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Energy Generation and Carbon Footprint of Waste to Energy: Centralised vs. Distributed Processing

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Abstract

Waste to Energy (WTE) carries a trade-off between energy generation and the energy spent on collection, transport and treatment. Major performance indicators are cost, Primary Energy Savings (PES), Carbon Footprint (CFP). This presentation analyses the trade-off introducing a new indicator – the Waste Energy Potential Utilisation (WPU). The results indicate that the impact of logistics and energy distribution can be significant, and distributed WTE architectures may be good candidates for optimal solution, subject to further economical and environmental assessment.

Keywords: Waste-to-Energy, Waste Energy Potential Utilisation, optimisation processing distribution

1. Introduction

Waste management has become a significant problem due to its environmental impact (Eurostat, 2011). It mainly relates to atmospheric emissions and aqueous effluents from landfills, waste collection, transport, and processing. The growing demands for securing cleaner energy supplies (EIA, 2011) make necessary to achieve maximum savings of fossil fuels at minimum Carbon Footprint (CFP) in an economically viable way.

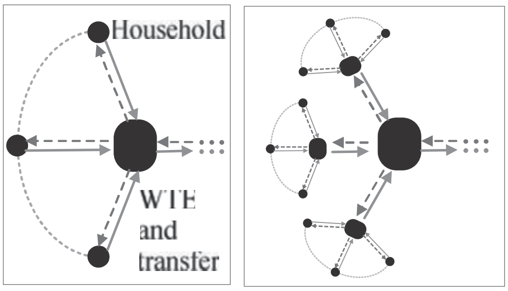
Studies of Waste-to-Energy (WTE) at the level of equipment and process design (Stehlík, 2011; Fodor and Klemeš 2012; Tabasová et al., 2012) and integrated waste utilisation (Singhabhandhu and Tezuka, 2010) have been published. There have been also studies on Carbon-Constrained economy targeting from New Zealand (Atkins et al., 2010) and Malaysia (Wong et al., 2011). Bastin and Longden (2009) compared fuel costs and CO_2 emissions of waste logistics networks with centralised vs. distributed location of UK waste processing, indicating 30 % higher fuel consumption for the centralised arrangement. A systematic evaluation of the CFP, energy saving and utilisation trends of WTE networks is important as well. One step in this direction for the synthesis of regional bioenergy networks has been the work by Čuček et al. (2010).

This contribution extends the analysis of WTE processing by defining a new performance indicator of the significance of the centralised versus distributed networks. The former allow larger and more efficient WTE plants but involve longer distances for waste transportation and energy distribution, while the latter feature the opposite trends.

2. Problem Description

The problem is to select a waste management network utilising the waste energy value optimally. The objective functions are typically minimum total cost, maximum waste energy utilisation or minimum environmental impact. Other criteria are also possible

(Zhang et al., 2011). The system includes households and intermediate WTE nodes, all connected with links for waste transportation and energy distribution (Figure 1).



(a) Single stage (b) Transfer hierarchy

Figure 1. Nodes connectivity

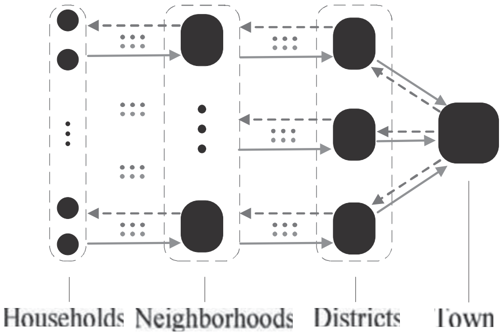


Figure 2. Network topology

WTE networks can be classified as reverse-logistics supply chain problems (Zhang et al., 2011). This work assumes that the household waste is separated to obtain a biomass fraction for anaerobic digestion to biogas. This is only one possible technology selected for the illustration the spatial development aspect. Other WTE technologies could be used too (Fodor and Klemeš, 2012).

