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Applications of the 3T Method and the R1 Formula as Efficiency Assessment Tools for Comparing Waste-to-Energy and Landfilling

Stergios Vakalis [1,2,*] and Konstantinos Moustakas [2]

[1] Faculty of Science and Technology, Free University of Bolzano, Piazza Università 5, 39100 Bolzano, Italy
[2] School of Chemical Engineering, National Technical University of Athens, 9 Iroon Polytechniou Str., Zographou Campus, GR-15780 Athens, Greece; konmoust@central.ntua.gr
* Correspondence: stergios.vakalis@outlook.com

Received: 1 March 2019; Accepted: 18 March 2019; Published: 20 March 2019

Abstract: The assessment of novel waste-to-energy technologies has several drawbacks due to the nature of the R1 formula. The 3T method, which aims to cover this gap, combines thermodynamic parameters in a radar graph and the overall efficiency is calculated from the area of the trapezoid. The present study expands the application of the 3T method in order to make it suitable for utilization in other energy-from-waste technologies. In the framework of this study, a 3T specialized solution is developed for the case of landfilling plus landfill gas recovery, with the potential inclusion of landfill mining. Numerical applications have been performed for waste-to-energy and landfilling by using both the R1 formula and the 3T method. The model Land GEM was used for the calculation of the total landfill gas. The Combined Heat and Power (CHP) efficiency of the landfill gas CHP efficiency was 16.6%–33.1%, and for the waste-to-energy plant, the CHP efficiency was over 70%. The full range of parameters, like metal recovery and quality of CHP, were not fully reflected by the R1 formula, which returned values of 1.07 for waste-to-energy and from 0.37 to 0.63 for different landfilling scenarios. Contrary to that, the 3T method calculated values between 0.091 and 0.307 for the waste-to-energy plant and values between 0.011 and 0.121 for the various landfilling scenarios. The 3T method is able to account for the recovery of materials like metals and assess the quality of the output flows. The 3T method was able to successfully provide a solution for the case of landfilling plus landfill gas recovery, with the potential inclusion of landfill mining, and directly compares the results with the conventional case of waste-to-energy.

Keywords: waste-to-energy; energy efficiency; energy-from-waste; landfill gas; landfill mining

1. Introduction

The European legislative framework categorizes the waste management strategies by separating them into two categories, recovery operations and disposal operations. This categorization was initially introduced in the Directive 2008/98/EU of the European parliament [1], where Annex I included the recovery operations and Annex II, the disposal operations. This categorization has been very useful because it highlights the valorization ability of each management strategy. Nevertheless, at the same, it creates a little bit of confusion for the case of "energy-from-waste" management strategies that can fit in both categories. The most common case by far among all "energy-from-waste" management strategies is the case of waste-to-energy technologies. The term "waste-to-energy" is being used loosely, but the strict definition refers to technologies that thermally treat municipal solid waste, with combustion of municipal solid waste being the most representative case.

The specific issue with waste-to-energy technologies can be condensed in the following argument; waste-to-energy technologies have the scope of producing energy, and thus it is considered to belong into category 1 of the recovery operations (R1). At the same time, the residues from this energy production process tend to be treated as waste and usually end up in the landfills and, for this reason, waste-to-energy belongs into category 10 of the disposal operations (D10). The crucial question is "How much energy production is sufficient in order to consider a waste-to-energy plant as an energy producing operation, and not as a waste destruction/disposal operation?" The European Commission tried to solve this issue with the introduction of the R1 formula, which assessed if a waste-to-energy plant can be considered a recovery operation and can fit in the category R1 [1,2]. The R1 formula has been a significant step towards the efficiency assessment of waste-to-energy plants and this aspect should be denoted. Although the R1 formula was a significant first step, the introduction of the formula has been met with some criticism because it is not thermodynamically consistent. The energy flows are defined ambiguously and the produced electricity and heat are multiplied by questionable factors (i.e., 2.6 and 1.1, respectively). In addition, the formula multiplies the denominator with a factor of 0.97, in order to account for energy losses from radiation, and this is not thermodynamically correct [3]. The utilization of the formula needs several clarifications that fortunately have been provided by means of a targeted legislative document [4].

This is a significant drawback because the formula is "specialized" for the case of waste combustion and not for other emerging technologies, like pyrolysis and gasification that—except producing electricity and heat—produce gaseous, liquid and solid biofuels. Although incineration plants have been dominating the market, novel waste-to-energy technologies are developing and are becoming commercial [5–7]. Vakalis et al., 2018 [8] developed the 3T method which provided a solution to this problem. In addition to the combined heat and power (CHP) efficiency, exergy analysis is used for the different output flows. In particular, the 3T method takes into consideration the output materials (i.e., the chemical exergy efficiency of the products and chemical exergy efficiency of the metals).

