NAXOS 2018

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

Stergios Vakalis, Konstantinos Moustakas and Maria Loizidou

13 June, 2018

What is “waste-to-energy”

- It is the term that addresses the energy production by means of thermal treatment of waste.
- It primarily refers to combustion of municipal solid waste.
  - Commercial and Industrial waste are also considered
  - Thermal processes like gasification and pyrolysis are becoming more popular.
- The term should not ne confused with “energy from waste”, which is a more general term that includes a broader ranger of technological possibilities.

Waste-to-energy data

- In 2014 more than 88 million tons of waste were thermally treated in waste-to-energy plants (Ella Stengler - C.E.W.E.P., 2016)
- For the production of:
  - 38 billion KWh electricity
  - 88 billion KWh heat
- After thermal treatment there are solid residues of approximately 30 % by weight and 10 % by volume that are primarily disposed to landfills.

The dual nature of waste-to-energy

- Historically, all the “Waste Framework Directives” that have been issued by the European Commission, separate the waste management strategies into Recovery Operations and Disposal Operations.
- Waste-to-energy technologies have the inherent problem that they do not belong entirely on the one category or the other.
  - Directive 2008/98/EU of the European parliament and of the council of 19 November 2008 on waste
  - 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.
  - 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.

Issues that derive from the “duality”

- The issue of “duality” has been of high importance because each waste-to-energy facility could be considered an energy production or a disposal facility according to the category that is assigned.

- This influences the level of the gates fees but also the overall taxation of the waste-to-energy facilities.

Introduction of the R1 formula

- 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.

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

- $R1 = \frac{(\text{Energy produced} - \text{Energy from fuels – Other energy imported})}{0.97 * (\text{Energy of waste input} + \text{Energy from fuels})}$

Utilization of the R1 formula

- 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.
- It should be denoted that 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 technologies where not fully understood by the lawmakers.
- Therefore, the significance of the R1 formula for the waste-to-energy sector should be stated.
- It must be pointed out that the R1 formula does not claim to be a pure energy efficiency formula but a “utilization efficiency” formula.

Drawbacks of the R1 formula

- It is not thermodynamically consistent and the results that are derived from the formula can't be comparable to other technologies outside the waste-to-energy bubble.
- 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.

Drawbacks of the R1 formula

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

- 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.

Drawbacks of the R1 formula

- It is not thermodynamically consistent and the results that are derived from the formula can’t be comparable to other technologies outside the waste-to-energy bubble.
- 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.

In 1 ton of bottom ash:

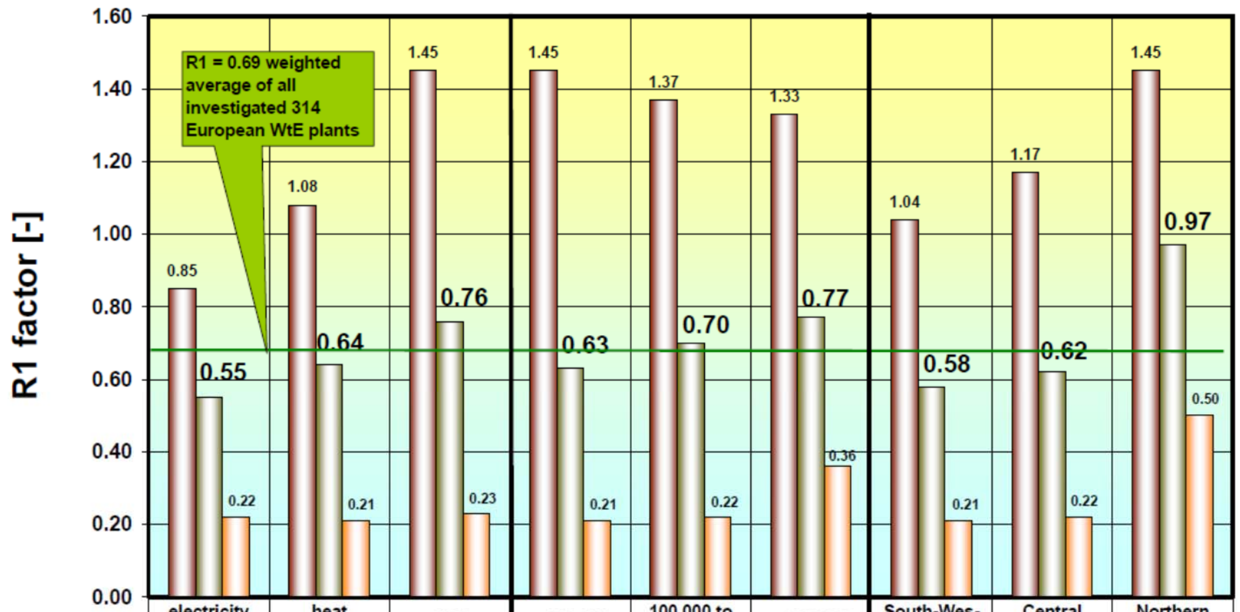
- 10 % -12 % by weight is metals
- 15 – 20 Kg of aluminium
- Recovery rate of ferrous metals only at 49%, and non-ferrous metals only at <8% (Source: Werner Sunk, 2006)
- The quality of secondary aluminum is affected by its oxidation level (Astrup & Grosso, 2016)