2.1. Major Factors and Degrees of Freedom

The main activities in WTE processing include waste generation, collection, separation, transportation, conversion, energy distribution. The separation and WTE conversion may be performed at any network layer (Figure 2). The most significant factor in selecting the distribution of the processing activities within the WTE network is the CFP reduction. It is represented by the Primary Energy Savings (PES) concept. Other indicators are the waste volume sent to landfills, the type of WTE technologies and their environmental and health impacts, and the operating and investment cost of the system.

The main degrees of freedom are the choices of the technologies and locations for WTE and separation plants. It is important which WTE technologies will be selected. It is a common misconception to identify WTE as only waste incineration with heat recovery, which is the most common application to date (Stehlík, 2011). Other options as anaerobic digestion to biogas with further use as a fuel can also be applied.

Other implications concern capital cost (equipment and vehicles) and land cost. Situating WTE plants closer to the waste sources (households) may impose higher land cost and emission problems, but could reduce transport cost. Building the WTE plants at a distance, outside cities, would tend to reduce the land cost and increase transport cost.

2.2. Constraints and Trade-offs

WTE location and technology have significant public acceptance implications affecting the project feasibility– e.g. incineration is frequently resisted in populated areas. A comprehensive solution must account for this. The current study focuses on the energy trade-off aspect. An interesting constraint of WTE lies in the duality of its goals. Firstly it is needed to safely treat the waste and minimise landfilling. But with increasing concerns for energy security and CFP minimisation (Dovì et al., 2009), energy recovery can be considered equally important. There is a maximum distance, at which the energy for transporting the waste becomes equal to its energy value. It depends on the ratio of the waste specific heating value and the energy consumption for transport.

2.3. General Solution Algorithm

The general solution to the problem can be carried out using various algorithms. Examples are the inexact reverse logistics (Zhang et al., 2011), an adaptation of the synthesis of biomass-based energy supply chains (Čuček et al., 2010; Iakovou et al., 2010), which involve rigorous mathematical models. The algorithm should be able to adapt to the size and circumstances accounting for the trade-off of centralised vs. distributed processing. It has to define the following stages: (i) System identification – boundaries, sizes, zones, waste generation rates and energy value, transportation distances, main constraints; (ii) Scoping, identification of the system interactions, trends limitations; (iii) Formulation of the network architecture using clustering (Lam et al., 2010); (iv) Detailed supply chain modelling and optimal synthesis inside each cluster.

3. Utilisation of the waste energy potential

Municipal Solid Waste (MSW) potential (Step ii above) can be utilised at several stages (Figure 2) – households, neighbourhoods, districts, city, regional level. Transport decreases its energy value. Heat and power distribution are associated with losses proportional to the distance. The appropriate indicator for evaluating these options is the Primary Energy Savings – PES (Pavlas et al., 2010), and the Waste Potential Utilisation (WPU) – defined in this work:

$$\mathrm{PES} = \mathrm{FDD} - \mathrm{FTr} \tag{1}$$

$$\mathrm{FDD} = \frac{Q_{rep}}{\mathrm{FQ} \cdot \mathrm{DQ}} + \frac{W_{rep}}{\mathrm{FW} \cdot \mathrm{DW}} \tag{2}$$

$$\mathrm{WPU} = \frac{\mathrm{PES}}{\mathrm{WEV}} \left[\frac{\mathrm{GJ}}{\mathrm{GJ}} \right]; \mathrm{WPU}^{*} = \mathrm{WPU} \cdot 100 \, [\%] \tag{3}$$

FDD is the fuel saving from displaced demand; FTr is the transport fuel, Q_{rep} and W_{rep} – the replaced heat and power user demands, FQ and FW – efficiency factors for conversion to heat and power, DQ and DW – distribution efficiency factors. WPU is the ratio of PES to the waste energy value (WEV) before conversion or transportation. Using these indicators, a task is to evaluate at which stage the WTE facilities would yield the best effect – maximum WPU.

