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Bioenergy & Biofuels LAB

2018 EEC/WTERT Bi-Annual Conference

October 5th , 2018

Applications of the 3T Method as an efficiency assessment tool for Waste-to-Energy facilities and numerical comparisons with the R1 Formula

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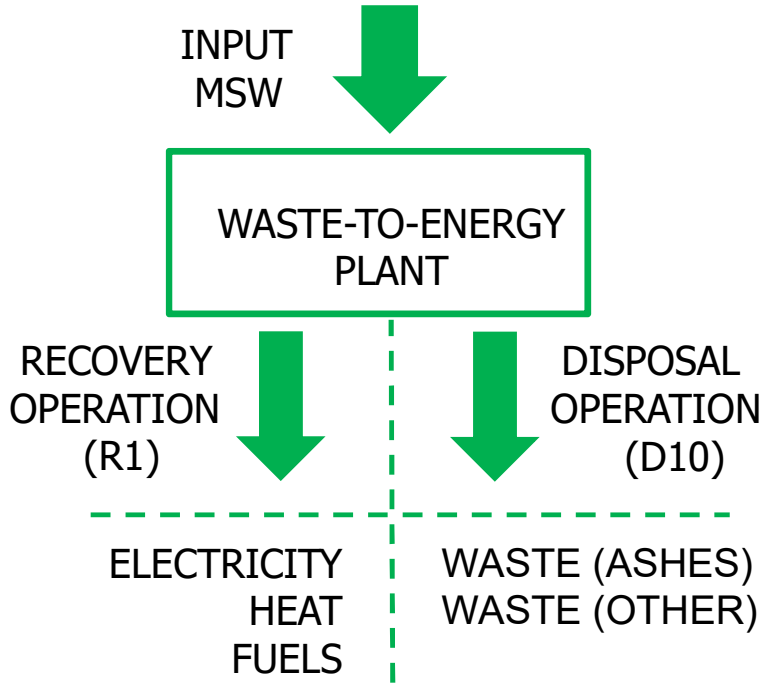
Introduction and Scope of the 3T Method

- The 3T method aims to assess the efficiency of waste-to-energy plants in an integrated way.
  - Quality of produced materials should also be taken into consideration.
- Waste-to-energy is the term that addresses the energy production by means of thermal treatment of (primarily) municipal solid waste; also commercial and Industrial waste can be considered.
  - Incineration is the most representative technology (by far), but also gasification and pyrolysis are gradually gaining ground and may be viable alternatives in the near future.
- Ultimately, the 3T methods aims to provide the framework for comparing waste-to-energy technologies with other "energy from waste" technologies.
  - "Energy from waste" which is a more general term that includes a broader ranger of technological possibilities.

The dual nature of waste-to-energy



Directive 2008/98/EU

(of the European parliament and of the council of 19 November 2008 on waste)

1. Waste is used principally as a fuel for energy generation and thus they belong to category 1 of the Recovery Operations (ANNEX I), i.e. R 1.

2. The residues of the treatment are landfilled on land and thus they belong to category 10 of the Disposal Operations (ANNEX II), i.e. D 10.

Introduction of the R1 Energy Efficiency Formula

- The issue of "duality" has been of high importance. Each waste-to-energy facility could be considered an energy production or a disposal facility according to the assigned category (for licensing, taxation etc.).
- In order to address this issue, European Commission integrated the R1 formula (that was developed by Dieter Reimann) in the second revision of the Waste Framework Directive of 2008.
- The parameters for each waste-to-energy facility are inserted to the R1 formula and the ones who have values over 0.65 (or 0.6 for older plants) achieve the R1 status.
- The R1 formula played an important role in assisting the waste-to-energy plants to receive a legal status, especially during a period that the specifics of the waste-to-energy sector where not fully understood by the lawmakers.
- **R1 formula is not portrayed to be a pure energy efficiency formula but a "utilization efficiency" formula.**

Thermodynamic inconsistencies of the R1 Formula

$$R1 = \frac{Ep - (Ef + Ei)}{0.97 * (Ew \quad Ef)}$$

2.6 for electricity
1.1 for heat
1 for other fuels

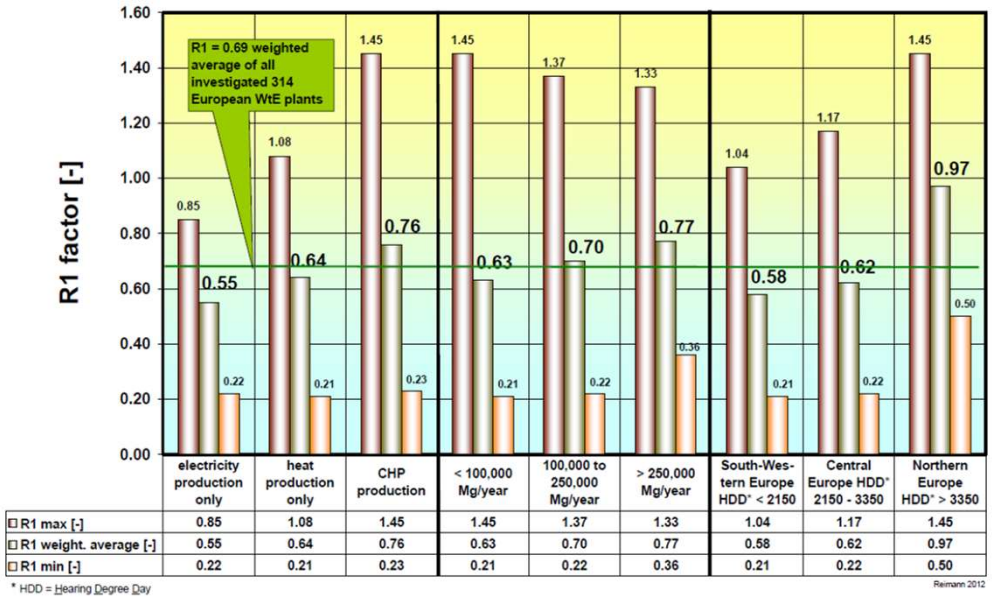
correction for radiation losses

$$R1 = \frac{\text{Energy produced} - (\text{Ener}}{0.97 * (\text{Energy of}}$$

Even with the bonus for electricity production, most plants need to produce heat in order to achieve R1 status.

