Unleashing the power in waste

A great potential that should not be wasted

CONCEPT
rev. 5; 1-8-2007 19:38; ARTICLE UNLEASHING THE POWER IN WASTE 2.1

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01/08/2007 18:22:00, Amsterdam
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Keywords: CO_2-evaluation, CO_2-avoidence, GreenHouse Gas, Municipal Solid Waste, Waste-to-Energy, Landfill, recovery, recycling, energy efficiency, exergy.

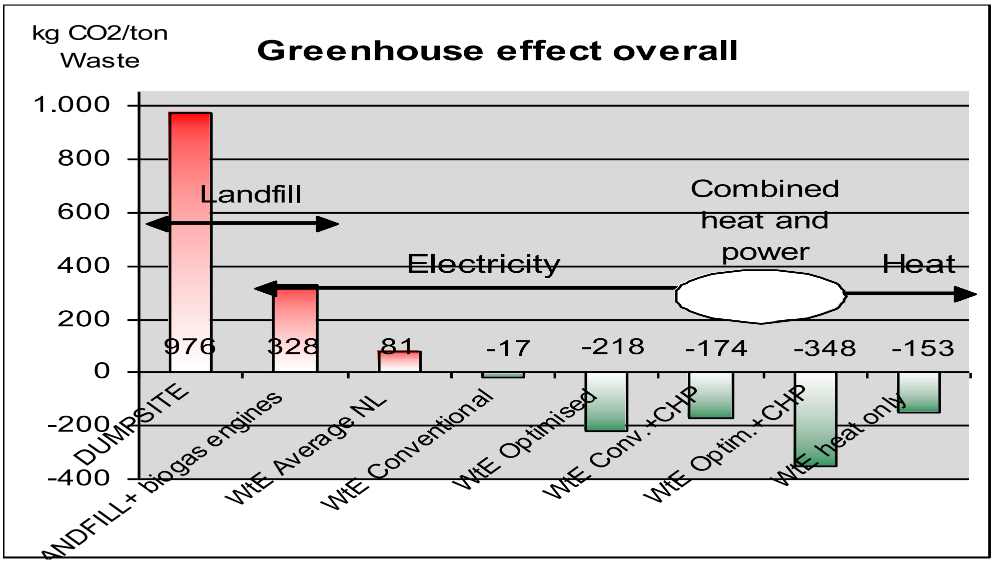
Abstract

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. 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 0,337 kgCO_2/kWh, lower than a gas fired electrical power plant. 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. For all performance indicators the same cases are used.

The study is focussing on the residual Municipal Solid Waste (MSW) and similar commercial waste, difficult streams remaining after all other possibilities of the waste hierarchy are exhausted. For this waste the normal choices are landfilling or 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, waste incineration 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.

The many variations in sorting of residual MSW are not dealt with in this note. They can be considered as combinations of partial landfilling, partial WtE and some other processes like biological drying or digestion. Their performance on energy recovery and on CO_2-emissions varies and is to a great extent depending on 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.

For all variants of WtE Best Available Technology (BAT) is taken as a starting point. This is taken as "conventional" (3rd-generation) of WtE which has been *"designed to be clean"* to guarantee that the process and stack emissions are fulfilling all standards.

For the optimised installations, additionally, the ***optimization of the recovery of energy and materials*** is taken as a starting point; 4th-generation: *"design for output".* For the recovery of energy and materials the BAT/BREF for WtE [1] [2] provides up to now limited reference, so new performance indicators are needed. The CO_2-greenhouse gas evaluation is compared with other methods in this paper.

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[1] BREF Waste Incineration: http://ec.europa.eu/comm/environment/ippc/brefs/wi_bref_0806.pdf

[2] Draft BREF Energy Efficiency: http://ec.europa.eu/comm/environment/ippc/brefs/ene_d2_0707.pdf or http://eippcb.jrc.es/pages/FActivities.htm

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 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. For the waste input in this study the *reference case* is that the waste is not produced, but remains in use or reuse. For the substituted electricity production the actual mix of power plants in Germany, is taken as the reference. Using actual CO_2-emissions from fossil fired power plants only 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. It could 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 [3] and translated into costs per avoided ton CO_2 in a partial Life Cycle Cost analysis [4].

2 LCA evaluation on CO_2

2.1 The evaluation method

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

Along with clean and hygienic treatment of waste the fundamental aim of waste management is 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 to 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 comprised between 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.