- Waste-to-energy plants are not only energy production units but also metal recovery facilities.

Weighted significance of CHP

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

2.6 for electricity
1.1 for heat
1 for other fuels



	electricity production only	heat production only	CHP production	< 100,000 Mg/year	100,000 to 250,000 Mg/year	> 250,000 Mg/year	South-Western Europe HDD* < 2150	Central Europe HDD* 2150 - 3350	Northern Europe HDD* > 3350
R1 max [-]	0.85	1.08	1.45	1.45	1.37	1.33	1.04	1.17	1.45
R1 weight. average [-]	0.55	0.64	0.76	0.63	0.70	0.77	0.58	0.62	0.97
R1 min [-]	0.22	0.21	0.23	0.21	0.22	0.36	0.21	0.22	0.50

* HDD = Hearing Degree Day

Reimann 2012

Is there a possible alternative?

Which parameters do we need?

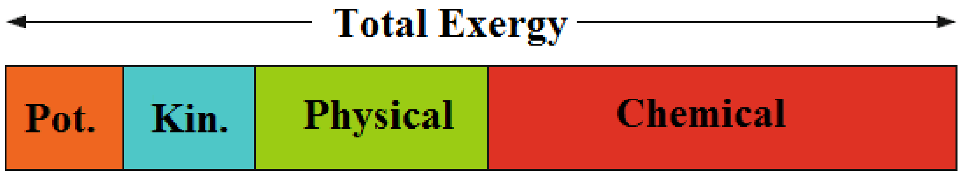
Combined Heat and Power efficiency

- CHP efficiency is the first basic parameter that we should take tinto consideration
- The case of heat vs electricity
  - Physical exergy instead of R1 factors (2.6 & 1.1)
- Chemical exergy of gaseous fuels, biooil etc
- Chemical exergy of metals

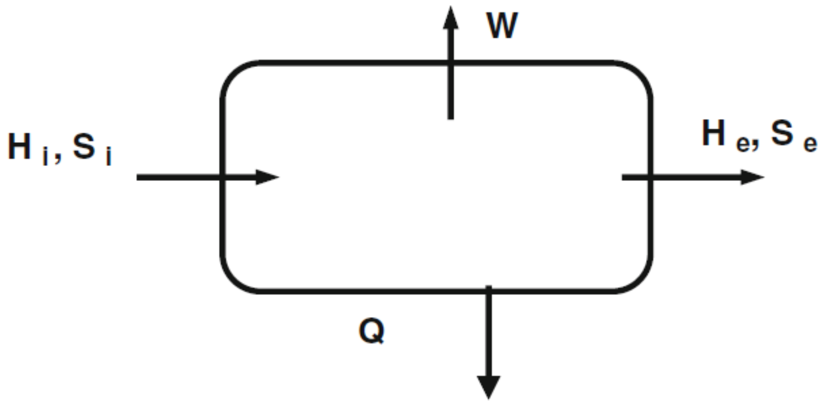
The concept of exergy

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.