weighted averages
only electricity plants: 0.55
only heat plants: 0.64

Source: CEWEP (Energy Report III, 2007 – 2010)



The introduction of the climate correction factor

COMMISSION DIRECTIVE (EU) 2015/1127
of 10 July 2015 amending Annex II to Directive 2008/98/EC of the European Parliament and of the Council on waste and repealing certain Directives

WtE plants in EU (2014)

HDD	**< 2150**	**2150 – 3350**	**> 3350**
Type *	S. Europe	C. Europe	N. & E. Europe
CHP	5 (3)	152 (131)	13 (13)
Electricity	36 (9)	65 (26)	0
Heat	5 (2)	35 (19)	5 (5)
CCF	**1.25 (or 1.12)**	**calc.**	**1**

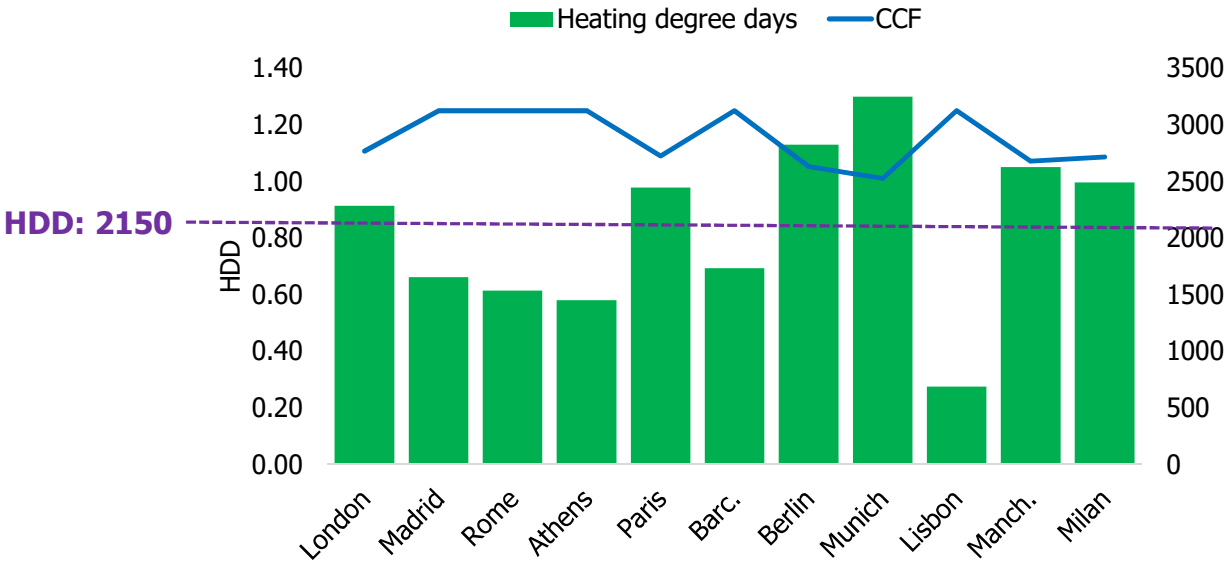
calc.= a) – (0,25/1 200) × HDD + 1,698 (old plants)
b) – (0,12/1 200) × HDD + 1,335 (new plants)

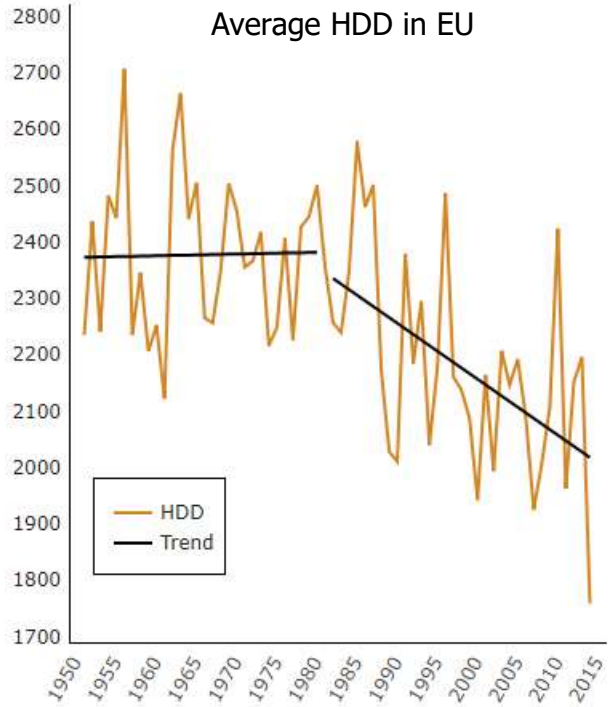
→ **New R1 values**

R1 × CCF

* Year 2014, Source: Report EUR 26720 EN

Application of the climate correction factor





- The selected values are consistent for the case of EU
  - But the average HDD/ year are dropping!
  - Also southern countries are clustered together!
  - This values are not applicable for USA!