For waste classes 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 on the long run exactly the same “output” will result as that is taken as natural “input” to our society. So the ever increasing amounts taken from nature, and the increasing variations in materials, will make the residual waste an ever more complex material.

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[3] J.Wandschneider, W+G; Studie zum Energiepotential van KVA in der Schweiz, June 2005; http://www.vbsa.ch/file/Energiepotenzial_KVA.pdf .

[4] Werner P.Bauer, Dr.Thomas Köning, Wolfgang Scholz: Kostenvergleich einer Deponie mit einer „Waste to Energy“Anlage im Großraum Sao Paulo nach der Methode des Total Costs of Ownership; Müll und Abfall, Nov 2006.

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 analyse, 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. 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 to a fixed value for all 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 is not studied, but in real plant design there could also be some optimization on this point.

Construction of the WtE plant 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
   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 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 [5]. The waste input is the same for all cases. The properties of the landfill or WtE plants are varied per case. All the

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[5] http://www.epa.gov/mswclimate/greengas.pdf ? new link ?

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 next parameters are used:

LCA-parameters [6]		
ELECTRICITY average overall in Germany	-0,594	kg CO_2 / KWh-Electr (German mix of all sources)
HEAT: gas fired boiler	-0,256	kg CO_2 / KWh-heat
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 what reference is chosen for the alternative primary source of primary energy that is 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 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) [7]. The fossil-only mix of Germany (1,037 kg CO_2 / kWh)[8] 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. 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. This is neglecting the important differences between the performances of the existing installations. Also it is using the complete range of installations, many of which are 20 to 30 years old and have never been designed for effective recovery of energy and materials.

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[6] [Fehrenbach,Weiss:VDI,sept2006München]

[7] E. van der Voet, et al (CML,SenterNovem): Greenhouse Gas Calculator for Electricity and Heat from Biomass: Draft, June 26, 2007

[8] [Fehrenbach,Weiss:VDI,sept2006München]

This study is specifically differentiating between the properties of several variants compared:

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

The landfill is considered in two variants. The dumpsite is a simple classical variant that is generally used and has no specific provisions for preventing the escape of landfill gases formed by the digestion processes. The optimised landfill 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.

The average WtE is taken as the installed base of existing WtE plants that have been build in the last 30 years in The Netherlands. It has a relatively low efficiency of 14,5% [9]. The "conventional WtE" considered here is taken as a plant which is nowadays state of the art with a net-electrical-efficiency of 20%. New installations tend to have net-electrical-efficiencies of 18% to 24% mainly depending on their size, steam parameters and air/water cooling. For all cases own consumption is taken as 3,5% of the energy input from the waste. So there is no differentiation on the choice of technology for flue gas cleaning, which could lead to an own consumption ranging from 2 to 4%.

The optimized WtE 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.

For Combined Heat and Power (CHP) it is assumed that 50% of the yearly available heat at 140°C 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 heating need is not matching 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. Only for the heat-only WtE a complete use of the available heat is taken, assuming a much larger demand that is partially met with specific heat production for covering the variations in the demand.

It is important to consider that heat delivery is an option that is relatively simple to implement 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 empowers the WtE with heat delivery 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 as any other power plant. Regulations for the use of heat are of great potential, but should have their own reasoning and structure, irrespective of the original source of energy. This is also needed to create a level playing field between different sources, for enabling the huge potential of the use of heat in combination with power production in general.

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[9] CEWEP, D.Reiman, 2005

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 [10, 11]. For sensitivity analysis some alternative equivalence figures have also been calculated based on different assumptions.

The judgment of processes is only possible in a *relative comparison*. There are no good or bad processes, only better or worse ones [12]. For the waste input in this study we chose a ***reference case, assuming the waste is not produced***. So in the reference the material is not set free from the source, but remains there in use (or reuse) without generating CO_2-emissions. This reference gives "absolute" values of emissions from the different options. When judging or choosing between different waste management options the difference between the respective CO_2-emissions should be taken.

The options 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.

