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R1 as Efficiency Indicator Status Quo and Optimization Potential

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Second International Conference, Oslo
16.-17. February 2010

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To assess Waste-to-Energy (WtE) plants it has inter alia to be taken into account:

their energy production and export,

their contribution to the national energy supply,

their saving of resources (primary fuels saving),

their reduction potential of CO2 emissions (greenhouse gases, climate relevance) etc.

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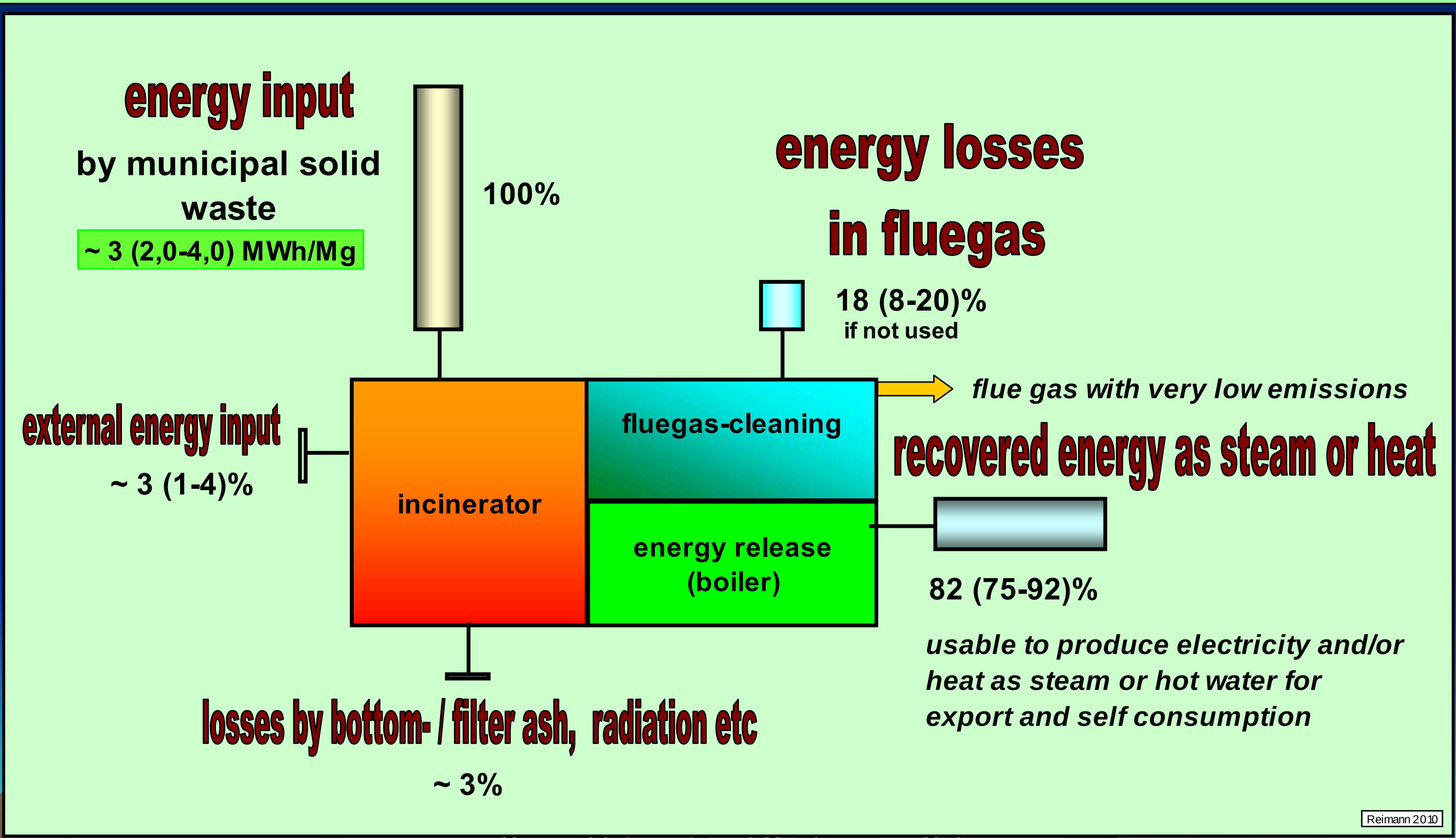
Energy balance of WtE plants

Waste-to-Energy (WtE) plants generate electricity and heat by the thermal treatment of mixed municipal solid waste (MSW).



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Directive 2008/98/EC on Waste and Repealing Certain Directives (WFD)
includes in ANNEX II a calculation formula to determine if a waste incineration installation is a recovery operation (R1)

or, if not meeting the fixed R1 energy efficiency factor, is classified as a disposal operation (D10).

R1: Use principally as a fuel or other means to generate energy.

This includes incineration facilities dedicated to the processing of municipal solid waste only where their energy efficiency is equal to or above:

- **0.60 for installations in operation and permitted in accordance with applicable Community legislation before 1 January 2009,**
- **0.65 for installations permitted after 31 December 2008, using the following formula[1]:**

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Energy efficiency = (Ep -(Ef + Ei)) / (0.97 x (Ew + Ef))

In which:

Ep means annual energy produced as heat or electricity. It is calculated with energy in the form of electricity being multiplied by 2.6 and heat produced for commercial use multiplied by 1.1 (GJ/year)

Ef means annual energy input to the system from fuels contributing to the production of steam (GJ/year)

Ew means annual energy contained in the treated waste calculated using the lower net calorific value of the waste (GJ/year)

Ei means annual energy imported excluding Ew and Ef (GJ/year)

0.97 is a factor accounting for energy losses due to bottom ash and radiation.