Sources: EUROSTAT, 2018 & EEA, 2018

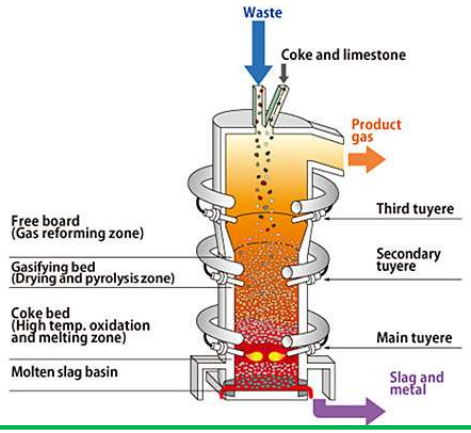
The main drawbacks of the R1 Energy Efficiency Formula

- The R1 Formula is not thermodynamically consistent and the results that are derived from the formula cannot be compared to other technologies outside the waste-to-energy bubble.
- The R1 Formula does not properly assess the production of electricity & heat and it doesn't consider fuels/ chemicals.
- The climate correction factor (CCF) is only applicable to European countries and the present climate trends indicate that a correction in the (correction) factor will be necessary.

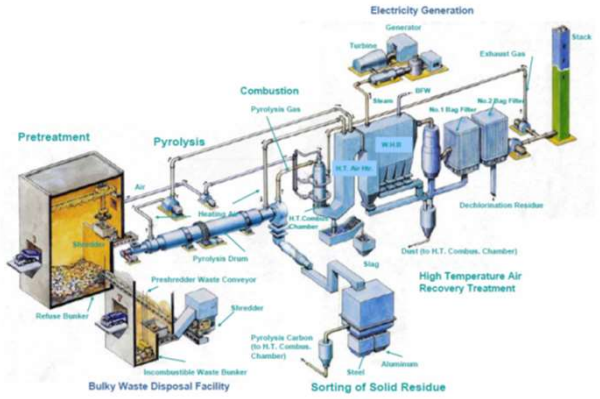
The framework of the energy efficiency should be expanded

- The R1 formula is restricted to incineration plants and does not provide a solid framework for the integration of novel technologies like pyrolysis and gasification which produce gaseous, liquid and solid fuels with significant heating value.
- Waste-to-energy plants are not only energy production units but also metal recovery facilities.

JFE Direct Smelting Gasifier



Mitsui Recycling 21 process



Source: M. Castaldi & N. Themelis (2010). The Case for Increasing the Global Capacity for Waste to Energy (WTE). Waste and Biomass Valor 1:91–105.

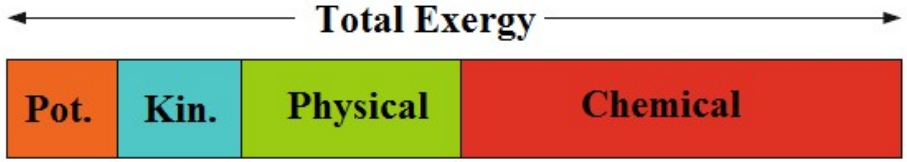
Question

Can we provide a more integrated method for assessing the operation of waste-to-energy plants?

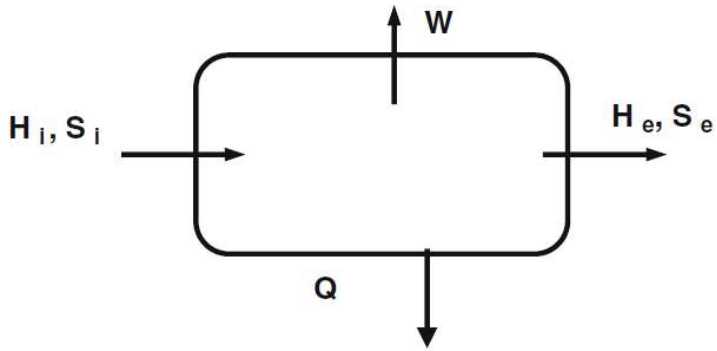
Application of exergy as a quality indicator

Measure of the maximum amount of work that can theoretically be obtained by bringing a resource into equilibrium with its surroundings through a reversible process.

$$[B = h - ho - To\ (s - so)]$$



- A linear combination of the entropy and energy balances
- Reflects the 'quality' of energy



The concept of exergy in waste-to-energy plants

Waste-to-energy can produce…

Energy (CHP production)		Materials/ Fuels/ Chemicals	
↙	↘	↙	↘
Electricity	**Heat**	**Biofuels**	**Metals**
Physical Exergy		Chemical Exergy	
Electricity → 1:1 conversion of energy to exergy **Heat** → conversion of energy to exergy is correlated to T and P, e.g. for a perfect gas with constant Cp: **B_{ph}= Cp [(T-To) – (To ln (T/To))] + R To ln (P/ Po)**		**Depends on the lower heating value and on the molecular structure of the products: B_{ch}= β * LHV** For biomass the β factor is: $\beta = \frac{1.0414 \quad .0177\left[\frac{H}{C}\right] - 0.3328\left[\frac{O}{C}\right]\left(1+0.0537\left[\frac{H}{C}\right]\right)}{1-0.4041\left[\frac{O}{C}\right]}$	