In addition to comparing different waste-to-energy technologies, the aspect of thermodynamic inconsistency does not allow any comparisons with other "energy-from-waste" strategies outside the strict conventional "waste-to-energy" niche. Such energy-from-waste strategies can be found across the board in respect to the available waste management strategies. For the conventional landfilling, Intharathirat and Abdul Salam (2016) highlighted the case of landfill gas [9]. This scenario is an interesting one for the case of developing countries that still utilize landfilling as a primer waste management strategy. Bourka et al. (2015) mentioned the case of anaerobic digestion, which—except from the production of biogas—produces the additional stream of digestate/compost, and thus it is a strategy with increased complexity [10]. In this case, the nature of the waste should be taken into consideration; in anaerobic digestion, the feedstock is primarily bio-waste that are usually separated at source. Finally, Clausen and Pretz (2016), present the mechanical–biological Treatment (MBT) as the other integrated waste management alternative to thermal treatment [11]. MBT is a strategy of even higher complexity than anaerobic digestion. Grando et al., (2017), have also highlighted these management strategies [12]. Although all these waste management strategies have interesting potentials and applications, the primer waste management strategy that should be compared with waste-to-energy is landfilling. The reason is that these two strategies compete for the mixed municipal solid waste. In addition, the enhancement of landfilling by recovering the landfill gas and valuable materials (landfill mining) have made these two strategies competitive on multiple levels.

The scope of this study is to propose a method for directly comparing waste-to-energy and landfilling, and this is the unique and novel contribution of this study. The use of the R1 formula would not be an ideal solution since the aspect of thermodynamic inconsistency does not allow any comparisons between different strategies. In addition, the recovery of the materials is not considered. Contrary to the case of the R1 formula, the use of the 3T method showed that it has the potential to be expanded for other waste management strategies beyond waste-to-energy [13]. The scope of this study is to investigate the ability of the R1 and 3T methods to analyze landfilling as a management strategy. The ultimate goal is to investigate the possibility that the 3T method becomes a universal efficiency tool that will compare not only waste-to-energy technologies but also all the other energy-from-waste technologies, including complex facilities like biorefineries. The critical parameters that should be considered in respect to the range of applicability of the 3T method in actual real cases, where waste management is not a one-step solution but a combination of several steps.

2. Materials and Methods

2.1. Energy Efficiency Tools

Two efficiency tools are presented and utilized in this study, the R1 formula and the 3T method. Their applicability was tested by using them for the assessment of a waste-to-energy plant and for the case of landfilling with landfill gas recovery. The main scope of the R1 formula was to separate the facilities that should be regarded as recovery operators from the facilities that should be regarded as disposal operators. In order to be considered energy producers (i.e., recovery operators), older facilities should have R1 values higher than 0.6 and newer facilities should have an R1 value of 0.65. The operation parameters of the facility were inserted in Equation (1) for this purpose:

$$\mathrm{R1} = (\mathrm{E_p} - \mathrm{E_f} - \mathrm{E_i})/0.97 * (\mathrm{E_w} + \mathrm{E_f}) \quad (1)$$

Vakalis et al., 2018 [8] developed the 3T method, which takes into consideration the physical exergy efficiency of CHP, the chemical exergy efficiency of the products and chemical exergy efficiency of the metals. On the one hand, the use of exergy analysis has been a very useful tool in the analysis of advance thermal treatments like gasification [14–17]. On the other hand, the use of a radar graph is also used for other efficiency calculations, as presented in previous studies, and the calculation of exergy analysis is presented in detail [18]. The combination of these parameters have allowed for the development of the 3T method and the direct comparison of all the waste-to-energy technologies (i.e., combustion, pyrolysis, and gasification), which is a task that was not feasible with the R1 formula, which only accounts for electricity, heat, and auxiliary fuels that assist the initiation of the incineration process [19].