Reduction of volume and material recovery of residues

→ **Energy efficiency = Ep / (0.97 x Ew)**

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R1 energy efficiency is a non-dimensional factor based on the 1st law of thermodynamics (energy input = energy output) combined with integrated political objectives (minimisation of primary heat demand)

The equivalence factors for energy are based on savings of primary fuels in dedicated power and/or heat plants and got to be used in the R1 formula for Ep (export plus self use) and Ei with:

2.6 for electricity

1.1 for heat

The equivalence factors are rounded results for energy as laid down in the BREF Waste Incineration (BREF WI)

2.6316 for electricity (100%/38%)

1.0989 for heat (100%/91%)

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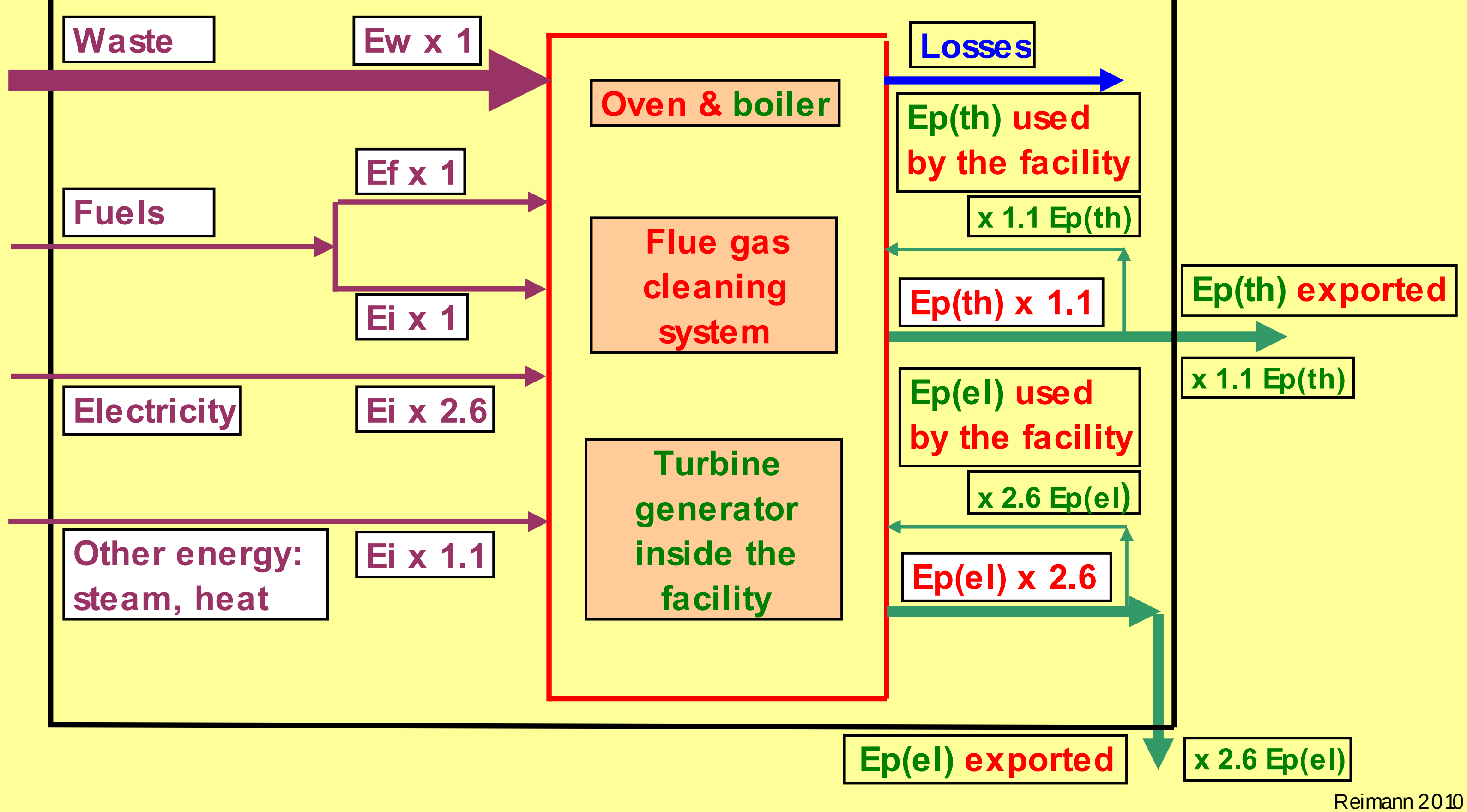
R1 formula boundary limits of a WtE facility



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Importance of accurate NCV (Ew) as denominator in the R1 formula

Many but not all of the plants have got a calculation model for NCV, delivered by the manufactorer of a plant, mostly for steering the incineration process;
other ones use other equations for the NCV calculation

These NCV results show quite often great deviations to reality.

Therefore a NCV formula is laid down in the BREF WI which is not only a very effective control instrument of the NCVs found by all the different methods but is also a very good solution to determine the real NCV of waste

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NCV formula out of BREF Waste Incineration, chapter 2, art. 2.4.1.2 and Annexes 10.4.2

$$NCV = (1.133 \times (m_{st\ w}/m) \times c_{st\ x} + 0.008 * T_b)/1.085$$ **(GJ/tonne)**

NCV = lower calorific value (NCV) of the incinerated waste with $m_{st\ w}/m \geq 1$ (GJ/tonne)

$$m_{st\ w} = m_{st\ x} - (m_f \times (c_f / c_{st\ x}) \times \eta_b)$$ **(tonne steam/tonne MSW)**