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[10] VDI München 2006: zie spreadsheet

[11] http://yosemite.epa.gov/oar/globalwarming.nsf/uniquekeylookup/shsu5bnpmv/$file/canada.pdf

[12] Oliver Gohlke, ea; Werkzeuge zur bewertung von Abfallbehandlungsverfahren, methoden und ergebnisse, VDI, Düsseldorf, April 2006. Ch.4 Ökobilanzen (=LCA's) + Ch.11

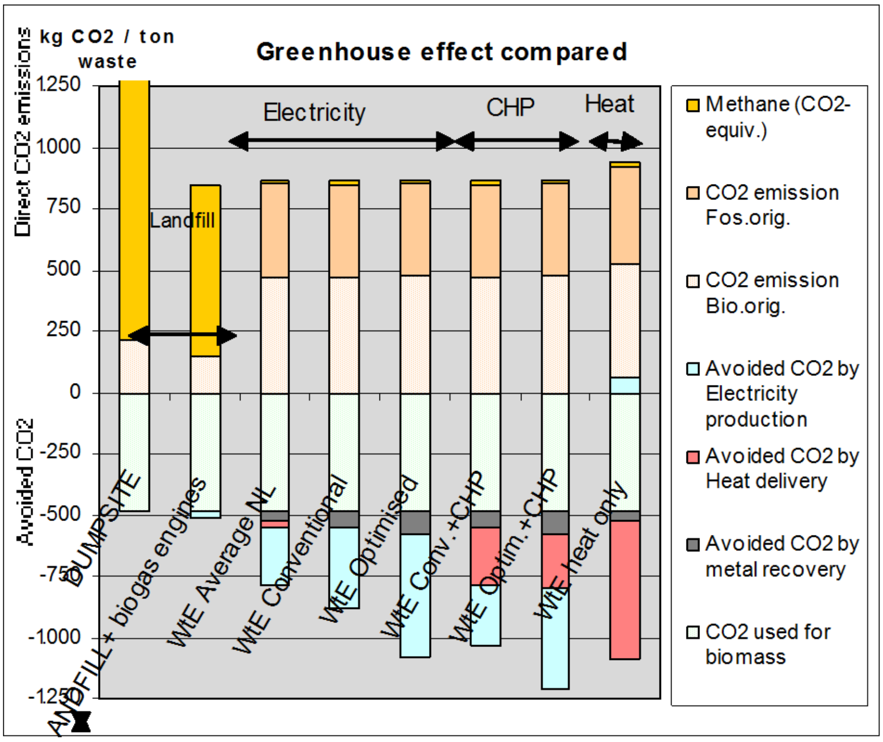

Figure: analyses of contributions to CO_2-effect

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. [13]

- The second largest effect is the direct CO_2-emission of land filling as well as 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, fossil as well as biological, in the waste 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 the WtE because only (part of the) carbon in the biological fraction is set free at the digestion process in the landfill.

- For the WtE electricity production is reducing the use of other power plants, so has an avoidance effect. It is shown that the conversion efficiency to electricity has a strong impact for the difference between the alternatives.

- The application efficiency (recovery rate) of the metals is generally a neglected value, but is shown to be a good contribution to the overall effect, even three times more than recovery of landfill gases. Inert materials however have a negligible impact on

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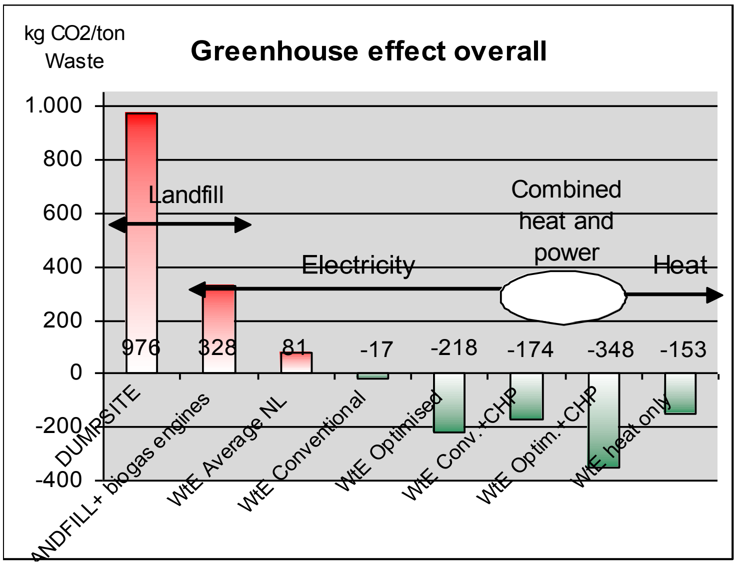
[13] United Nations Framework Convention on Climate Change: Tool to determine methane emissions avoided from dumping waste at a solid waste disposal site; http://cdm.unfccc.int/EB/026/eb26_repan14.pdf

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 is reducing 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 CO_2-reduction potential. Because heat delivery has only a limited impact on the electrical efficiency high use 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 combined power cases. This sets optimised WtE at the same position as energy produced from pure biomass, wind or solar energy.