The Equations (2)–(5) show the calculation of these parameters. These four parameters were plotted in a radar graph and the area of the trapezoid was calculated as shown in Equation (6). The calculated area of the developed trapezoid provides a unique value that is representative of each technology. As presented by Vakalis et al. (2018), the abbreviations that are used are the following "$\mathrm{CHP_{eff}}$: The net combined heat and power efficiency; Prod-$\mathrm{Bch_{eff}}$: The chemical exergy efficiency of the products of thermochemical conversion; $\mathrm{Bph_{eff}}$: The physical exergy efficiency of produced heat and power; $\mathrm{Bch_{eff}}$ {m}: The chemical exergy efficiency of the recovered metals" [8]. It has to be denoted that for the case of waste incineration, the 3T method uses a specialized solution, where the trapezoid is simplified into a triangle since the exergy of output materials/products is effectively zero. This solution is presented in Equation (7). For the case of technologies with more output streams, the more complicated trapezoid solution should be applied.

$$\eta_{\mathrm{el}} = (\mathrm{P_{el}} - \mathrm{P_{aux}})/(\Phi_{\mathrm{waste}} \times \mathrm{LHV_{waste}}) \quad (2)$$

$$\eta_{\mathrm{th}} = (\mathrm{P_{th}})/(\Phi_{\mathrm{waste}} \times \mathrm{LHV_{waste}}) \quad (3)$$

$$\mathrm{B} = \mathrm{h} - \mathrm{h_0} - \mathrm{T_0}\,(\mathrm{s} - \mathrm{s_0}) \quad (4)$$

$$\mathrm{Bch} = \beta \times \mathrm{LHV} \quad (5)$$

$$\sin\left(\tfrac{\pi}{2}\right)/2 \times [(\text{Prod-Bch}_{\mathrm{eff}} \times \mathrm{Bph_{eff}}) + (\mathrm{Bph_{eff}} \times \mathrm{CHP_{eff}}) + (\mathrm{CHP_{eff}} \times \mathrm{Bch_{eff\{m\}}}) + \ldots (\text{Prod-Bch}_{\mathrm{eff}} \times \mathrm{Bch_{eff\{m\}}})] \quad (6)$$

$$[(\mathrm{Bph_{eff}} + \mathrm{Bch_{eff\{m\}}}) * \mathrm{CHP_{eff}})]/2 \quad (7)$$

$$(\mathrm{Bpheff} \times \mathrm{CHPeff})/2 \quad (8)$$

Figure 1 shows the novel 3T specific solution that is proposed in this study for the case of landfilling. The first individual solution that is presented is the recovery of landfill gas with CHP. This is the simplest method to be analyzed with the recovery of the landfill gas, being the only valuable stream that is produced. In this case, the utilization of landfill gas for CHP production can be directly assessed from the Equation (8). As shown in Figure 1, the chemical exergy efficiencies of products and metals was zero. The flexibility of the 3T method was reflected from the aspect that the scenario of landfill mining can be examined individually, or also added to the previous case of landfill gas recovery. The values that were used in Figure 1 did not represent any specific energy-from-waste facility and were used only for exhibiting the method. Nonetheless, in the framework of providing a comparison basis for the different technologies, a range of metal recovery percentages were used. The percentage of metal recovery relates to the percentage of exergy efficiency of the recovered materials (i.e., from landfill mining or separation from bottom ash) and is always calculated in respect to the specific exergy input.

