even better effect of high-temperature steam delivery to industry.

Threshold values of 0,6 for existing and 0,65 for new plants are in discussion now. From the graph it can be concluded that for existing plants 0,6 is high, except for plants with heat delivery. For new plants to be built the 0,65 is not challenging for full optimisation.

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[1] E_p = annual energy produced as heat or electricity.
E_f = annual energy input to the system from fuels contributing to the production of steam
E_w = annual energy contained in the treated waste calculated using the lower net calorific value
E_i = annual energy imported excluding Ew and Ef (GJ/year)
0.97 = factor chosen for accounting for energy losses due to bottom ash and radiation.

4.6 Exergy efficiency

Energy efficiency considerations are of interest only to determine the output of useful energy. EXergy is ***that part of energy that can perform (mechanical) work*** [2].

For each type of energy there is a physical relation that determines how much that part is (the equivalence factor, or "exchange rate") [28]:

$$\text{EXergy}\ efficiency = \frac{\text{Net Electr}_{\cdot\text{from waste}} + \text{k}_{\text{heat}} * \text{Heat}}{\text{Input from waste}} =$$

$$= \text{Net Electr. Efficiency}_{\text{from waste}} + \text{k}_{\text{heat}} * \text{Heat Efficiency}$$

The R1/D10 formula above essentially uses a similar approach only using non-physical factors for equivalence between heat and electricity. In the exergy formula the factor "k_{heat}" has a value depending on the temperature of the heat produced, and is thereby covering the differences between steam or hot-water production [29].

To correct for fuel used:

$$\text{Net Electr}_{\cdot\text{from waste}} = \text{Net Electr}_{\cdot\text{total}} - \text{k}_{\text{fuel}} * \text{Fuel}$$

Where k_{fuel} is the standard electrical efficiency for power plants with that type of fuel and Fuel is the amount of energy in the used fuel. In this study this practical estimate for the exergy out of the fuel is taken as 54% for natural gas.

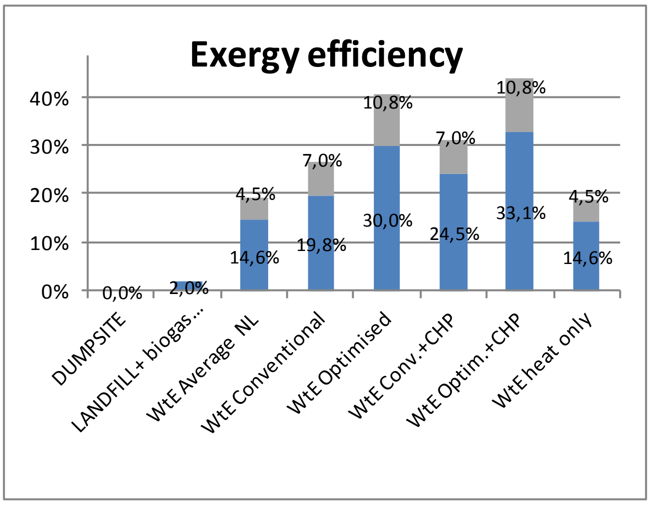
The exergy approach has some fundamental advantages:

- The method is "absolute", no reference case is needed in the definition.
- Electrical efficiency for a plant can be measured by an established definition (ISO 1940).
- Variations in heat-delivery temperature (steam or hot water) are evaluated in a physically correct manner.
- The biogenic content in the waste, that is impractical to measure, is not needed.

This approach has some disadvantages:

- The offset from the biogenic content in the waste is not taken into account.
- Material/metal recovery is not taken into account.

Although the exergy only accounts for direct energy in/output, it is possible to add the "embedded exergy", used for the production of materials in analogy to standard LCA practice of calculation of substituted process. In this way recovered iron (k_{iron}* Iron) and other metals can be shown. For exergy the values shown in the table have been used [30].



The results show that the material recovery from the bottom ashes has an important contribution to the overall performance of WtE, and that a significant improvement can still be made [31]. To stimulate the use of this potential it is important that the performance indicator used for regulation of WtE includes the substitution effect of recovered materials.

The physically correct thermo dynamical approach is the (implicit) basis for many different energy efficiency considerations. The R1/D10-formula above is one of these, using estimated and politically chosen equivalence factors. The Dutch regulation for stimulation of Environmental Effectiveness of Power Production (MEP) uses a similarly politically chosen k_{heat}=2/3. This is an overestimation of the thermodynamic equivalence of heat. Hereby the "credit" for district heating (avoided exergy loss at the user) is transferred from the application to the producer (the power plant, in this case WtE).