$m_{st\ w}$ = amount of the steam produced from the waste in the same time period to $m_{st\ x}$ e.g. per year (tonne/yr)
$m_{st\ x}$ = total amount of the steam produced in a defined time period e.g. per year (tonne/yr)
m_f = amount of supplementary fuel in the corresponding time period e.g. per year (tonne/yr)
m = mass of incinerated waste in the defined time period e.g. per year (tonne/yr)
$c_{st\ x}$ = net enthalpy of steam i.e. enthalpy 0f steam minus enthalpy of boiler water (GJ/tonne)
c_f = net calorific value of the supplementary fuel that add to steam production (GJ/tonne)
T_b = temperature of flue-gas after boiler at 4 - 12% O2 in flue-gas (°C)
0.008 = specific energy content in flue-gas (GJ/tonne x °C)
1.133 and 1.085 = are constants derived from regression equations
η_b = efficiency of heat exchange to the boiler (approx. 0.80)

Note: From the measured amount of $m_{st\ w}$

double counted steam quantities got to be deducted

e.g. steam for heating up of combustion air if it is extracted after the steam measuring device

not measured steam quantities got to be added

e.g. steam for sootblowing straight out of the drum or injection of water or NH4OH for SNCR

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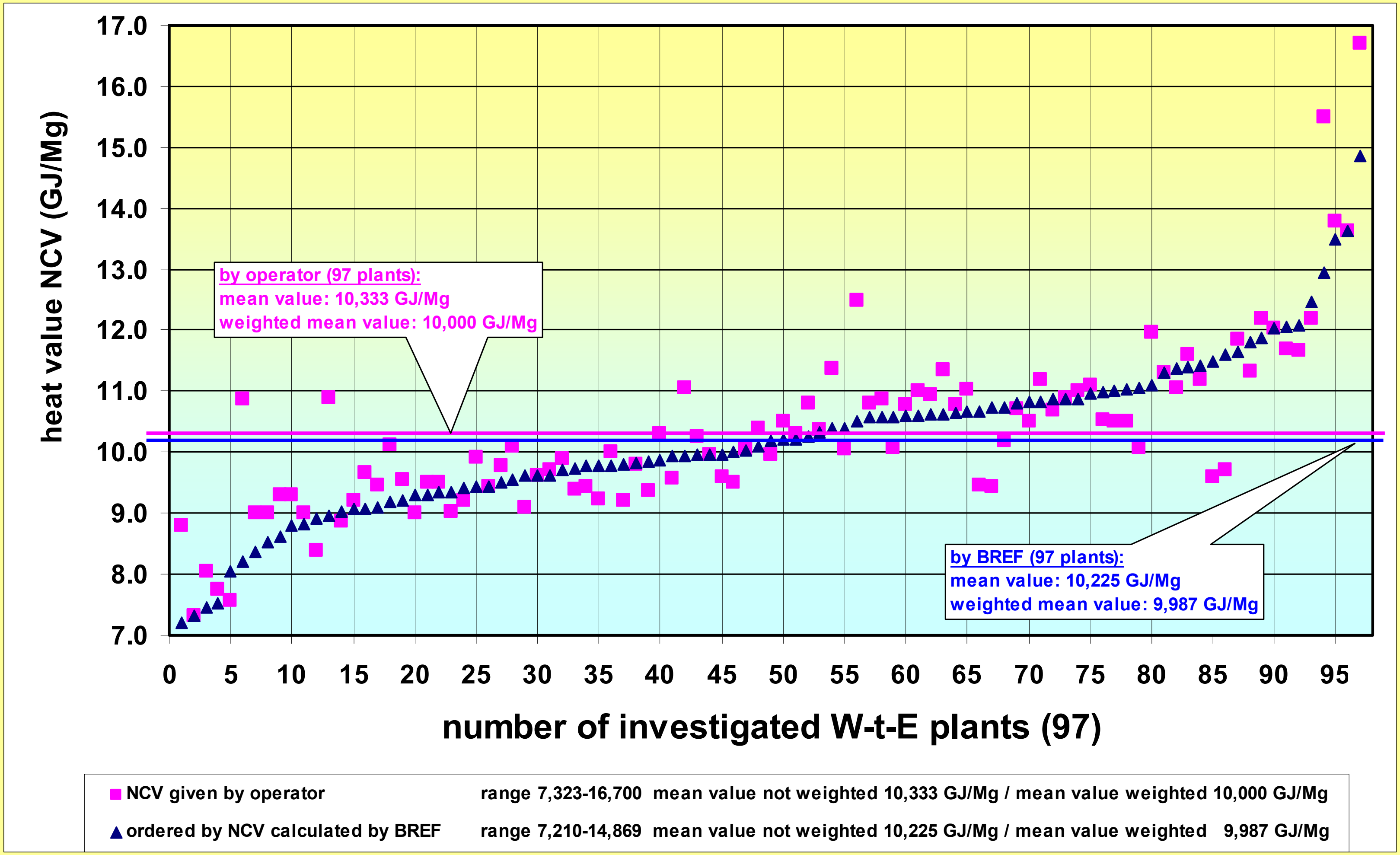

(Reimann 2005)

Figure 1: Net Calorific Value (NCV)
- calculated using the BREF-formula as well as indicated by the operator including NCV mean values weighted and not weighted for 97 W-t-E plants (status 2001-2004)

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Net Calorific Value (NCV) of MSW[1)] from the countries included in the CEWEP Energy Report II (status 2004-2007) as min., max. values and weighted averages