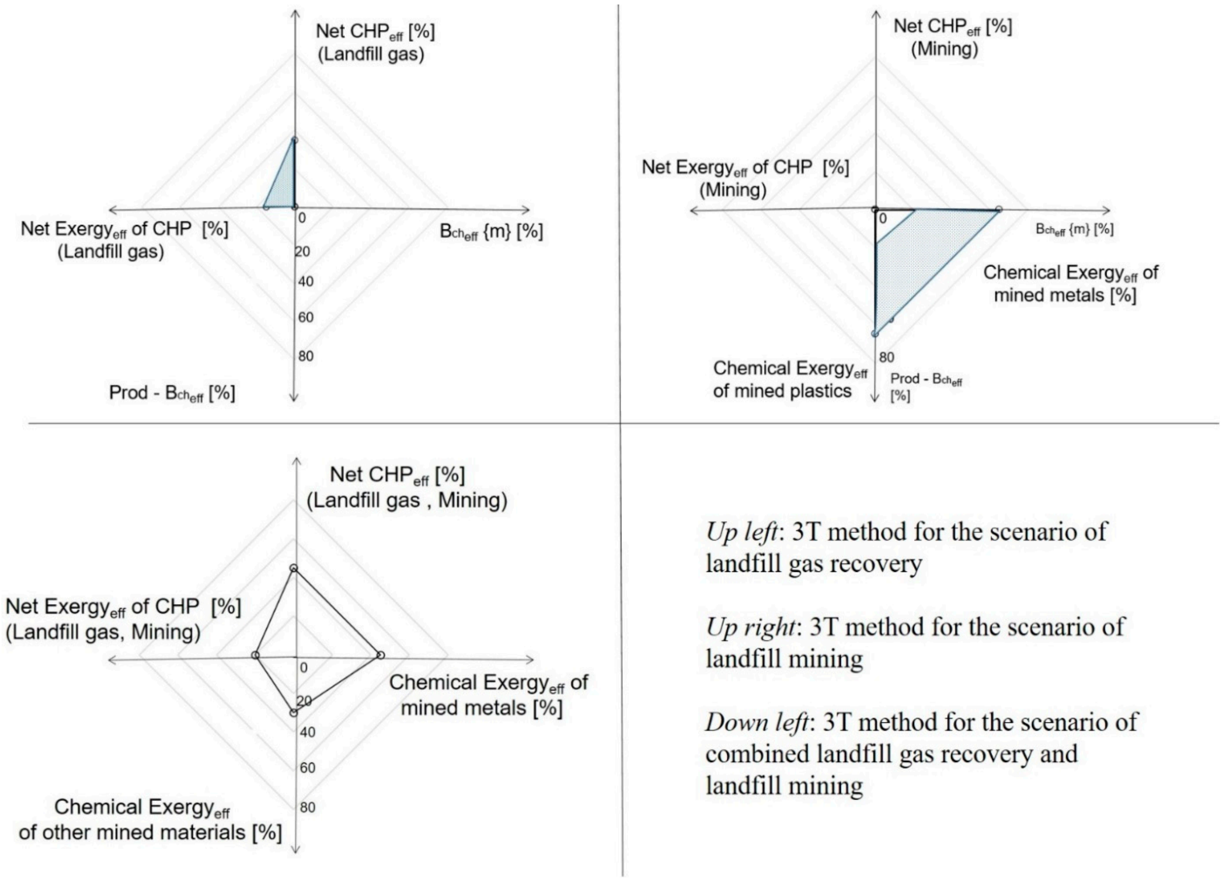

Figure 1. Specific solution of the 3T method for landfilling and landfill gas recovery.

2.2. Landfill Gas Modeling and Application Parameters

The projection of the estimated landfill gas has been performed by means of the landfill gas emissions model (LandGEM), which is a tool for the estimation of landfill emissions and has been introduced by the Environmental Protection Agency (EPA) [20]. The model operated on an Microsoft Excel interface and the user can insert several parameters, like the number of years of the landfill operation, the potential methane generation capacity, the methane generation rate, the mass of input waste per year, and the year time increment. The user can freely decide the methane content of the landfill gas, although a standardized 50% by volume is set as initial value, which is similar to the value that most of the other available models are using [21]. In addition, the user can pick custom values for several of the above-mentioned parameters (e.g., methane generation rate) and this aspect provides additional flexibility on the model. The main purpose of this tool is the estimation of the generated total landfill gas from municipal solid waste landfills, which includes methane, carbon dioxide, other organic compounds, and other individual air pollutants. The main scope of LandGEM is the estimation of the annual generated methane emissions and it uses a first-order decomposition rate equation in order to perform this estimation. This methane production estimation is presented in Equation (9).

$$QCH_4 = \sum_{i=1}^{n} \sum_{j=0.1}^{n} k\, Lo \left(\frac{Mi}{10}\right) e^{-kt} \quad (9)$$

The tools that are provided above (i.e., the R1 formula, the 3T method, and the LandGEM model) were applied for the operating parameters that are presented in Table 1. The operational parameters of the waste-to-energy plant were used from Vakalis et al. (2018) [8]. A Jenbacher CHP landfill gas engine (JMS 320 GS-BL) was chosen for this scenario, as presented by Chacartegui et al., 2015 [22]. A range of different percentages of metal recovery were considered, both for the cases of waste-to-energy and landfilling plus landfill mining. The estimated landfill gas production was calculated by means of LandGEM and is presented in the results section.

Table 1. Parameters of representative plants for the calculation of the R1 formula and 3T method for the comparison of waste-to-energy and landfilling.

	Waste –to-Energy Plant	**(Landfill) Lo = 100/k = 0.05**	**(Landfill) Lo = 170/k = 0.05**
Electrical efficiency (%)	17	40.8	40.8
Thermal efficiency (%)	55	41.7	41.7
Temperature of output heat (°C)	85	90	90
Exergy efficiency of metals (%)	0%–60%	0%–40%	0%–40%

3. Results

The 3T method and the R1 formula were applied for the case of a waste-to-energy plant and the results are presented in Figure 2. The R1 formula returned the constant result of 1.07 independently of the percentage of metal recovery. Contrary to that, the 3T method provided a range of results and the percentage of metal recovery was reflected significantly on the final 3T value.