	Ore: Exergy, [MJ/kg]	Metal: Exergy, [MJ/kg]	Processing Exergy [MJ/kg]
Iron	0,695	6,750	22,2
Aluminium	4,118	32,805	98,2
Copper	61,6	2,112	45,6
Stainless steel			30
Other NF-metals			40
Inert materials	0,1	0,0	0,15

4.7 GHG from electricity produced

Instead of the evaluation of GHG-effect related to waste, it is also possible to relate it to the output of electricity. This evaluation gives a clear perspective of

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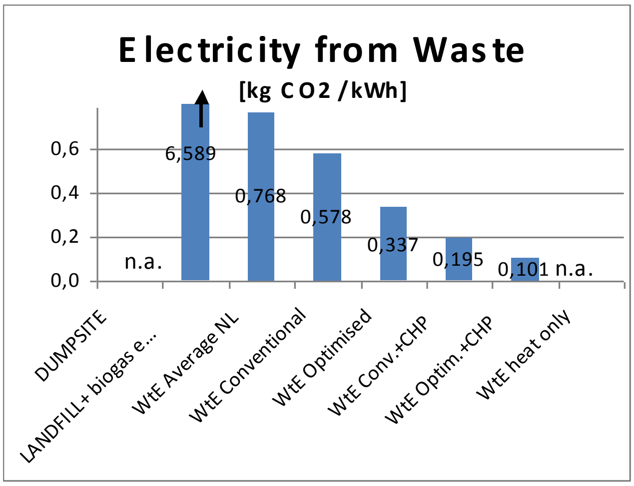
[2] Read: http://en.wikipedia.org/wiki/Exergy: "…Exergy is useful when measuring the efficiency of an energy conversion process. The exergetic, or 2nd Law efficiency, is a ratio of the exergy output divided by the exergy input. This formulation takes into account the quality of the energy, often offering a more accurate and useful analysis than efficiency estimates only using the First Law of Thermodynamics. ….."

the performance of waste seen as a fuel for a power plant. Hence for many energy considerations, it is the most useful performance indicator.



The GHG value consists of the direct emissions from WtE, minus the absorbed CO_2 for biomass and the avoided CO_2-emissions from heat and recovered materials. No substitution of electricity is included and as a consequence this performance indicator does not need the sensitive assumption for the reference for substituted power production. It is shown that, although biomass is half of its input, the average WtE-plant still has a relatively high GHG-effect due to its low efficiency. Still, it is significantly below the mix of fossil fuel power plants in Germany.

The conventional WtE-plant has a GHG-effect in the range of the mix of all sources in Germany. The optimized WtE is equivalent to the best gas fired power plant. WtE-plants with CHP have a significantly lower GHG-effect per kWh than any of the listed alternatives they are substituting.

Electricity production	**kg CO_2 / kWh**
Gas fired power plant (best)	0,379
Gas fired power plant (Average, complete chain)	0,551
Mix of all sources in Germany (also REFERENCE used in this study for SUBSTITUTION)	**0,594**
Mix overall Netherlands [32]	0,698
Mix of fossil power in Germany	1,037
Coal fired power plant	1,200

5 Potential available in residual waste

In this chapter the total potential of Energy-from-Waste is briefly investigated for Europe.

Potential in Waste			
	The Netherlands	**Europe**	
Combustible waste amount	10	182	M-ton /year
Caloric value waste	10	10	MJ / kg
Energy in waste =	100	1820	PJ-prim / year
Net electrical efficiency	30,0%	30,0%	when processed in high efficiency W2E's
Potential power production from waste			
=	8.333	151.667	GWh-Electr / year
=	951	17.314	MW-electricity
=	**9,2%**	**7,5%**	**EU total power stations**
Total Produced Electricity in EU-15	90.412	2.020.038	GWh-electr / year
Which is equivalent to	10	231	GW e-continuous
Avoided CO_2-equiv. compared to Landfill			
CO_2 emission Optimized WtE	**-0,218**	**-0,218**	kg CO_2 / kg waste
CO_2 emission Optimised Landfill	**0,328**	**0,328**	kg CO_2 / kg waste
Avoided CO2 =	**5.457**	**99.320**	**kton / year**
Avoided CO_2 by optimizing WtE infrastructure			
CO_2 emission Optimised WtE	**-0,218**	**-0,218**	kg CO_2 / kg waste
CO_2 emission Average WtE	**0,081**	**0,081**	kg CO_2 / kg waste
Avoided CO2 =	**2.985**	**54.330**	**kton / year**

From the current amount of 50 million ton/year residual MSW that is treated in WtE installations in the EU there is roughly the potential to yield the following increase in output:

- A factor 4 on amount of waste to WtE.

And for every ton of waste going to WtE:

- A factor 2 on electricity production.
- A factor 2 on the recovered metals.

Additionally there is a large potential for CHP from WtE, which is limited more by the distribution infrastructure than by WtE capacity itself.

Including the effect of avoided landfilling, the GHG-balance shows a reduction of 546 kg CO_2 / ton waste, for every ton of waste that is treated in an optimised WtE-plant instead of landfilled in an optimised landfill. Compared to classical landfilling the avoidance is even more than double at 1194 kg CO_2/ton of waste. U upgrading from the average WtE in the existing infrastructure, to an optimised WtE in a future infrastructure, reduces GHG another 299 kg CO_2/ton of waste.