Country		Net Calorific Value (NCV) of MSW[1)] calculated by BREF Waste Incineration (BREF WI)[2)]		
		weighted average	min	max
		GJ/Mg MSW[1)]	GJ/Mg MSW[1)]	GJ/Mg MSW[1)]
Austria	**AT**	**8.635**	8.343	10.081
Belgium[3)]	**BE**	**10.258**	9.370	12.345
Czech Republic	**CZ**	**8.921**	8.693	9.220
Denmark	**DK**	**10.547**	9.532	12.420
France[3)]	**FR**	**9.457**	*5.806*	15.425
Finland	**FI**	**11.939**	(-)	(-)
Germany[3)]	**DE**	**10.156**	7.965	12.715
Hungary	**HU**	**8.607**	(-)	(-)
Italy	**IT**	**10.171**	8.619	14.701
Netherlands	**NL**	**9.609**	6.402	11.867
Portugal	**PT**	**8.412**	7.945	8.770
Spain[3)]	**ES**	**9.128**	8.050	10.221
Sweden[3)]	**SE**	**11.462**	9.316	14.357
UK	**GB**	**8.442**	(-)	(-)
Luxembourg	**LU**	**10.469**	(-)	(-)
Switzerland	**CH**	**11.055**	10.366	12.047
total investigated	**total**	**10.129**	**5.806**	**15.425**

1) 'municipal solid w aste'(MSW) means w aste from households as w ell as commercial, industrial and institutional w aste, w hich, because of its nature and composition is similar to w aste from households

2) BREF WI: Formula for NCV calculation see Chapter 2, article 2.4.2, pg. 83-84

3) 1 plant BE (biogas), 1 plant SE (co-combustion w ith w ood chips and peak), 8 plants FR (no energy recovery/boiler or unplausible data), 1 plant ES (co-combustion w ith gas), 1 plant DE (pyrolysis) have not been taken into account because not comparable w ith the investigated 231 European WtE plants.

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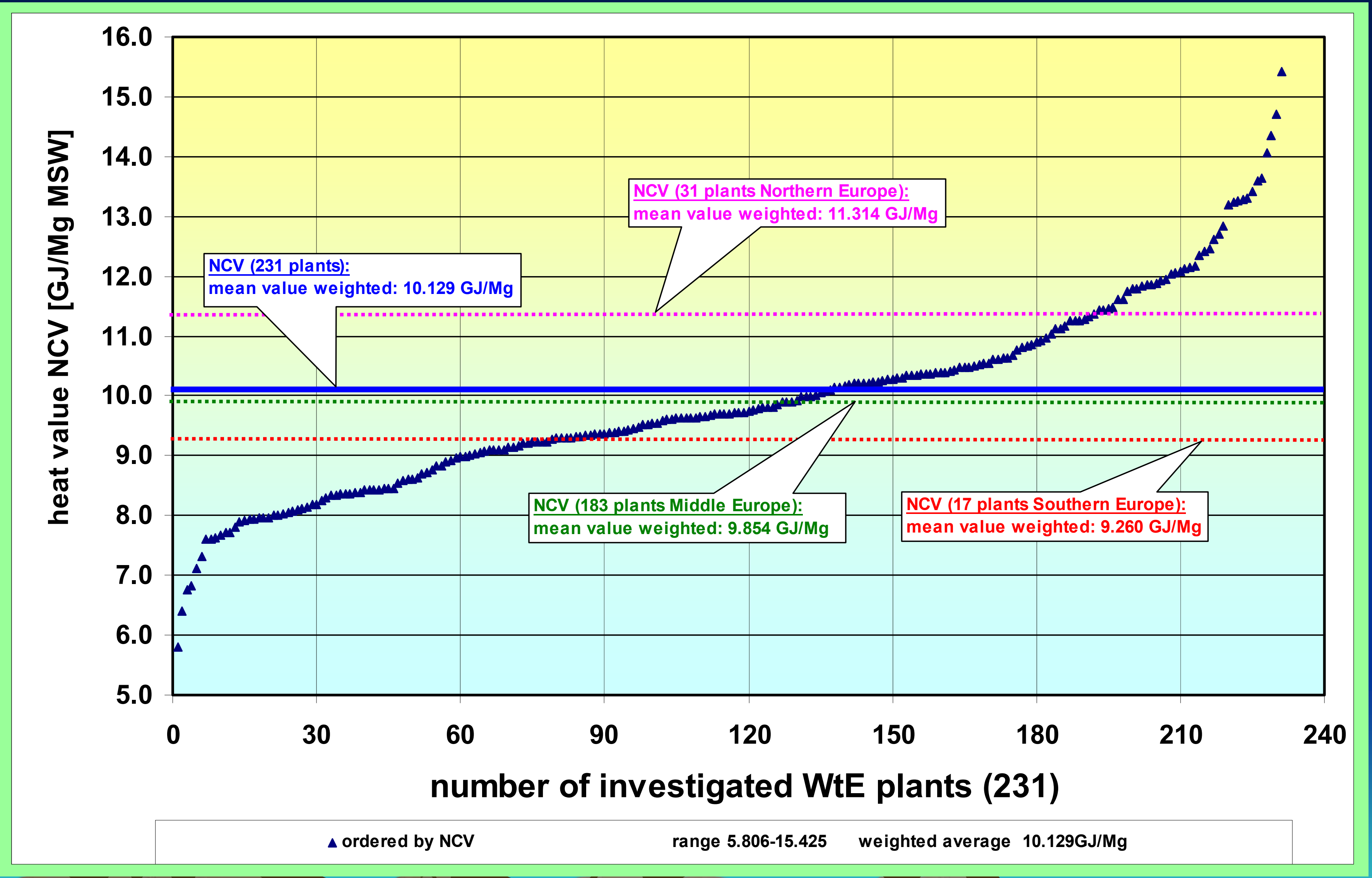