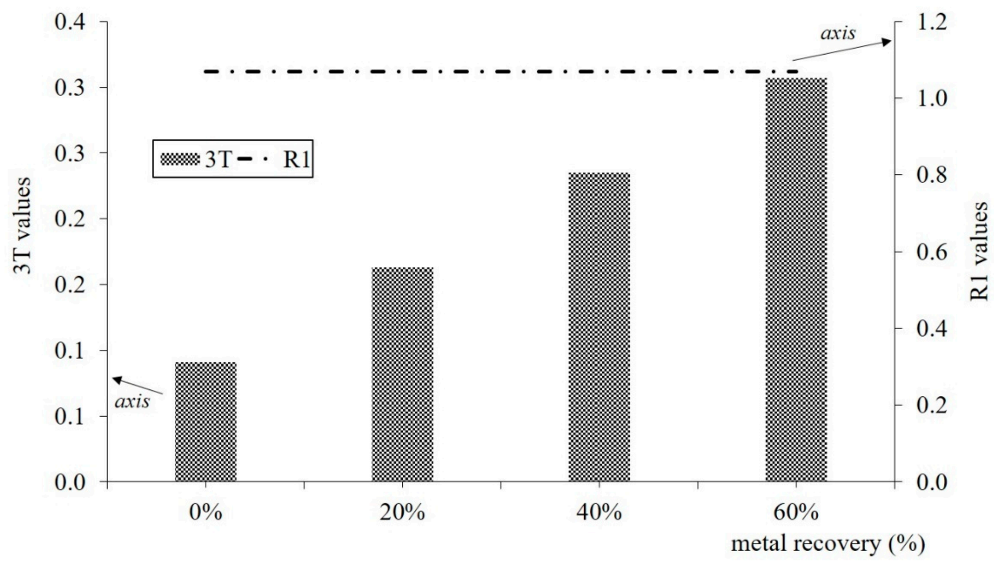

Figure 2. Results of applying the R1 formula and the 3T method for a waste-to-energy plant.

Figure 3 shows the annual production of total landfill gas, methane, and carbon dioxide as calculated by LandGEM. It should be pointed out that, although the volumetric contents of methane and carbon dioxide were 50%, the molecular weight of carbon dioxide was significantly higher, and thus the annual produced mass of the two gases varied by a large margin. The production of total landfill gas increased annually and reached a maximum at the fiftieth year of landfill operation. From this point on, the production declined but still remained significant for at least twenty more years. The simulated curves were similar to the curves that are calculated by other studies (e.g., Fallahizadeh et al., (2019) [23]).

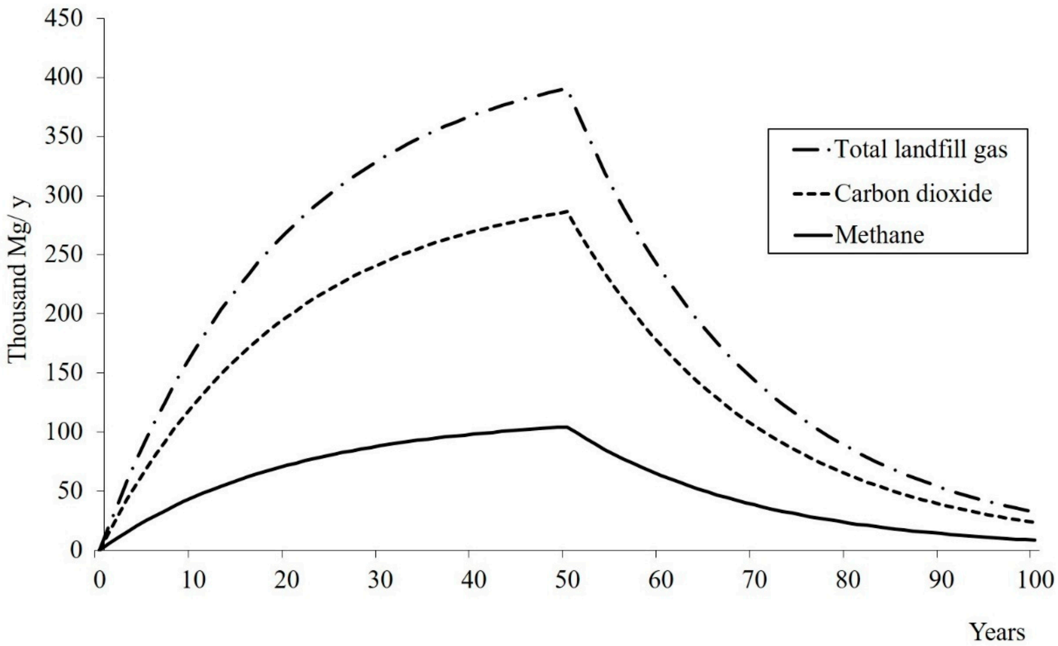

Figure 3. Simulated landfill gas production by using the model LandGEM.