4. Illustrative Example

The defined framework is illustrated on an example of a town of 100,000 inhabitants, with an average of 4 persons per household (HH). The town has 3 districts with 4 neighbourhoods (NH) in District 1 (D1), 3 NH in D2 and 4 NH in D3. The average waste generation is 450 kg/y per inhabitant (Eurostat, 2011). From that 30 % is suitable for energy generation, LHV = 0.01 GJ/kg, translating to waste heating value WHV = 135,000 GJ/y for the town. Each HH has an average demand of 4,500 kWh/y for power and 12,000 kWh/y for heat. Fuel consumption for waste transport is 0.02 GJ/(t·km). The performance of the energy conversion plants is specified in Table 1. It is assumed that WTE processing takes place at only one of the four potential levels – HH, NH, D, town. In this case the WEV is completely offset after transportation to 500 km, so this is not constraining for the scale of the system (smaller than 100 km). The energy trends for the network are summarised in Figure 3.

It can be seen from Figure 3 that the WPU features a trend with a maximum, explained on by the trade-off between two factors as follows. The increasing distance from the waste source tends to decrease the PES via FTr. Also the WTE conversion efficiency increases with the plant scale to a saturation point. The WPU can be above 100 %, which means that more fossil fuel energy can be saved than the energy value of the utilised waste. This is caused by the distribution losses for heat and power, associated with the fossil based reference system for central utility supply and of the WTE options.

Table 1. Performance factors for the WTE plants

	BGD	**FQ**	**FW**	**DQ**	**DW**
	GJ/GJ	GJ/GJ	GJ/GJ	GJ/GJ	GJ/GJ
Reference system (fossil based CHP)	-	0.55	0.30	0.88	0.95
Biogas based heating at HH level	0.58	0.8	0	1	1
Biogas based CHP – NH level	0.58	0.55	0.24	0.92	0.98
Biogas based CHP – districts	0.58	0.55	0.24	0.90	0.96
Biogas based CHP – town	0.58	0.55	0.24	0.88	0.95

CHP: Combined Heat and Power generation; BGD: BioGas Digester efficiency

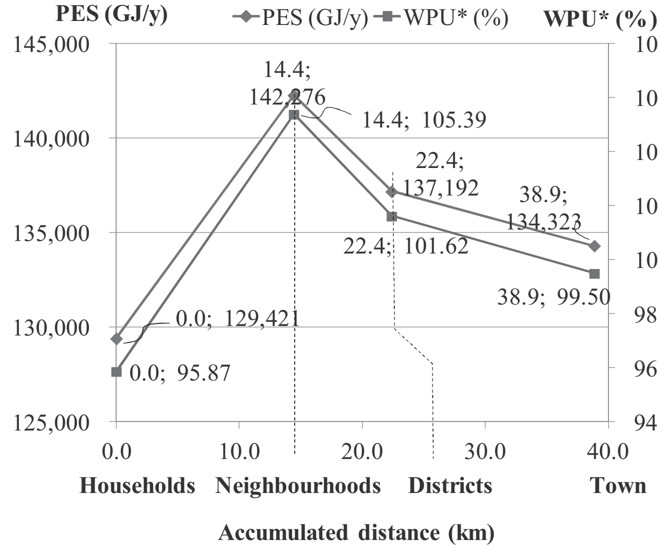


Figure 3. Energy trends for the illustrative example

5. Conclusions and Further Work

This work analyses the trend of utilising the waste energy value between distributed and centralised WTE processing. A new indicator – the WPU, has been formulated. The impact of the waste transport and energy distribution distances can be significant, reaching up to 10 % WPU variations even for smaller urban systems. The results also indicate that the WTE processing location between completely centralised or completely distributed arrangements has to be explored systematically with further indicators, as even an intermediate level such as neighbourhood-scale WTE facilities may be optimal. It should be also considered that the problem is not static, but developing with changing conditions as population growth, fuels prices increase, more efficient transport means.

Future work should involve a more detailed formulation of a systematic procedure for optimal WTE networks synthesis within the context of the waste management priorities and more accurate specification of the efficiency for energy conversion. It should include additional indicators – such as CFP and the other footprints as well as economic performance – especially the economy of scale (Čuček et al, 2012). A number of constraints should be satisfied – social acceptance, health regulations, availability of land for the WTE plants as well as for landfills. To solve this extended problem a multi-objective optimisation would be an obvious approach.

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