$$[B = h - h_o - T_o (s - s_o)]$$



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



Exergy of different streams

Physical Exergy	Chemical Exergy	
CHP	Products (e.g. Gaseous fuels)	Residue metals

Physical Exergy – CHP

- Conversion of electricity into work on a 1:1 basis

Exergy of heat depends on temperature and pressure

e.g. Steam with 100 MJ
(P: 1 atm, T: 450 K) → 33.3 MJ
(P: 1 atm, T: 550 K) → 45.5 MJ
(P: 1 atm, T: 650 K) → 63.9 MJ

Chemical Exergy – Products (e.g. Gaseous fuels)

Sustance	Chemical exergy
Carbon Monoxide	275 kJ/mol
Hydrogen	236 kJ/mol
Methane	831 kJ/mol
Carbon (graphite)	410 kJ/mol
Carbon Dioxide	20 kJ/mol

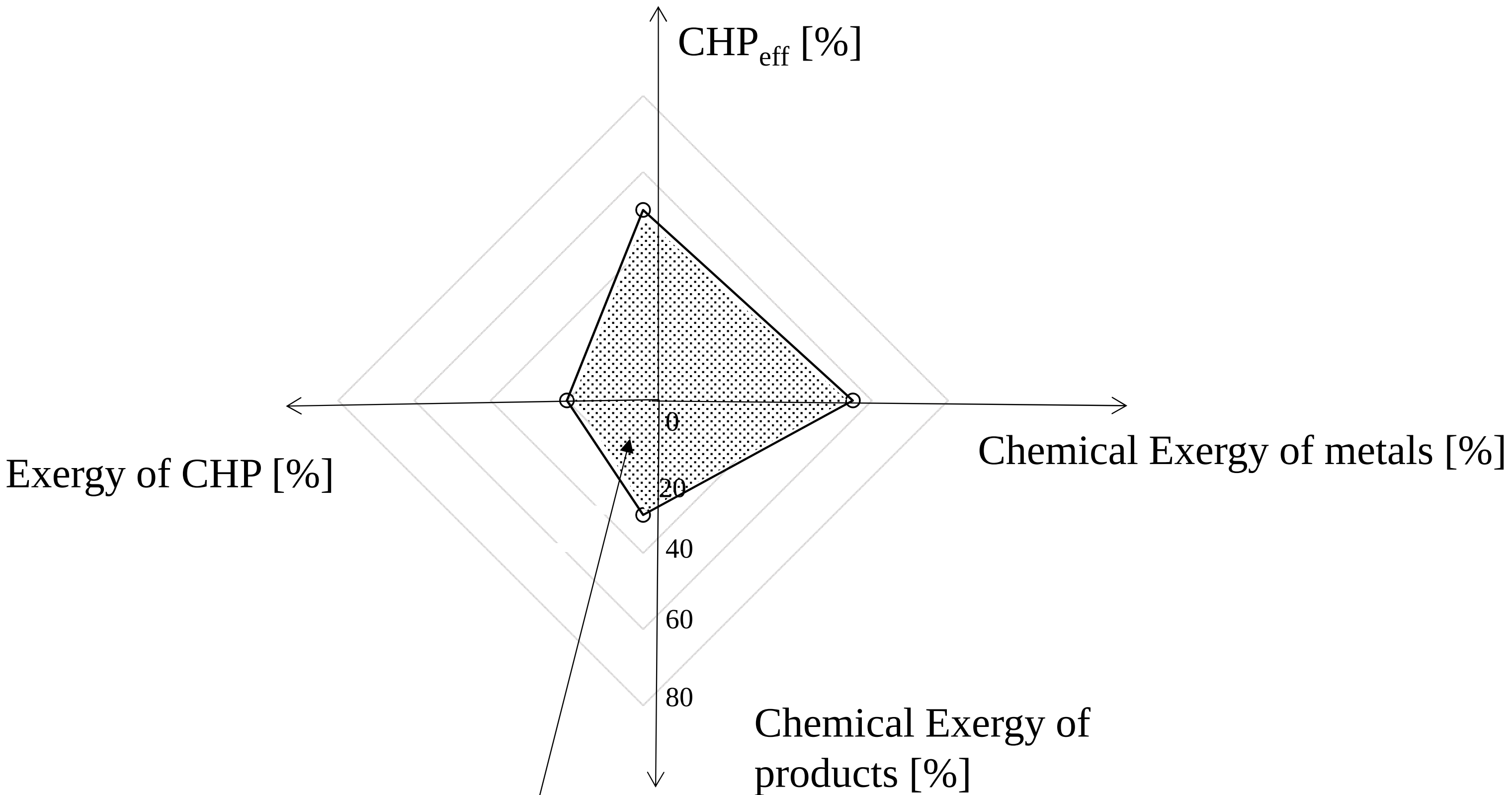
Chemical Exergy – Residue metals

Substance	Chemical Exergy
Ni (II)	232.7 ($kJ\ mol^{-1}$)
Zn (II)	339.2 ($kJ\ mol^{-1}$)
Cu (II)	134.2 ($kJ\ mol^{-1}$)
Pb (II)	232.8 ($kJ\ mol^{-1}$)