A significant aspect of this analysis was the energy recovery potential from the operation of landfill gas CHP, and this answer was not a straightforward one. As seen in Figure 3, the produced amounts of total landfill gas varied, and at the same time the time span of landfill emission was far too long (i.e., around 80–90 years). A possible strategy is the selection of a time range with the maximum potential energy recovery. For our analysis, we considered that the years 20 to 60 were the optimal range because, during this period, the annual production of methane exceed the level of 100,000 Mg. The results from the energy analysis for the two different scenarios of potential methane generation capacity are presented in Table 2.

Table 2 shows the calculation of two different energy efficiency values:

- The net energy efficiency, which is the energy produced in years 20 to 60, divided by the input waste for the years 20 to 60.
- The gross energy efficiency, which is the energy produced in years 20 to 60, divided by the input waste for the years 0 to 60.

Although both parameters were significant, the real value was the gross energy efficiency, since the waste that were dumped in the landfill in years 0–20 were acting synergistically with the waste that were being disposed during the years under consideration (i.e., years 20–60). Nonetheless, we included both energy efficiencies for the analysis with the R1 formula and the 3T method. Figure 4 shows the calculation of the R1 values by applying the calculated parameters of Table 2 in the R1 formula. The results show that, for the case of potential methane generation capacity 170 m^3 Mg^{-1} and for the case of net energy efficiency, the R1 value exceeded the level of 0.6, which was the limit for old plants, and was very close to the 0.65 limit, which was set for new facilities. For the other cases, the values were lower, but still the case of landfilling with landfill gas recovery seems appealing if we use the R1 value as the metric. It should be stated that the R1 formula has a different purpose and has not been used for assessing landfill operations, but one of the scopes of this study is to assess its suitability.

Table 2. Results from the energy recovery of landfill gas, as returned by the model LandGEM.

Parameters of Analysis	Lo = 100	Lo = 170
Total energy input (waste, PJ)	12,000	12,000
Energy input years 20–60 (waste, PJ)	4800	4800
Energy in landfill Gas Years (Y) 20–60 (PJ)	1455.01	1926.37
Recovered energy in Landfill Gas (LG) (total) (%)	22.99	24.67
Recovered energy in LG (Y 20–60) (%)	12.13	16.05
Gross recovered energy in LG Y 0–60 (%)	20.21	26.76
Net recovered energy in LG Y 20–60 (%)	30.31	40.13
Net/gross electrical efficiency (%)	12.37/8.25	16.37/10.92
Net/gross thermal efficiency (%)	12.64/8.43	16.74/11.16
Net/gross Combined Heat and Power efficiency (%)	25.01/16.67	33.11/22.07
Total exergy efficiency net/gross (%)	14.63/11.23	19.37/14.87