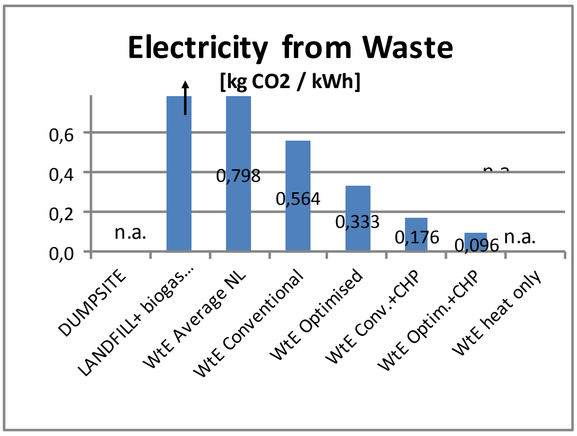
By using all possibilities to improve conversion-efficiency, as well as resource and application efficiency, there is a great potential available.

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.

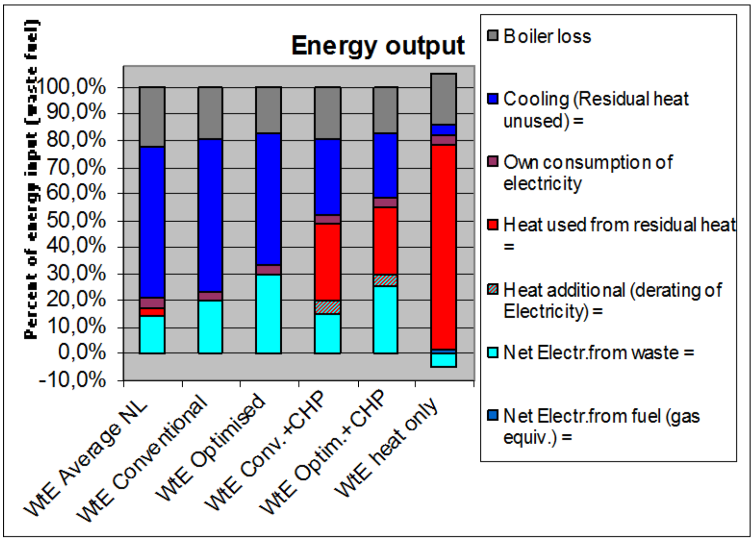
This is the reason why WtE plants are normally not built with a net electrical efficiency above 22%. With higher electricity prices there is a tendency to achieve higher efficiencies. With traditional steam conditions (40 bars, 400°C) and good optimisation, up to 26% net electrical efficiency can be 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)[14].



With rising electricity prices, installations with increased net electrical efficiency seem 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 is however increasing 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

3.3 Material recovery

Generally the iron is recovered from the bottom ash with magnets. Because the incineration removes the structure of the waste, the recovery of iron is more efficient then removing iron

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[14] "Value from Waste": AEB-Amsterdam, M.AJ. van Berlo, 2006; http://www.afvalenergiebedrijf.nl/bijlagen/value%20from%20waste.pdf

directly from the untreated residual waste. Especially small particles can be retrieved to 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 particle size is above about 10 mm.

For the optimised WtE we use figures from an improved process for the processing of the bottom ash, where more and different technologies are used. An example is described in [15]. 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 full-scale pilot plant.