Selected parameters

- CHP
- Exergy of CHP
- Exergy of Products
- Exergy of Metals

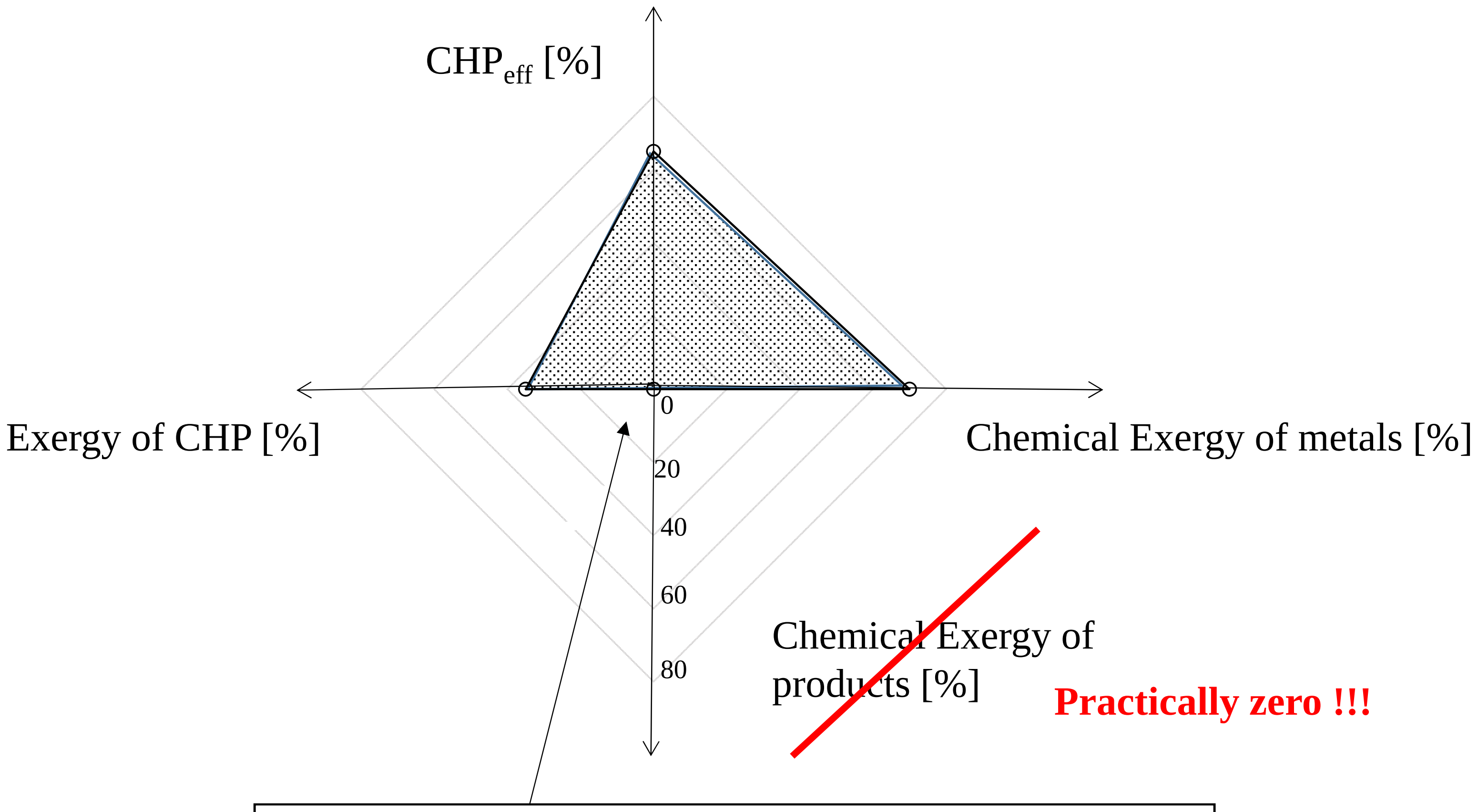
Introducing the 3T Method



Integrated efficiency index - General solution for all thermal treatments

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

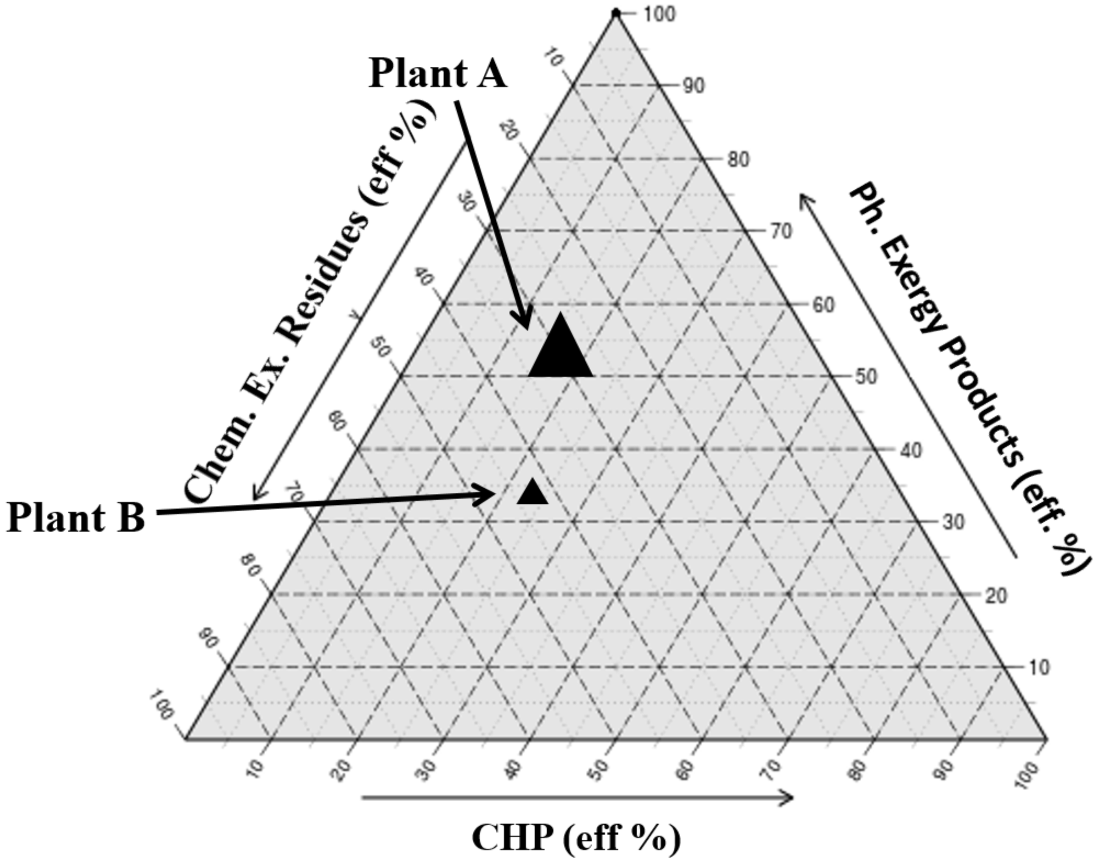
Speciacialized 3T Solution for incineration