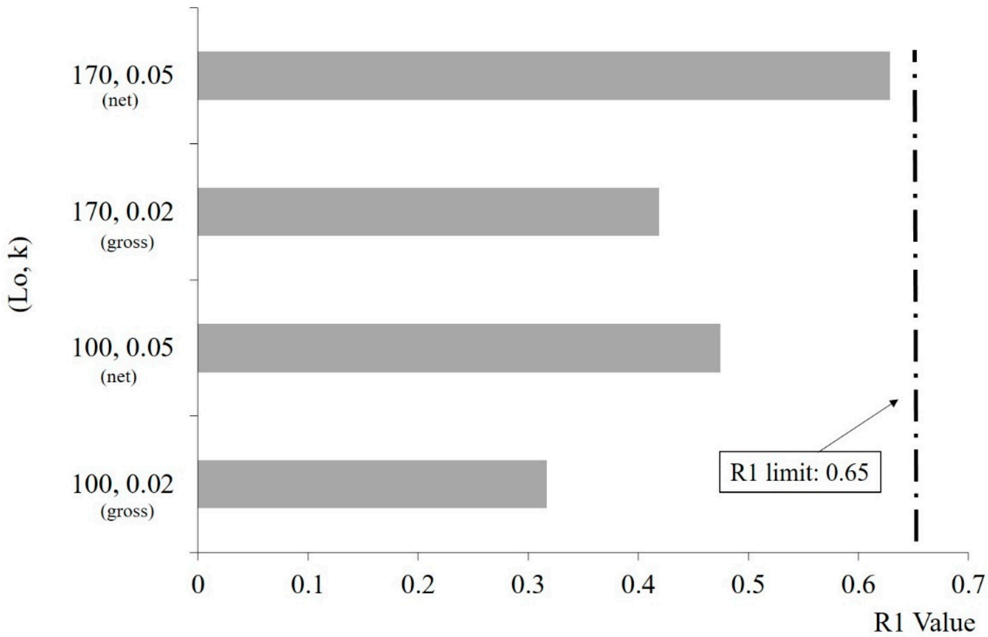

Figure 4. R1 values for CHP from the simulated landfill gas.

The analysis of the landfilling plus landfill gas recovery by means of the R1 formula returned values that were clearly lower than the values calculated for the case of an average waste-to-energy plant. However, the values were still comparable between the two cases, and this was a counterintuitive result. At the same time, the assessment of the metals was not considered and cannot be considered with the existing formula. Figure 5, presents the analysis of the landfill plus landfill gas recovery operation by means of the 3T method. In this case, the efficiency of landfilling in comparison with waste-to-energy was an order of magnitude lower. At the same time, the recovery of metals (and potentially other materials) increased significantly the 3T value of the operation. This aspect highlights the importance of resource efficiency and that landfill mining could increase the value of future landfilling operations that would be closer to the concept of circular economy [24].

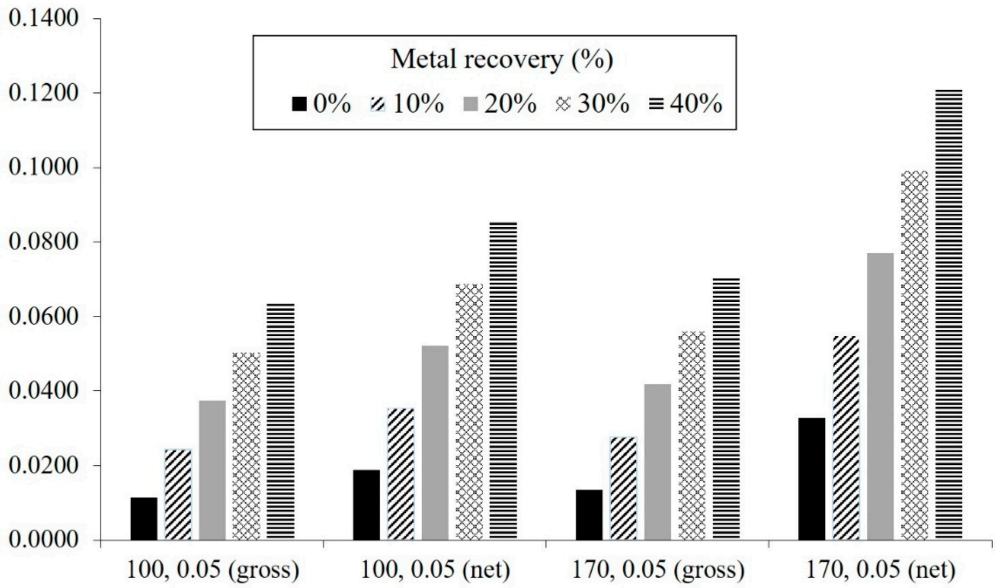

Figure 5. 3T values for CHP from the simulated landfill gas and different recovery percentage of metals.