Selected energy and exergy parameters for application

I. CHP efficiency

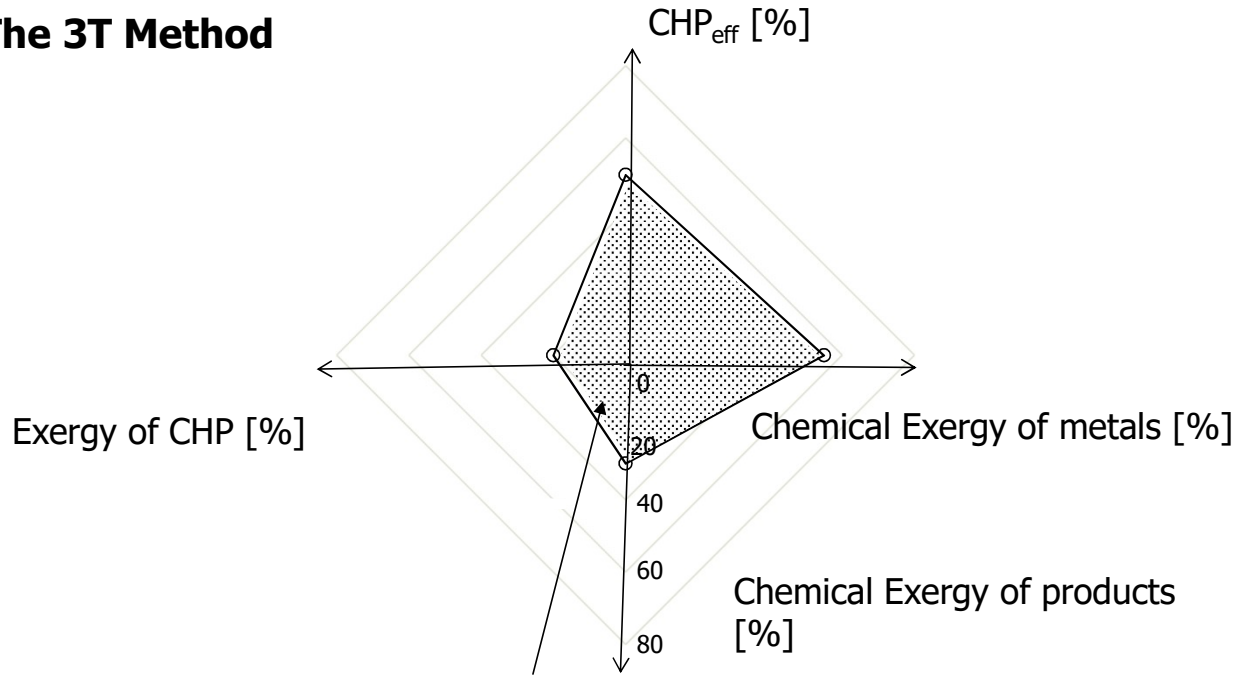
II. The physical exergy of CHP efficiency

- instead of R1 factors (2.6 & 1.1)

III. Chemical exergy efficiency of gaseous fuels, biooil etc.

IV. Chemical exergy efficiency of metals

The 3T Method

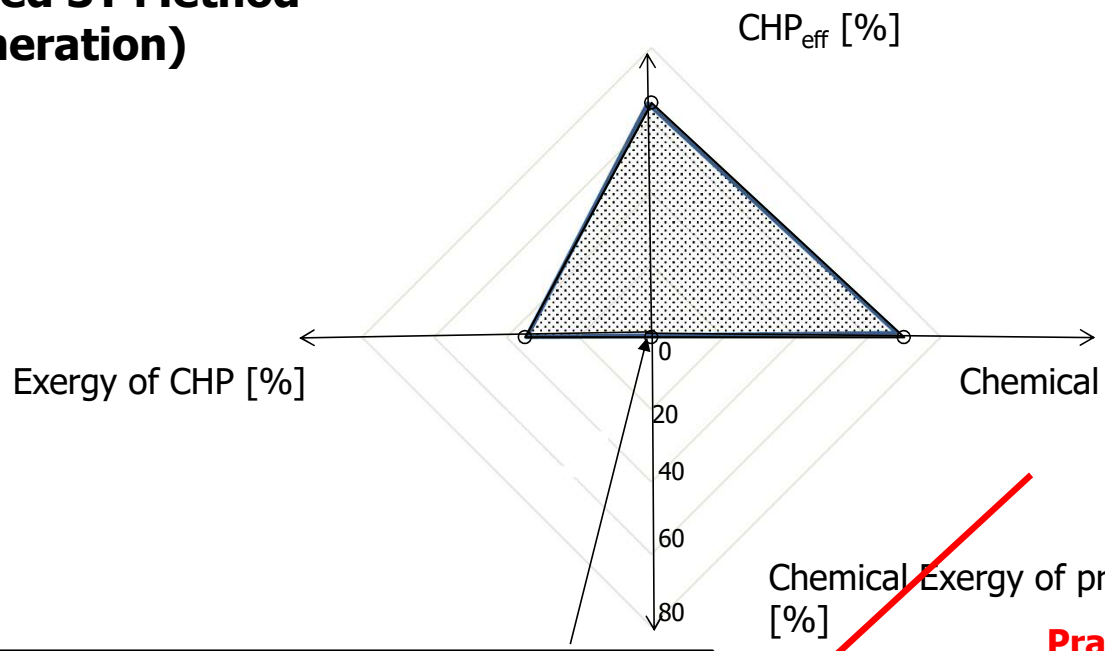


Integrated efficiency index - General solution for all thermal treatments

$$\sin\left(\frac{\pi}{2}\right) / 2*[(Prod- Bch_{eff} * Bph_{eff}) + (Bph_{eff} * CHP_{eff}) + (CHP_{eff} * Bch_{eff}\{m\}) + (Prod- Bch_{eff} * Bch_{eff}\{m\})]$$

Source: S. Vakalis, K. Moustakas and M. Loizidou (2018). Assessing the 3T method as a replacement to R1 formula for measuring the Efficiency of waste-to-energy plants. Waste Management & Research 36, 810 – 817

Specialized 3T Method (incineration)



Chemical Exergy of products [%]

Practically zero !!!