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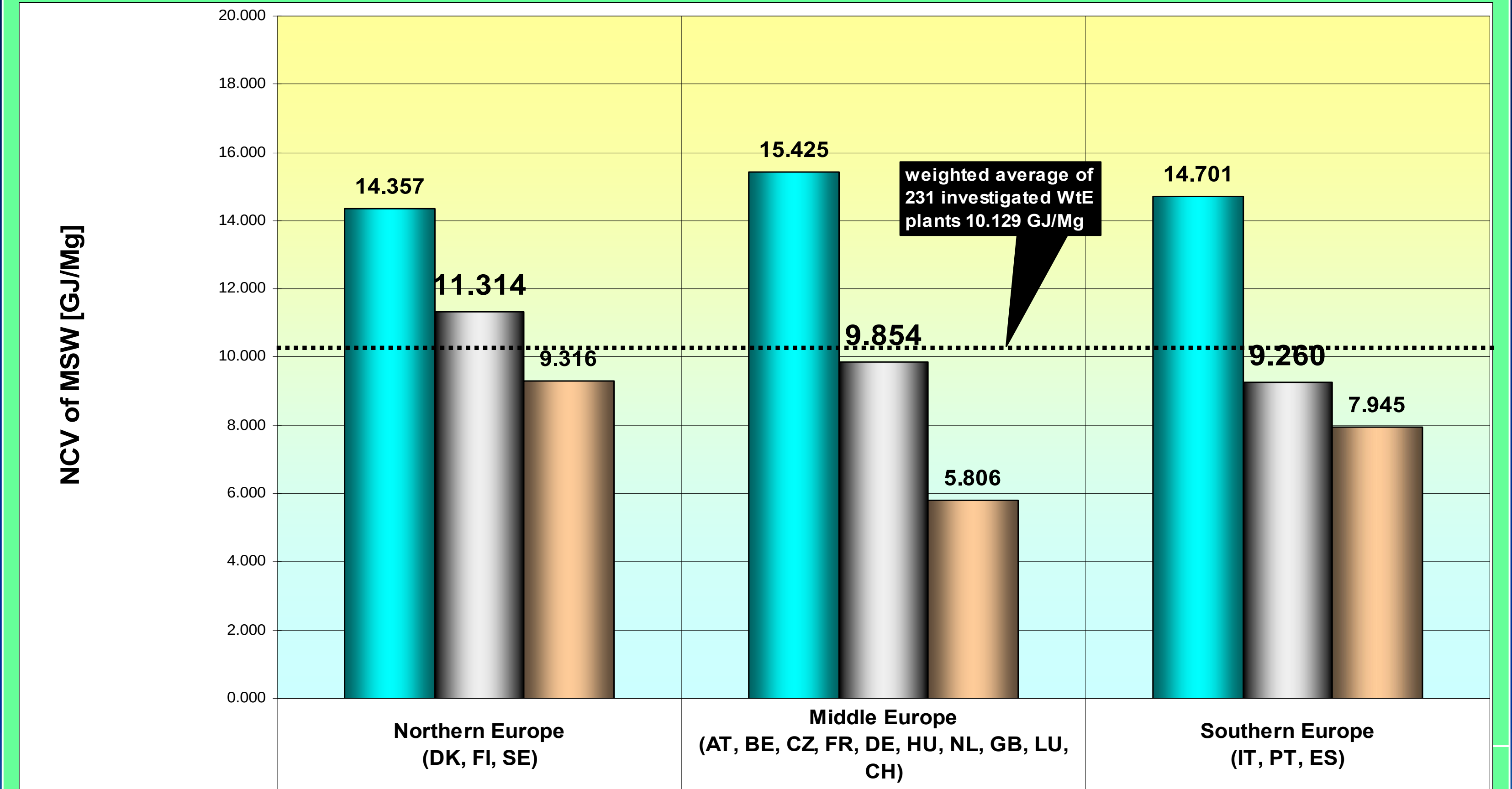
Diagram 4:

Net calorific value (NCV)[1)] of MSW[2)] of 231 WtE plants in the CEWEP Energy Report II (status 2004-2007), classified into 3 European Regions such as Northern, Middle and Southern Europe as min., max. values and weighted



	Northern Europe (DK, FI, SE)	Middle Europe (AT, BE, CZ, FR, DE, HU, NL, GB, LU, CH)	Southern Europe (IT, PT, ES)
max	14.357	15.425	14.701
average weighted	11.314	9.854	9.260
min	9.316	5.806	7.945

1) BREF WI: Formula for NCV calculation see Chapter 2, article 2.4.2, pg. 83-84

2) mixed municipal w aste'(MSW) means w aste from households as w ell as commercial, industrial and institutional w aste, w hich, because of its nature and composition is similar to w aste from households

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Produced energy (exported plus self used) (Ep) as numerator in the R1 formula

Overview on numbers, throughput and NCV ot MSW, total energy input and specific produced energy and energy demand for all 231 WtE plants as well as classified into 75 plants only electricity, 41 plants only heat and 115 plants CHP producing (status 2004-2007)