Compared to optimum landfilling, which currently is not the case by far, the reduction potential of optimised WtE for all MSW would be 100 Mton

CO_2/year for the EU-15. The improvement from the average efficiency of existing WtE to just optimised WtE for all MSW, would yield a 50 Mton CO_2/year reduction for the EU15.

6 Conclusions

The purpose of this study is to model the energy and greenhouse related performance of a range of different landfill and WtE-plants. All assumptions are based on literature references or actual experience. Where there is a choice from several possibilities this is marked. The detailed calculation model is available at info@afvalenergiebedrijf.nl. All outputs (energy and materials) are evaluated on their greenhouse effect through the use of equivalent CO_2-emissions. The choice for the reference case has been made as clear and conservative as possible:

- For the input the reference situation is that the waste is avoided and the materials remain in (re)use.
- For the output of electricity substitution, of the actual mix of power plants in Germany is taken, including all non-fossil generated power.

It is shown that there are great differences between the GHG-effect of a classical dumpsite, an optimised modern landfill, and different variants of the WtE-plants. Instead of opposing to either landfilling or WtE, this demonstrates the importance to distinguish the wide range of differences within these options and to work on optimal implementation of a chosen option.

It is shown that, due to the biomass content and the avoidance effect due to the recovery of energy and materials, conventional WtE has a near zero CO_2-balance per ton of waste. Optimised WtE can have a significant negative overall CO_2-balance (net avoidance of CO_2) of 200-300 kg CO_2/ton of waste. Comparing this to optimised landfilling, which is often the alternative for the difficult residual MSW that goes to WtE, the overall avoidance is in the range of 500-650 kg CO_2/ton of waste. Compared to classical landfilling the avoidance is in the range of 950-1400 kg CO_2/ton of waste.

In order to get a good insight into the effects of the performance of the different variants, the GHG-effect per ton of waste is compared with other performance indicators, such as: primary materials and disposal rate, energy efficiency, R1-D10 formula for efficiency from the EU Waste Framework directive, exergy efficiency, CO_2 per ton of waste and CO_2 per kWh electricity.

If WtE is evaluated as a power plant, an optimised plant can have an emission of only 0,337 kg CO_2/kWh, lower than a gas fired electrical power plant. With CHP this can be reduced even further.

The total potential of Energy-from-Waste for Europe is shown to be about 7,5% of the total electricity production. This can be achieved by replacing landfills with WtE-plants that are optimised for maximum electricity production. In addition, doubling the amounts of heat and metals recovered is possible with available technology.
It is shown that the performance indicators that combine conversion efficiency of the WtE-plant with resource efficiency (substitution of primary materials) and application efficiency (at what temperature is the heat used) can be a stimulant to more effective variants of WtE.

Key performance indicators	**LANDFILL**		**WTE**	**WTE**		**WTE-CHP**		**WTE**	
	Classical	**Optimised**	**Average**	**Classical**	**Optimised**	**Classical**	**Optimised**	**Heat only**	
Electricity from Waste (net)	-	54,8	395	558	834	424	708	-100	kWh/ton Waste
Heat from Waste (net)	-	3,2	92	-	-	895	773	2120	kWh/ton Waste
Energy efficiency	-	2%	17%	**20%**	**30%**	47%	53%	71%	Energy output/input
R1/D10 factor	-	0,05	0,50	0,63	0,91	0,87	1,10	0,77	EU-formula
Exergy efficiency	0,0%	2,0%	14,5%	19,7%	29,9%	24,1%	32,9%	13,4%	EXergy useful produced / energy in waste
Exergy equiv. Recovered metals	0,0%	0,0%	4,5%	7,0%	10,8%	7,0%	10,8%	4,5%	EXergy useful produced / energy in waste
Net Greenhouse effect	n.a.	6589	801	566	337	206	112	n.a.	gram CO_2 / kWh_{el}
Net Greenhouse effect	976	328	82	-15	-219	-164	-341	-132	kg CO_2 / ton of waste
CO_2-equiv. rel. to average-WtE	895	246	-	-97	-301	-246	-423	-213	kg CO_2 / ton of waste
CO_2-equiv. rel. to optim.landfill	0,649	-	-246	-343	-547	-492	-669	-459	kg CO_2 / ton of waste
CO_2-equiv. rel. to class.dumpsite	-	-649	-895	-992	-1195	-1141	-1318	-1108	kg CO_2 / ton of waste

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[29] **k_{heat}= Carnot Heat Quality Factor = 1 – T_0/ T_{heat},** where T_0 is the reference (15°C = 288,15K).
The factor "k" expresses the maximum physical conversion factor between heat and mechanical/electrical energy according to the Carnot law. This relation is generally named **exergy**. All types of energy can be expressed in to their equivalent exergy.
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