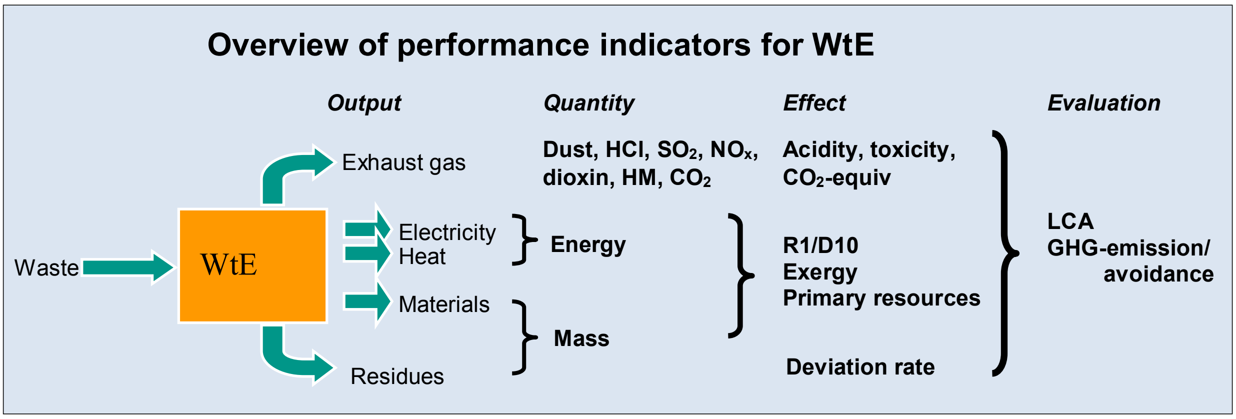
Table Material recovery					
	Metal content	Conventional Recovery	Optimised Recovery	Embodied EXergy	Substituted GHG
	kg metal / ton waste			GJ / kg metal	kg CO_2 / kg metal
Iron	25,	70%	90%	22,2	-2,4
Aluminium	5,	30%	55%	131,	-10,06
Copper	1,5	30%	80%	53,6	-5,53
Stainless steel	2,	40%	70%	40,	-5,
Non-Ferro metal	1,5	30%	80%	50,	-4,
Inert residue	220,	95%	85%	0,15	-0,0039

These values are used in the CO_2-evaluation of the classical and optimised WtE. For the inert residue use in road construction is assumed in the case of conventional WtE. For 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. This is not jet accounted for in the exergy and CO_2 calculations.

4 Other performance indicators for WtE potential

4.1 Output evaluation

The evaluation of the potential of WtE can be done on 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.

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[15] L.Muchová, P.C. Rem; Pilot plant for wet physical separation of MSWI bottom ash; Delft University of Technology.

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. [% 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[16] [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 [17]. 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 is however different depending on the carbon-hydrogen ratio in the material. Thereby the relative advantage of natural gas in the CO_2-evaluation is avoided by the evaluation according to the use of primary materials.
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). However for 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.

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[16] IPPC Draft Reference Document on the BAT for Waste Incineration, EU-JRC; http://eippcb.jrc.es or http://www.epa.ie/Licensing/IPPCLicensing/BREFDocuments/FileUpload,8905,en.pdf chapter 3.5.4.3

[17] Comparison of different evaluation methods: Nandan U. Ukidwe and Bhavik R. Bakshi: Thermodynamic Input-Output Analysis of Natural and Economic Capital – Implications for LCA and Supply Chain Management http://www.lcacenter.org/InLCA2004/papers/Ukidwe_N_paper.pdf

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, reuse of plastics).
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 reuse has more specific and stringent requirements for the materials that should be reused and as a consequence the amount of rejects is 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 of reuse.

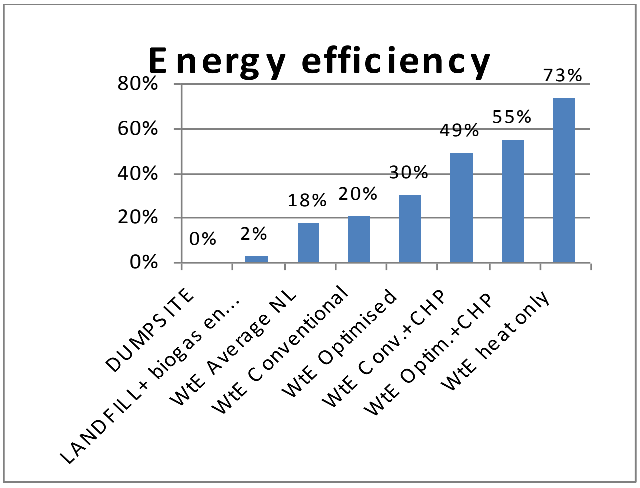
For WtE the diversion rate mainly depends on the regulation for the application of bottom ash. In countries where bottom ash can be used in road construction the diversion rate of a typical WtE-plant can be as high as 98%. When the bottom ash has to be landfilled is limited to about 75%. An improved bottom ash treatment recovering more metals and producing clean sand and granulate is not visible in the diversion rate.