4. Discussion

Although the advantages of the study were presented and analyzed, the limitations should also be acknowledged. The composition of municipal solid waste may fluctuate significantly and the real-time assessment of the input is a challenge. The numerous types of metals and other products from the different processes (e.g., biooil, char, etc.) require the development of specific guidelines. Specifically, the assessment of exergy inputs is not a straightforward task and a standardized methodology should be decided upon. A possible future expansion of the method could include several other waste management strategies. The case of anaerobic digestion would be a possibility. Except from the recovered biogas, a by-product of the process is the digestate/compost that has (usually) carbon contents around 20%, and thus a noticeable amount of chemical exergy. Therefore, in this case an additional value was added for the calculation of the 3T value, which is the chemical exergy efficiency of the products. The feedstock that is used for anaerobic digestion should be biodegradable, thus it is usually presorted or gathered separately. The main strategy is the separation at source by the end users, but further separation may be necessary in some circumstances. This case needs to be further analyzed in order to assess the energy demands of such a separation task in addition to other onsite energy demanding tasks, like the operation of pumps. The correlation between the fuel quality and efficiency of waste-to-energy processes cannot be overstated [25]. Nonetheless, organic waste has center of attention [26] and an expansion of the method would be an interesting future pathway. Another case for consideration could be MBT, which is by far the most complex and integrated solution. MBT primarily focuses on the separation/recovery of the materials and the stabilization of the biodegradable fraction. The recovery operation translates to final recovered materials of significant chemical exergy, thus the chemical exergy efficiency of the products and of the metals (as a separate stream) is very high. Kourkoumpas et al. (2015) also presented the recovery aspects of the MBT, where the authors mentioned the recovery of metals and the production of Refuse Derived Fuel (RDF) [27]. At the same time, MBT is an energy consuming technology and this should be reflected in the radar graph. Thanopoulos et al., (2018) presented the possibility of combining MBT with anaerobic digestion in order to increase efficiency [28]. On the opposite side of the spectrum, a limitation of the method is that it is only applicable to waste management strategies that recover energy and materials, and not for cases of simple disposal like conventional landfilling. In addition, the method stays within the boundaries of an energy efficiency tool and does not provide any information about the environmental impact of waste management strategies [29]. The role of each waste management strategy should be eventually evaluated in accordance to the compatibility with circular economy principles [30].

An interesting future use of the 3T method could be the correlation of the 3T values with the loops, formats, and the intrinsic performance C-indicators. Nonetheless, the 3T method can only be part of the solution since the evaluation of circular economy is done in a much broader framework, which includes also indicators that provide perspective and usage scenarios.

5. Conclusions

This study presented a standardized efficiency method in order to compare directly different energy-from-waste strategies. A previous work by the authors had introduced the 3T method, which is a technique to compare the efficiency of waste-to-energy plants by taking into consideration not only the CHP efficiency but also the produced fuels and the recovered metals. This study extended the use of the 3T method in order to compare waste-to-energy with the case of landfilling plus landfill gas and potentially landfill mining. The 3T method was compared with the R1 formula for both waste-to-energy and landfilling scenarios. The R1 formula returns results of 1.07 for waste-to-energy and from 0.37 to 0.63 for different cases of landfilling. The 3T method returned values from 0.091 to 0.307 for waste-to-energy and from 0.011 to 0121 for landfilling. The two methods evaluate the different waste management strategies differently and 3T method favors more waste-to-energy operations in comparison to the R1 formula. An interesting parameter is that the 3T method takes into consideration the recovery of materials. Therefore, the final 3T value can be significantly altered in accordance to the degree of material recovery and this aspect enhances resource efficiency and the concept of "circular economy".

Author Contributions: Conceptualization, S.V. and K.M.; methodology, S.V. and K.M.; software, S.V. and K.M.; formal analysis, S.V. and K.M.; investigation, S.V. and K.M.; data curation, S.V. and K.M.; writing—original draft preparation, S.V. and K.M.; writing—review and editing, S.V. and K.M.; visualization, S.V. and K.M.; project administration, S.V. and K.M.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

β	chemical exergy factor
Φ_{waste}	waste mass flow rate (kg/s)
B, B_{ph}, B_{ch}	exergy, physical exergy, chemical exergy (MJ)
E_p	annual energy produced as heat or electricity
E_f	annual energy from fuels contributing to the production of steam (GJ/year)
E_w	annual energy contained in the treated waste (GJ/year)
E_i	annual energy imported excluding E_w and E_f (GJ/Year)
i	1-year time increment
j	0.1-year time increment
k	methane generation rate (y^{-1})
L_0	potential methane generation capacity (m^3 Mg^{-1})
LHV	lower heating value (MJ/kg)
M_i	mass of solid waste disposed in the ith year (Mg or ton)
n	year of the calculation—initial year of waste acceptance
η_{el}	net electric efficiency
η_{th}	net thermal efficiency
P_{el}	electric power
P_{aux}	electric self-consumption of the auxiliary equipment
P_{th}	thermal power
QCH_4	estimated methane generation flow rate (m^3 y^{-1})
S, s	entropy, specific entropy (J K^{-1}, J K^{-1} kg^{-1})
T, T_0	temperature, temperature of environment (K)
t_{ij}	age of the j_{th} section of waste mass disposed in the i_{th} year

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