Kind of energy recovery		tag	all investigated WtE plants not classified	% of A/A; B/B; E/E; (F_1 to $F_{5.5}$)/D	tag	WtE plants only heat producing	% of A1/A; B1/B; E1/E; ($F1_1$ to $F1_{5.5}$)/D1	tag	WtE plants only electricity producing	% of A2/A; B2/B; E2/E; ($F2_1$ to $F2_{5.5}$)/D2	tag	WtE plants CHP producing	% of A3/A; B3/B; E3/E; ($F3_1$ to $F3_{5.5}$)/D3
Number of WtE plants	[-]	A	231	100	A1	41	17.7	A2	75	32.5	A3	115	49.8
Total throughput of MSW	Mg/year	B	45,518,189	100	B1	4,568,219	10.0	B2	12,722,342	28.0	B3	28,227,628	62.0
Specific energy input by MSW (without import) (NCV)	MWh abs. /Mg	C	2.814	-	C1	2.953	-	C2	2.618	-	C3	2.867	-
Total specific energy input (included import)	MWh abs. /Mg	D	2.876	-	D1	3.056	-	D2	2.664	-	D3	2.922	-
Total energy input (incl. import)	MWh abs. /Mg	E	130,910,312	100	E1	13,960,477	10.7	E2	33,892,319	25.9	E3	82,481,129	63.0
Specific electricity produced (Ep)	MWh abs. /Mg	F_1	**0.413**	**14.4**	$F1_1$	**0**	**0.0**	$F2_1$	**0.551**	**20.7**	$F3_1$	**0.416**	**14.2**
Specific electricity exported	MWh abs. /Mg	F_2	**0.318**	**11.1**	$F1_2$	**0**	**0.0**	$F2_2$	**0.457**	**17.2**	$F3_2$	**0.306**	**10.5**
Specific heat prod. and used (Ep)	MWh abs. /Mg	F_3	**1.202**	**41.8**	$F1_3$	**2.486**	**81.3**	$F2_3$	**0.400**	**15.0**	$F3_3$	**1.341**	**45.9**
Specific heat exported	MWh abs. /Mg	F_4	**0.790**	**27.5**	$F1_4$	**2.111**	**69.1**	$F2_4$	**0.000**	**0**	$F3_4$	**0.932**	**31.9**
Spec. total energy demand ((part of Ep)+Ef+Ei(th+el))[1)]	MWh abs./Mg	F_5	**0.569**	**19.8**	$F1_5$	**0.521**	**17.0**	$F2_5$	**0.530**	**19.9**	$F3_5$	**0.592**	**20.3**
Incl. in total spec. demand as Ef	MWh abs. /Mg	$F_{5.1}$	0.015	0.5	$F1_{5.1}$	0.018	0.6	$F2_{5.1}$	0.010	0.4	$F3_{5.1}$	0.009	0.3
Incl. in total spec. demand as Ei(el)	MWh abs. /Mg	$F_{5.2}$	0.019	0.7	$F1_{5.2}$	0.101	3.3	$F2_{5.2}$	0.004	0.2	$F3_{5.2}$	0.017	0.6
Incl. In total spec. demand as Ei(th)	MWh abs. /Mg	$F_{5.3}$	0.028	1.0	$F1_{5.3}$	0.027	0.9	$F2_{5.3}$	0.022	0.8	$F3_{5.3}$	0.031	1.1
Incl. in total spec. electricity prod. as Ep (self used electricity)	MWh abs. /Mg	$F_{5.4}$	0.095	3.3	$F1_{5.4}$	0.000	0.0	$F2_{5.4}$	0.094	3.5	$F3_{5.4}$	0.111	3.8
Incl. in total spec. heat prod. as Ep (self used heat)	MWh abs. /Mg	$F_{5.5}$	0.412	14.3	$F1_{5.5}$	0.375	12.3	$F2_{5.5}$	0.400	15.0	$F3_{5.5}$	0.424	14.5

[1)] In the energy self used (demand) are taken into account beside the imported energy 100% i.a. energy self used for boilerw ater heating up from an average temperature basis of 70°C to the boilerw ater temperature and 100% energy self used for heating up of combustion air as w ell as the steam to soot blow ers, SCR re-heating, pipe heating, building heating; because the possibility to take local conditions e.g. climate, market for heat etc. as mentioned in Directive 2008/98/EC – Interpretation and adaptation to technical progress, Article 38, 1. para. 2 of 19 November 2008 is up to now not yet w orked out, it therefore could not be taken into account.

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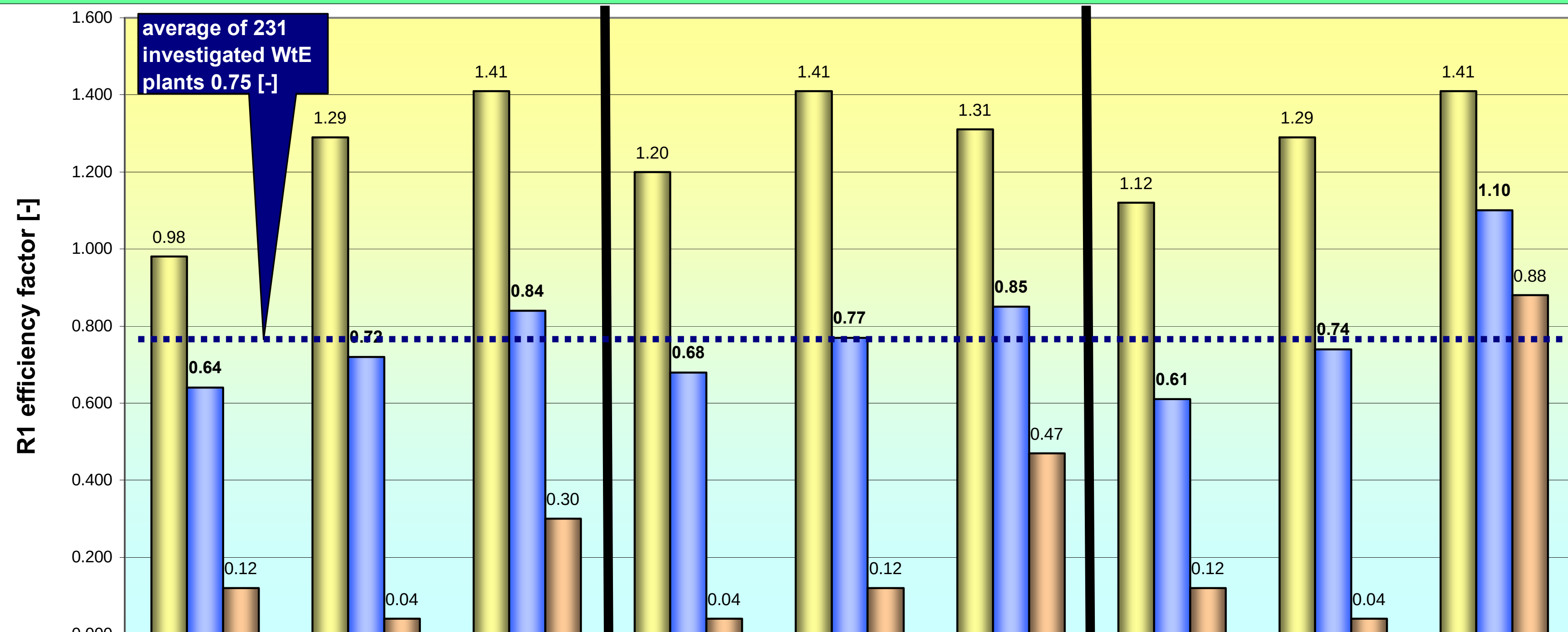
R1 efficiency factors for the investigated 231 WtE plants with distinction between the categories size, region and energy recovery