Integrated efficiency index - Specialized solution for combustion

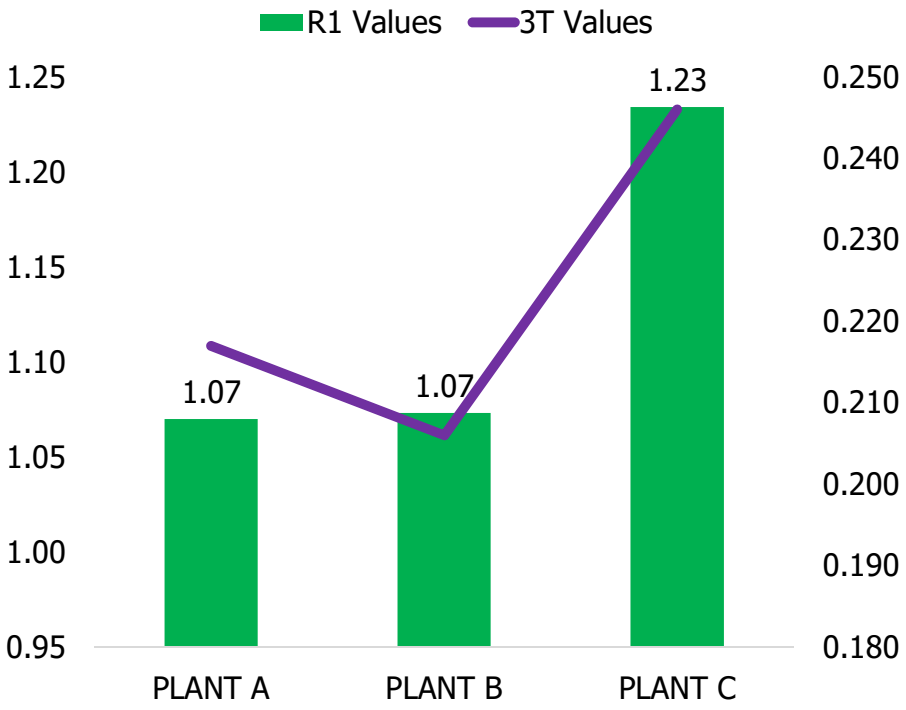
$[(Bph_{eff} + Bch_{eff}\{m\}) * CHP_{eff})] / 2$

Source: S. Vakalis, K. Moustakas and M. Loizidou (2018). Assessing the 3T method as a replacement to R1 formula for measuring the Efficiency of waste-to-energy plants. Waste Management & Research 36, 810 – 817

3T & R1 application on Waste-to-Energy plants

	Plant A	Plant B	Plant C
Electrical efficiency [%]	17 %	21 %	27 %
Thermal efficiency [%]	55 %	45 %	45 %
Temperature of output heat [°C]	85	85	85
Physical exergy efficiency [%]	25.22 %	27.46 %	33.23 %
Exergy efficiency of metals [%]	35	35	35

3T method vs. R1 formula comparison



- Plants A & B have (almost) the same R1 values.
- For the same cases, the 3T method provides vastly different results.
- The discrepancy in the results is such, that it becomes clear that the two methods take different things into consideration.
- The recovery of metals is (for example) one significant parameter.