<u>Integrated efficiency index - Specialized solution for combustion</u>

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

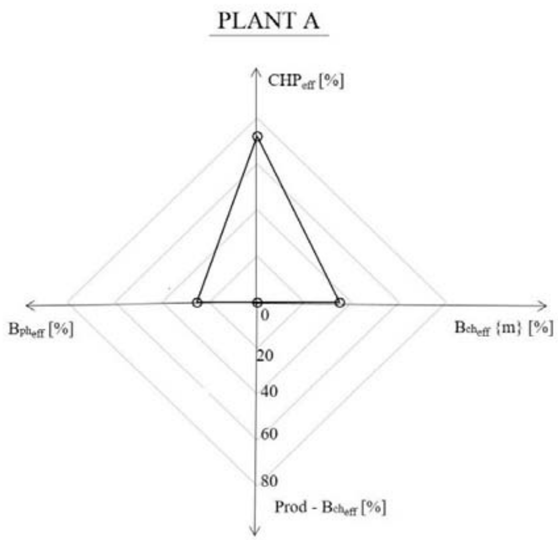
Mapping of waste-to-energy plants

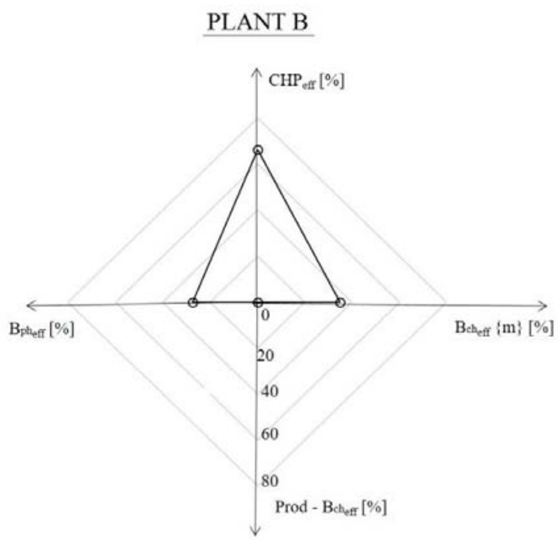


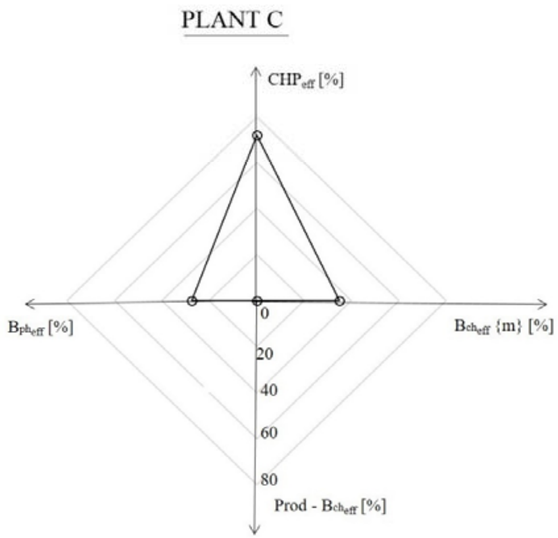
- The individual efficiencies of each plant are normalized in order to add to 100.
- Placing each plant into a ternary diagram acts as visual mapping.
- The size of each plant's triangle corresponds to the overall value of the T3 value.

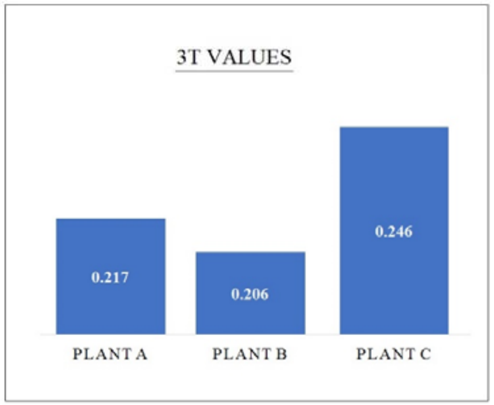
Examples of the 3T application

	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
Chemical exergy of products [MW] *	-	-	-