4.4 Energy efficiency

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

$$Energy\ efficiency = \frac{\mathrm{Heat\ +\ Gross.Electr}}{\mathrm{Input\ from\ waste}}$$

The energy efficiency for the different options considered shows the low efficiency of the recovery of biogas production and recovery from a landfill. The three cases on the righthandside show the high contribution of heat delivery for increasing the energy efficiency. The net-electrical efficiency in this study varies from 14,5% (Dutch average), 20% for state of the art conventional WtE and 30%, for the most optimized case. For all cases own consumption of electricity is taken as 3,5% of the energy input from the waste.



Many different evaluation methods have been proposed for energy efficiency. In a Dutch study alone, already 11 methods that are used in different legislation have been listed[18,pag14]. This is mainly due to different definitions, deviations from the laws of physics and using specific parameters and assumptions.

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 equally 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.

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[18] Analysis of energy efficiency definitions for policy making (in Dutch), H.Erbrink, B.Strortelder, W. Ruijgrok (KEMA), Drs.G.J.J. Smakman (NOVEM).2001, Reportnr: 2EWAB01.03, publicatiecentrum@novem.nl

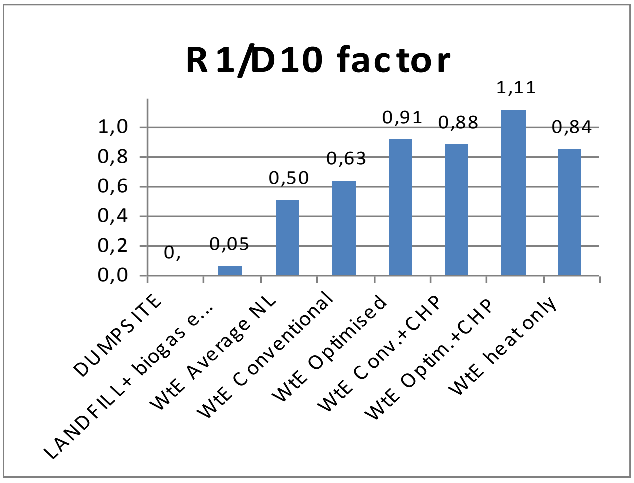
4.5 EU: R1/D10 formula

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 [19]:

$$R1/D10efficiency = \frac{\mathrm{Ep} - (\mathrm{Ef} + \mathrm{Ei})}{0.97 \times (\mathrm{Ew} + \mathrm{Ef})}$$

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. 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:

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



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, that is impractical to measure, is not needed.
- Electrical efficiency for a plant can be measured by an established definition (ISO 1940).

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

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.[20]
- 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.

4.6 Exergy efficiency [21]

Energy efficiency considerations are interested only in the output of useful energy (the laws of energy conservation makes assessing all energy will yield a trivial 100% efficiency for all cases).

Exergy is ***that part of energy that can perform (mechanical) work***.

For each type of energy there is a physical relation that determines how much that part is (the equivalence factor, or "exchange rate") [22]:

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

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

Essentially the R1/D10 formula above 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 [23].

To correct for imported fuel:

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

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 54% from natural gas is used.

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[20] Christian Tebert, Ökopol gmbh, Institute for environmental strategies;The energy efficiency Formula of annex ii of the Waste framework directive; A critical review. http://www.eeb.org/activities/waste/20060630-Okopol-Brief-on-MSWI-efficiency-formula-v5-final.pdf

[21] 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. ….."

[22] Full formula is available in: IPPC Draft Reference Document on the Energy Efficiency Techniques , EU-JRC; chapter 1.3.3.2 ; http://eippcb.jrc.es or http://www.jrc.es/pub/english.cgi/d1216237/33%20The%20first%20draft%20of%20Reference%20Document%20on%20Energy%20Efficiency%20Techniques%20-%203.2Mb

[23] **k_{heat}= Carnot Heat Quality Factor = $1 - T_0/ T_{\text{heat}}$**, 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.
See for example: www.tsb-energie.de/service/publikationen/2004/tsb_lisbon.pdf