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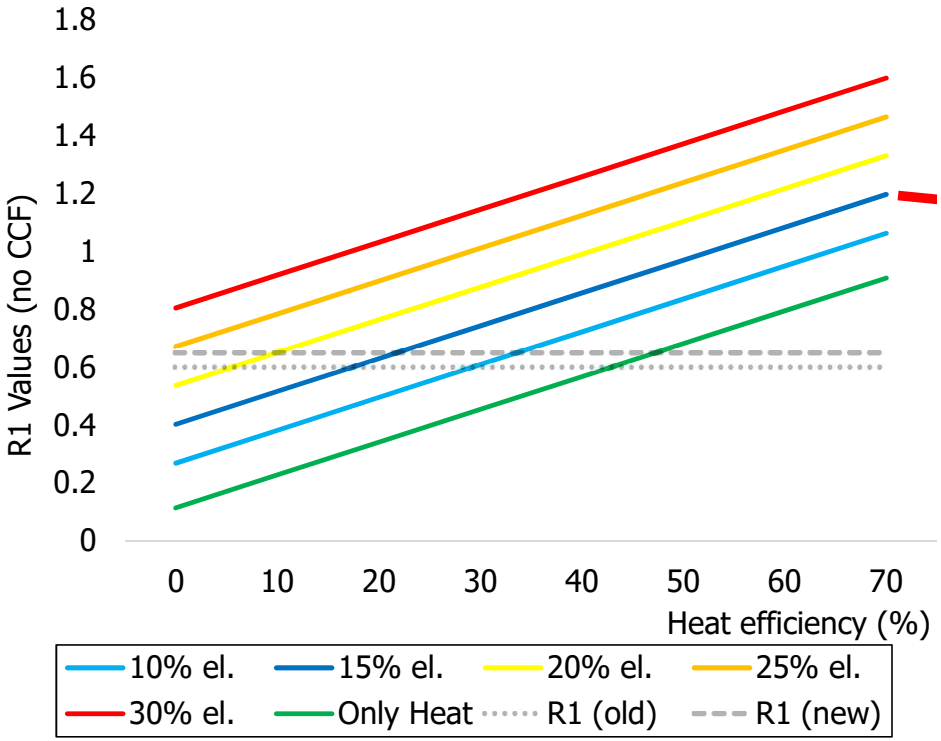
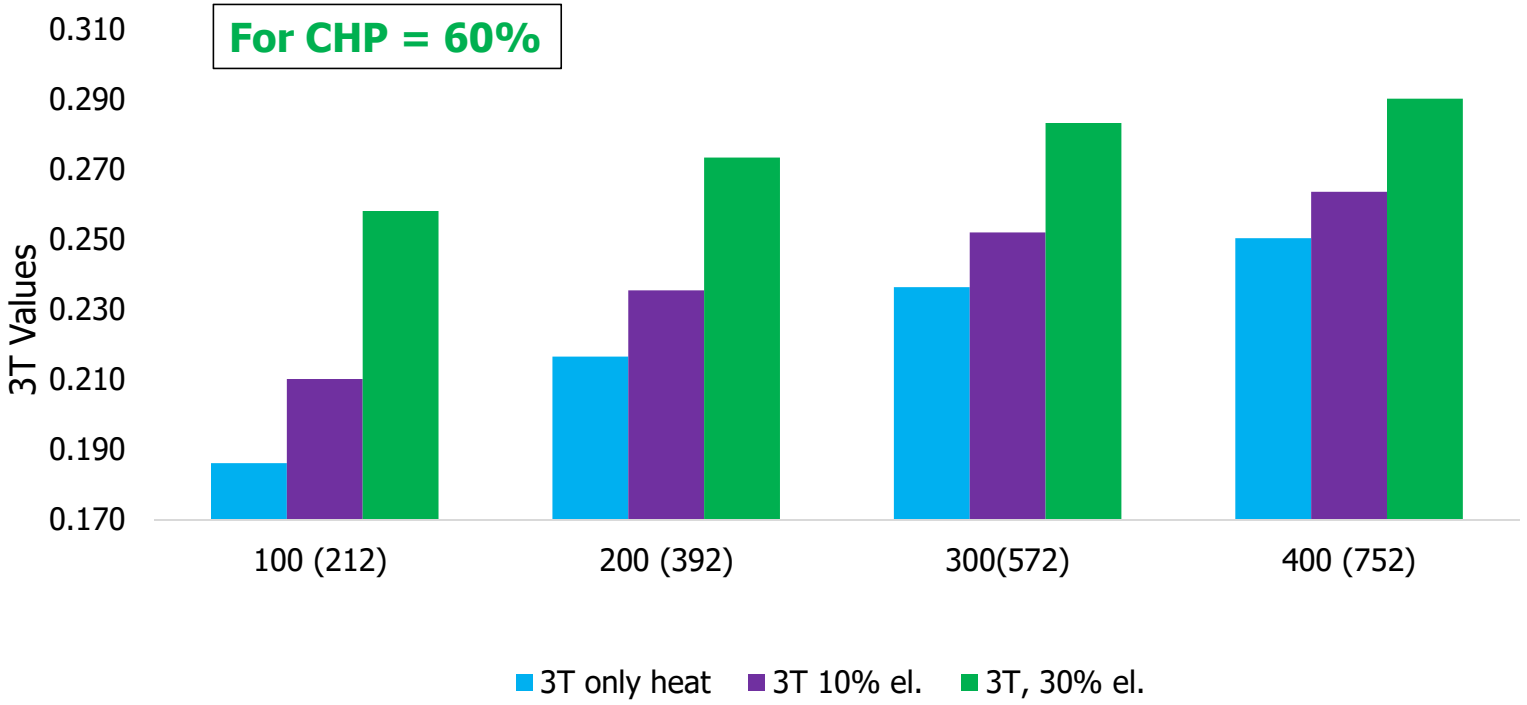
Numerical results of R1 vs 3T – Recovering the metals