	electricity only	heat only	CHP	< 100.000	100.000-250.000	> 250.000	South-West Europe	Middle Europe	North Europe
max	0.98	1.29	1.41	1.20	1.41	1.31	1.12	1.29	1.41
average	0.64	0.72	0.84	0.68	0.77	0.85	0.61	0.74	1.10
min	0.12	0.04	0.30	0.04	0.12	0.47	0.12	0.04	0.88

[1)] R1 calculation in accordance to the Directive 2008/98/EC (WFD), Annex II, with equivalence factors: for electricity produced and imported 1 MWh el = 2.6 MWhel equ; for heat produced and commercially used 1 MWh th = 1.1 MWhthe equ and according to BREF WI for imported fuel 1 MWh fuel = 1.0 MW fuel equ. The heat used by the plant to treat the waste includes all uses of steam, particularly steam to the deaerator and to the air heater.

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Optimisation potential for R1

The kind of operation and type of energy recovery of existing, new or rebuilt plants are decisive parameters for R1. In many cases influenceable by the operator of a plant.

Optimisation of thermal process/operation (low to medium investment),
e.g. by reduction of combustion air/O_2 content, avoidance of fouling in boiler, low flue gas temperature after boiler (200°C), increase of availability by effective processing

Optimisation of the plant consumption in primary energy/fuels (low to medium investment),
e.g. by less combustion air during start up and shut down, optimized distribution and addition of combustion air to keep the combustion temperature at low NCV of waste without using primary fuels, heating up of flue gases for SCR instead with primary fuels with self produced steam.

Increase in electricity production (medium to high investment),
e.g. more often cleaning of heat exchanger tubes of air condenser, cooling by water sprinkling over the air condenser during periods with high temperatures, using heat energy in flue gas for heating up boiler water, increase of boiler water temperature, use of Rankine Cycles, new turbine, new boiler with higher steam parameters (often no optimal equipment available for small plants/units).

Increase in heat utilisation as steam, district heat or district cool (medium to very high investment):
e.g. by using heat better also condensing energy out of the flue gas for heating up the backflow of district heating or for condensate heating up, instead of air or water cooling of LP steam in condensers use of this steam for useful purposes (i. a. drying of sewage sludge).
By far the most effective mean but not possible everywhere since it depends essentially on the presence of customers for heat, and the length of the heating (cooling) period (climate zone) and the local energy market conditions (prices).