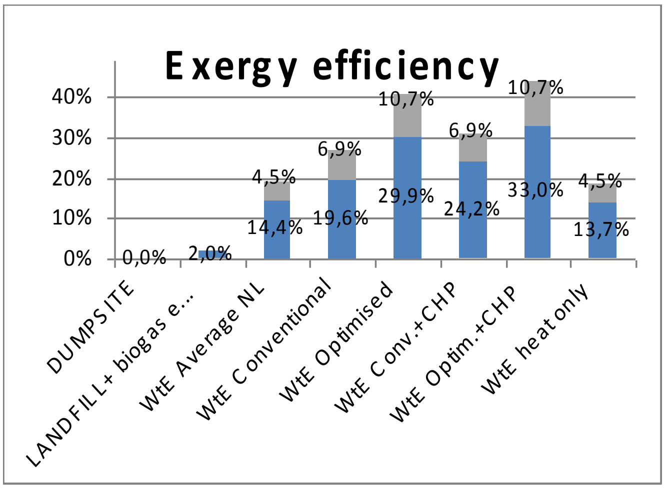
This approach has some fundamental advantages:

- 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 compensated 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.
- For the inclusion of material recovery

Although the exergy only accounts for direct energy in/output, it is possible to add the “embedded exergy” in 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 [24].



	Ore: Exergy, [MJ/kg]	Metal: Exergy, [MJ/kg]	Total including processing Exergy [MJ/kg]
Iron	0,695	6,750	22,2
Aluminium	4,118	32,805	131
Copper	61,6	2,112	53,6
Stainless steel			50
Other NF-metals			40
Inert materials	0,1	0,0	0,15

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 is possible [25]. For stimulation 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 overestimate 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).

4.7 GHG on produced electricity

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 the performance of waste

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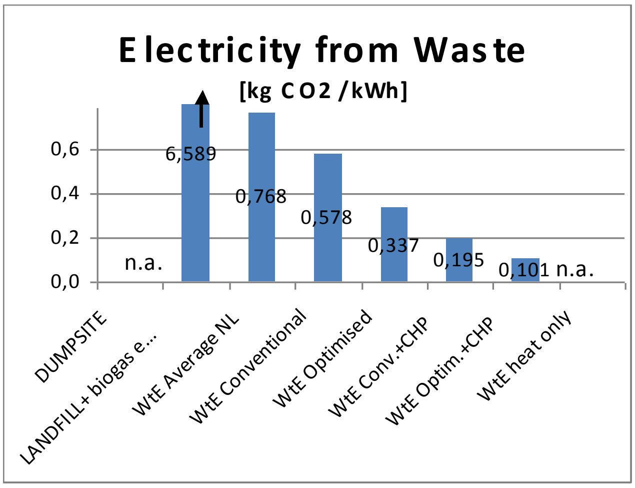
[24] Robert U. Ayres, Leslie W. Ayres and Ingrid Råde: The Life Cycle of Copper, its Co-Products and By-Products, MMSD, Jan 2002, http://www.iied.org/mmsd/mmsd_pdfs/ayres_lca_main.pdf, page 22,par.2.4 Exergy and exergy flows.

[25] Defra/ERM/Golder Associates: Carbon Balances and Energy Impacts of the Management of UK Wastes, Defra R&D project WRT237, dec 2006

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 (substituted) reference for power production.



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	0,594
Mix overall Netherlands [26]	0,698
Mix of fossil power in Germany	1,037
Coal fired power plant	1,200

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.

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[26] Dutch figures taken from: E. van der Voet, et all (CML,SenterNovem): Greenhouse Gas Calculator for Electricity and Heat from Biomass: Draft, June 26, 2007

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:

- Factor 4 on amount of waste to WtE.

For every ton of waste going to WtE:

- Factor 2 on electricity production.
- Factor 2 on the recovered metals.

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

Including the effect of avoided landfilling the GHG-balance is 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 1194 kg CO_2/ton of waste.
The upgrading from the average WtE in the existing infrastructure to optimised WtE for future infrastructure reduces 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. Only the improvement from the average efficiency of existing WtE to optimised WtE for all MSW would yield 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 for a range of different landfill and WtE-plants. All assumptions are based on literature references or actual experience, and where there is a choice from several possibilities this is marked. The detailed calculation model is available via 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 mix of power plants in Germany is taken, including all non-fossil generated power.

It is shown that there is a great variation within the GHG-effect of a classical dumpsite, an optimised modern landfill, and different variants of optimised WtE-plants. Instead of opposing to either landfilling or WtE, this makes it more and more important to distinguish the wide range of differences within these options and to work on optimal implementation.

In order to get a good insight on the effects of the performance of different variants the GHG-effect per ton of waste is compared with other performance indicators: 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.

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.
If this is compared 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.

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.

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