R1 Formula



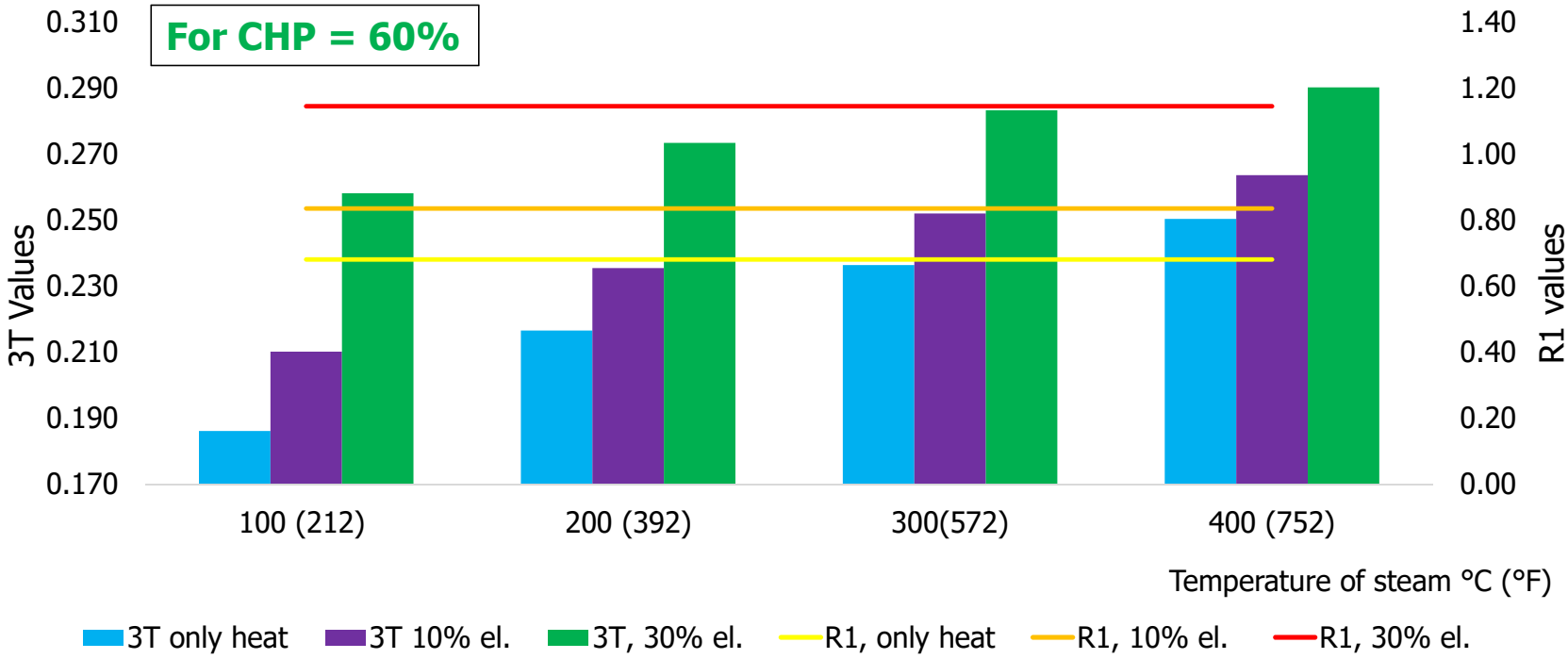
Note: Simple numerical calculations for steam in atmospheric pressure

Numerical results of R1 vs 3T – The effect of temperature



Note: Simple numerical calculations for steam in atmospheric pressure

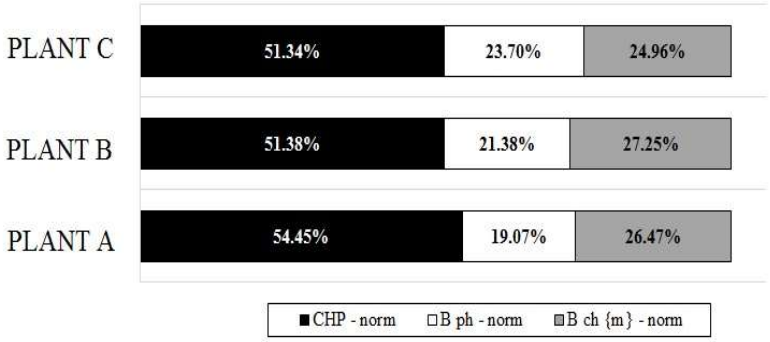
Numerical results of R1 vs 3T – The effect of steam temperature