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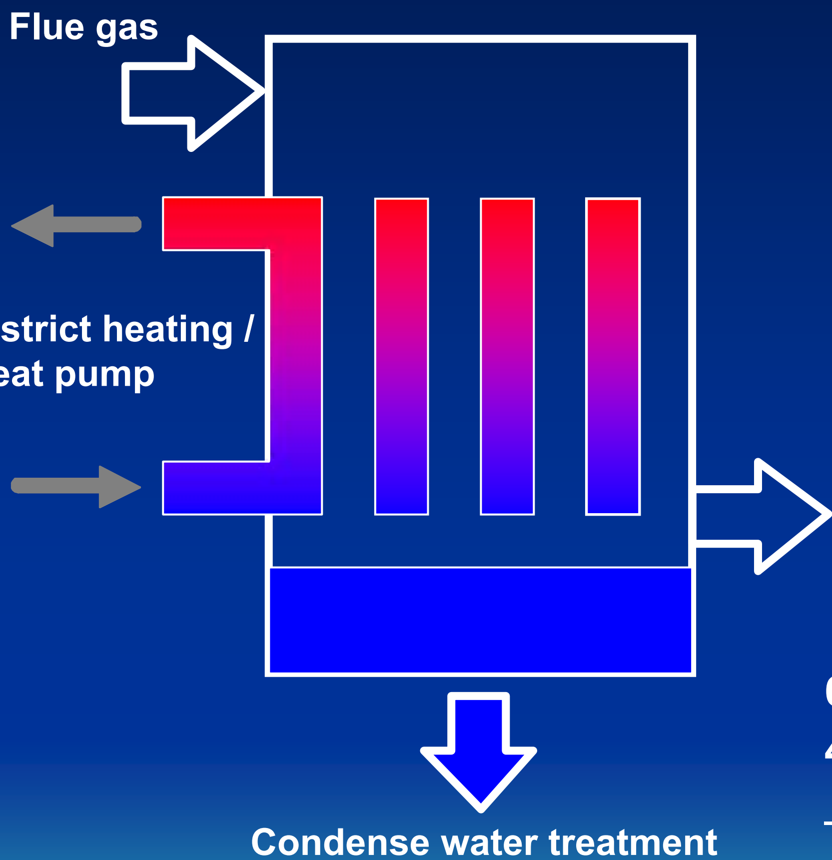
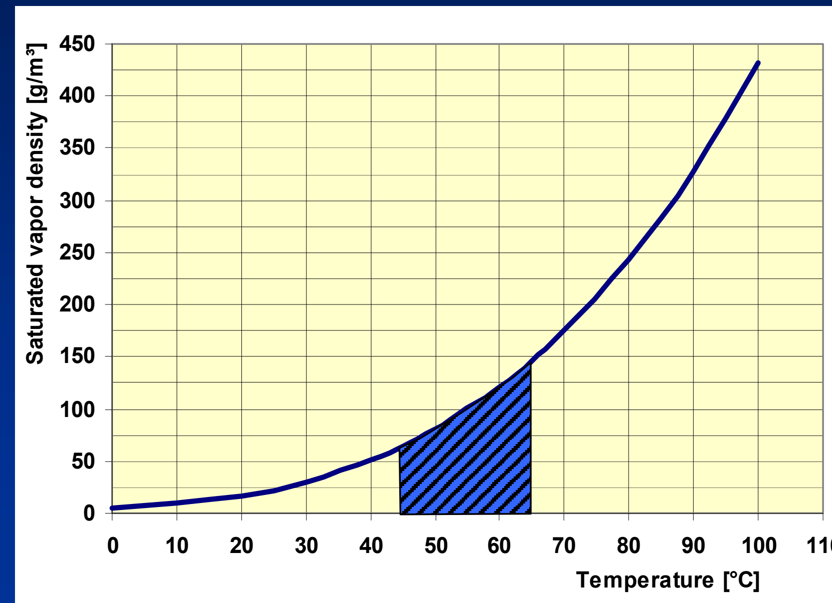
Energy Recovery from Flue Gas by Temperature Reduction combined with Steam Condensation





65°C → 146 g H_2O/m^3

45 °C → 65 g H_2O/m^3 ➔ Δ 81 g H_2O/m^3

100.000 m³ flue gas/h with 16% saturated steam

➔ 1,3 m³ condense water/h

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Optimisation potential for R1

The size of an existing plant, an important parameter for R1, cannot be influenced by the operator of a plant. This is only an option for the planning of new installations or rebuilding of plants.

The location of a plant in a European geographical region (climate zone), the most important parameter for R1, can neither be influenced by the operator of a plant nor by the designer of new installations or rebuilding of plants.
Therefore the adaption of a R1 climate factor is in discussion in the EU Commission

Because currently a R1 guideline is in the works by the EU Commission some of the results and statements may change but only marginally

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Necessary efficiency rates to reach R1 of at least 0.60 (0.65)

All data in % of the total energy input (Ew including Ef + Ei (el+th))

Solely electricity production incl. self used heat

External electricity demand (Ei el) 0.2%, external heat demand (Ef) 0.6%, (Ei th)1.0%,
produced (Ep el) 20.3%, (produced Ep th self used) 6.8% for R1 = 0.60
prod. (Ep el) 22.1%, (prod. Ep th) 6.8% for R1 = 0.65

Solely heat/steam production

External electricity demand (Ei el) 3.4%, external heat demand (Ef) 0.6%, (Ei th)1.0%
produced (Ep el) 0%, (produced Ep th) 60.6% for R1 = 0.60
prod. (Ep el) 0%, (prod. Ep th) 64.5% for R1 = 0.65

CHP production (only as an example)

External electricity demand (Ei el) 0.2%, external heat demand (Ef) 0.6%, (Ei th)1.0%,
produced (Ep el) 12.0%, (produced Ep th) 26.4% for R1 = 0.60
prod. (Ep el) 12.0%, (prod. Ep th) 30.7% for R1 = 0.65

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For MSW plants beside R1 proof also the BATs 61- 63 of BREF Waste Incineration concerning energy recovery have to be met

BAT 61: for new installatons: total energy heat/ steam export of **1.9 MWh/Mg MSW (65.5%)**
based on an average energy input of 2.9 MWh/Mg MSW

BAT 62: where less than 1.9 MWh/Mg MSW export at an energy input of 2.9 MWh/Mg MSW:

a.) electricity production:
0.40 (13.8%) – 0.65 (22.4%) MWhe/Mg MSW plus additional heat/steam supply as far as practible in the local conditions

b.) generation of at least the same amount of electricity as the annual average electricity demand of the entire installation

BAT 63: Reduction of average installation electricity demand below **0,150 MWhe/Mg MSW**

Conclusions

By increasing the R1 efficiency factor comparing to the recent situation this results i. a. in a positive contribution to the national energy supply, in saving of resources combined with a reduction potential of CO2 emissions

By the comparison of the R1 results between the individual plants a competition to be better and more effective than another one is started for the benefit of the environment

In the case that in the future Industrial Emission Directive (IED) BREFs will become mandatory than also the BATs of BREF Waste Incineration (WI) and BREF Energy Efficiency (ENE) will be decisive for energy recovery.

In the case that a WtE plant reaches the R1 target this plant fullfills automatically almost the upper limits of the energy BATs of BREF WI.

Only in case that an individual WtE plant reaches the R1 target this plant may treat beside waste mentioned for disposal also waste for recovery.

More information about the energy flows, NCV and R1 of 231 European WtE plants are published in the

CEWEP Energy Report II (Status 2004-2007)

http://www.cewep.eu/studies/climate-protection

Thank you for your attention