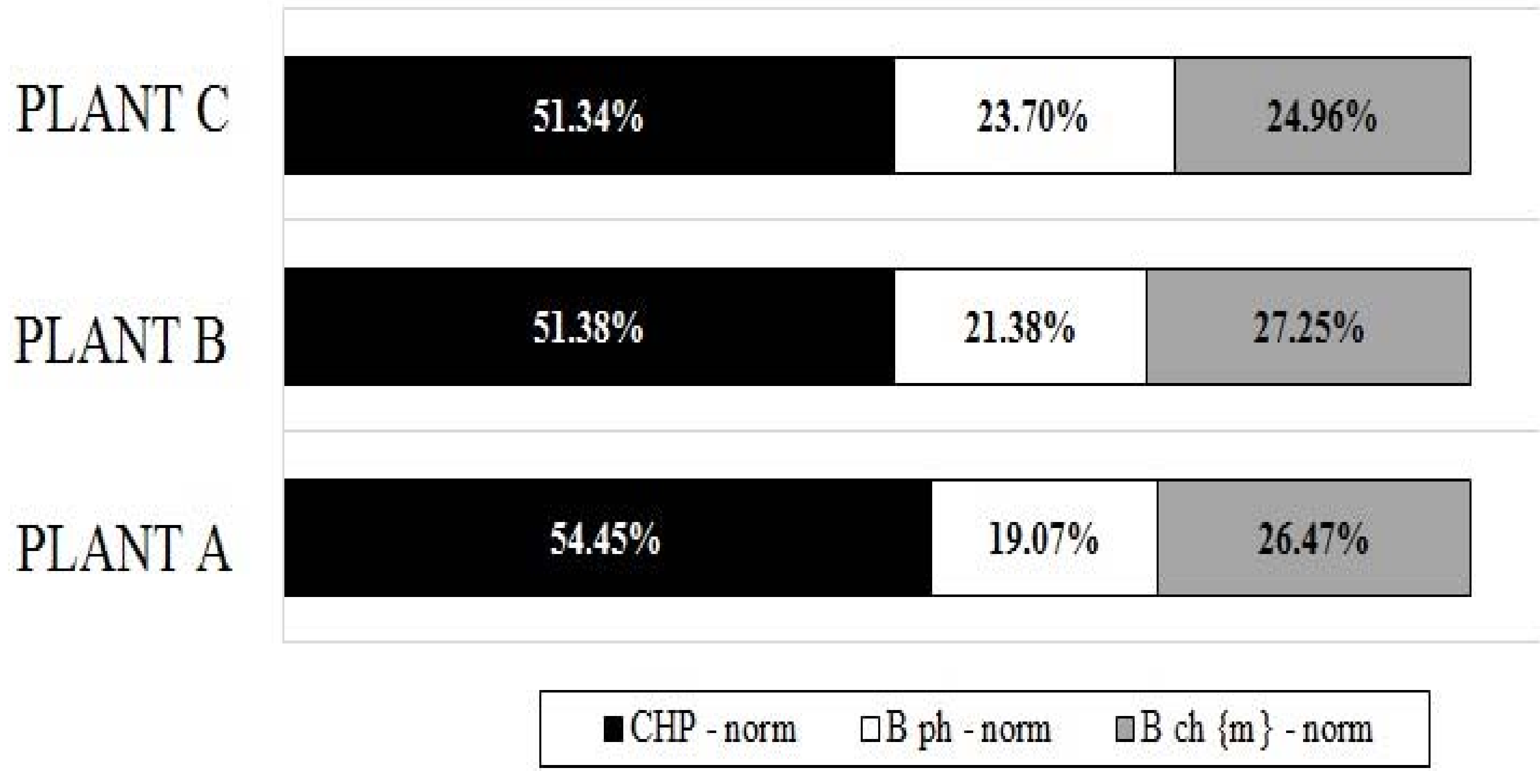


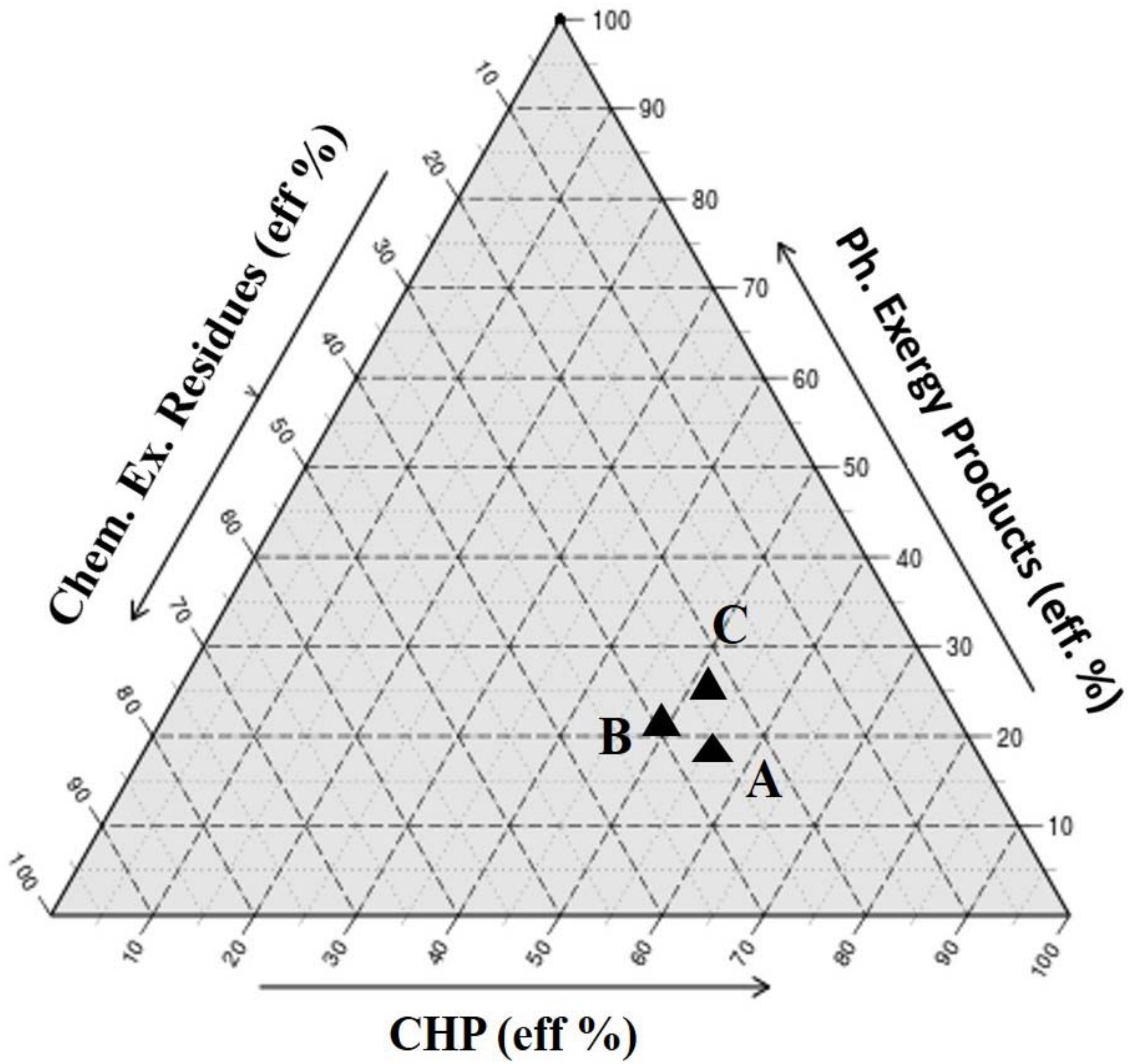


R1 results

PLANT A – 1.07
PLANT B -1.07
PLANT C – 1.23

Normalized distribution of efficiencies





Chem. Ex. Residues (eff %)
Ph. Exergy Products (eff. %)
CHP (eff %)
A
B
C
10
20
30
40
50
60
70
80
90
100

Conclusions

- R1 formula has been a great first tool for assessing waste-to-energy plants.
- But the assessment of novel waste-to- energy technologies requires the development of new tools that will be more compatible.
- 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 comparison of different technologies becomes possible.
  - The specialized solution allows the data mapping of incineration WtE plants.
- The method includes also the recovery of metals and is in good agreement with the concept of “circular economy”.

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

Stergios Vakalis, Konstantinos Moustakas and Maria Loizidou

THANK YOU FOR YOUR ATTENTION

email: stergios.vakalis@outlook.com