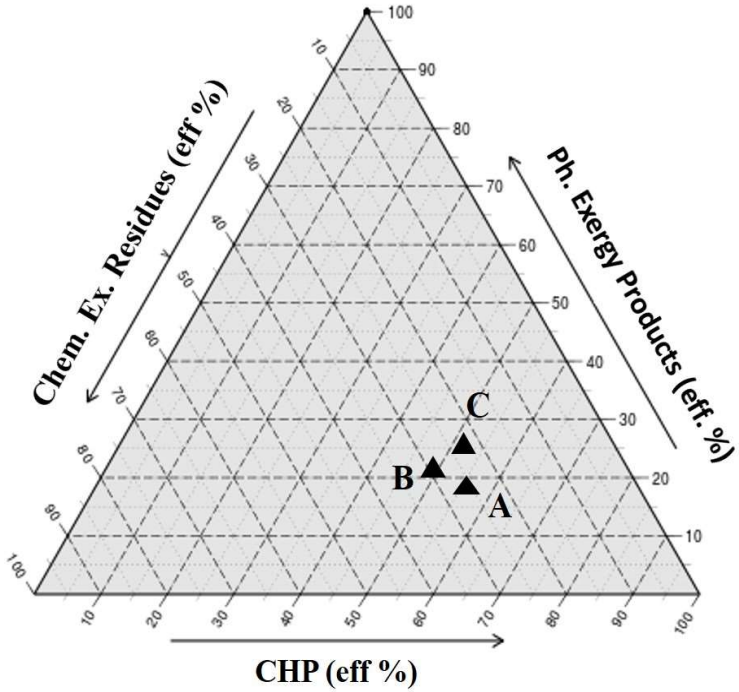


Note: Simple numerical calculations for steam in atmospheric pressure

Visual Mapping with the 3T Method

Normalization of each individual efficiency



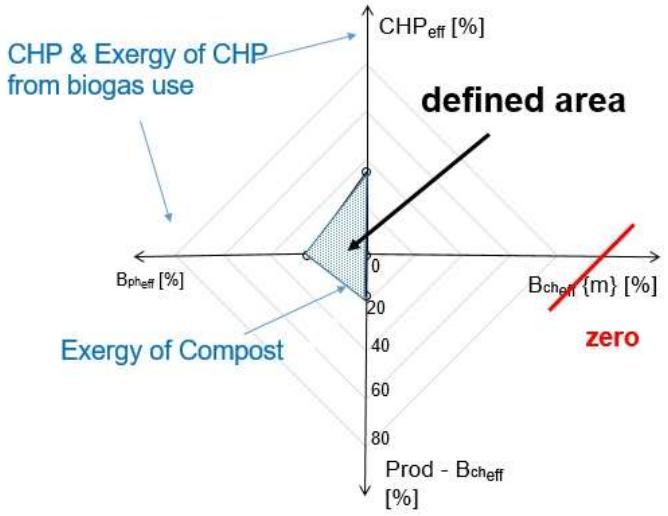


One additional feature of the 3T Method

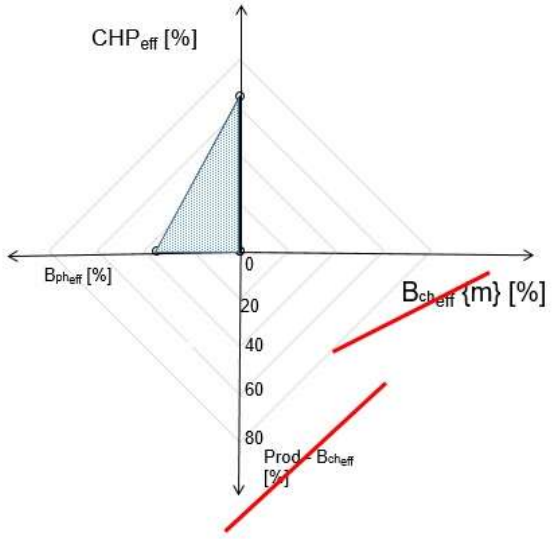
- The 3T method can be used in order to directly compare waste-to-energy with other waste management strategies.
- The method is applicable to waste management strategies that recover energy and materials (i.e. EfW technologies).
  - e.g. the case of simple landfilling would not be a useful example.
  - but AD can be compared directly with waste-to-energy (example provided)
- Some other (recovery) strategies could be the following:
  - Mechanical Biological Treatment
  - Landfill (with landfill gas recovery) plus landfill mining

Comparison of different Energy-from-Waste strategies

Anaerobic Digestion



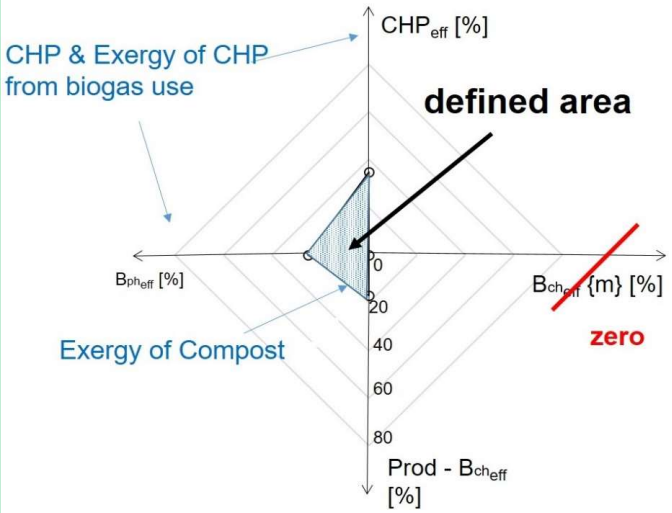
Waste-to-energy (incineration)



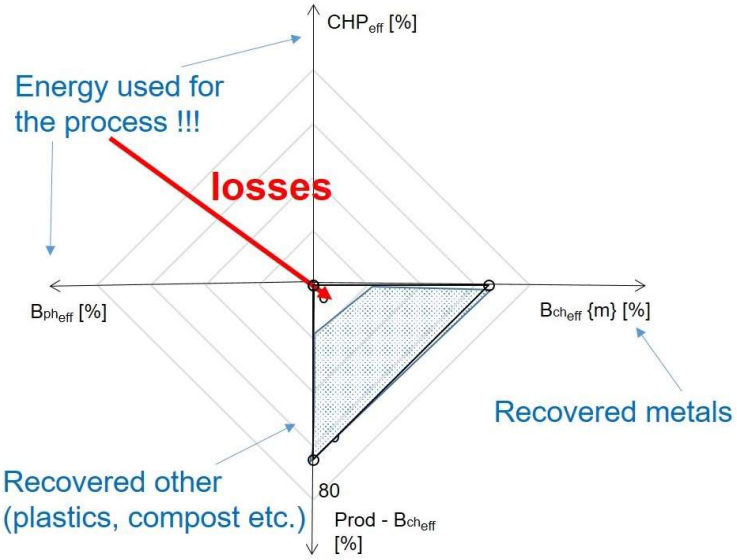
Source: S. Vakalis, K. Moustakas, M. Baratieri, M. Loizidou (2018). The 3T method as an assessment tool for comparing different waste management strategies - (submitted to) Waste and Biomass Valorization

Possible combination of different Waste Management strategies

Anaerobic Digestion (AD)



Mechanical Biological Treatment (MBT)



Source: S. Vakalis, K. Moustakas, M. Baratieri, M. Loizidou (2018). The 3T method as an assessment tool for comparing different waste management strategies - (submitted to) Waste and Biomass Valorization

Conclusions

- R1 formula has been a great first tool for assessing waste-to-energy plants.
- The gradual commercialization of novel waste-to-energy technologies requires the development of new tools that will be more flexible and will go beyond the case of incineration.
- This work proposes the 3T method, where thermodynamic parameters are combined in a radar graph and the overall efficiency is calculated from the area of the trapezoid.
- The method includes also the recovery of metals and is in good agreement with the concept of "circular economy".
- The 3T method calculates different results (with different trends) when compared to the R1 formula, i.e. the R1 is not considering important parameters even for the simple case of incineration.
- By using the 3T method the comparison not only of different waste-to-energy technologies, but also other waste management strategies, becomes possible.

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THANK YOU FOR YOUR ATTENTION !

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