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Waste to Energy for Small Cities: Economics versus Carbon Footprint

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The main activities in Waste to Energy processing include waste generation, collection, separation, transportation, conversion, energy distribution, and ultimate waste disposal. Waste to Energy carries a trade-off between energy generation and the energy spent on collection, transport and treatment. Major performance indicators are cost, Waste Energy Potential Utilisation, and Carbon Footprint. This presentation analyses the potential of small cities to substitute part of their fossil fuels use by energy derived from Municipal Solid Waste.
Several factors are considered in the study. The impact of waste logistics and the losses from energy distribution systems – natural gas pipeline and electricity grid are the most significant ones on the side of the supply chain. Further, the waste processing part, including the energy recovery from the waste involves the evaluation of a number of technologies linked with each other to form a distributed integrated processing system. In this study, the options for converting waste into thermal energy include (a) biogas digestion and burning and (b) waste incineration with off-gas cleaning. It is also possible to use the biogas in advanced cogeneration systems based on engines or fuel cells. The proposed procedure takes all these options into account and derives the optimal processing configuration from the waste generation to energy supply and residual waste deposition to landfill.

1. Introduction

Waste generated from residential, commercial, institution and public parks is collectively termed as municipal solid waste (MSW) (Fodor and Klemeš, 2012). This MSW generation burdens the local governments for collection, handling and disposal of MSW efficiently. 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.
Generally, MSW is treated in three ways: (i) thermal conversion; (ii) biochemical conversion; and (iii) landfilling (Chua et al., 2011) . Thermal conversion of MSW uses heat energy to reduce the volume of MSW and generate biofuels, e.g. syngas, char, bio-oil, etc. Typical thermal conversion technologies include incineration, pyrolysis and gasification. Biochemical conversion of MSW uses enzymes and micro-organisms to break down organics for biogas production and collection of value-added products. Biochemical conversion processes include anaerobic digestion, fermentation and composting. It should be noted that all thermal and biochemical conversion processes leave MSW residues that have to be landfilled or released to the atmosphere. The general MSW processing technologies and their typical products are illustrated in Figure 1. With proper waste handling and management practice, MSW treatment can reduce environmental impacts as well as supplementing a portion of energy input (Fodor and Klemeš, 2012).

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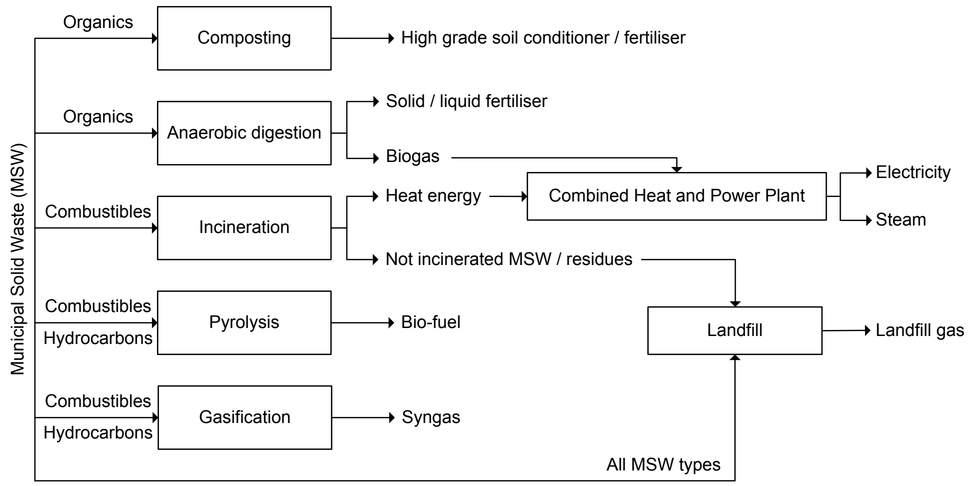

Figure 1: General MSW processing technologies and their typical products

This work extends the study by Varbanov et al. (2012) to evaluate the economic trend and carbon footprint resulted by centralised and distributed MSW processing networks in the border of a small city. In the current work, the significance of centralised versus distributed networks for MSW processing is investigated further using a supply chain model.

2. Problem statement

A novel design model for MSW allocation networks in small cities is proposed. The study considers waste incineration and biogas digestion as MSW processing technologies, because of their higher practical application potential. However, the existence of other Waste to Energy (WTE) technologies is acknowledged (Fodor and Klemeš, 2012). This problem investigates the waste management network at four different levels: household (HH) level, neighbourhood (NH) level, district (DT) level and town (TW) level. Models at different levels are optimised based on economic criteria while fulfilling the local heat and energy requirement. MSW from source *a* with known digestable fraction *X* and combustible fraction *Y* is sent to technology *i* to produce products *j*. This combustible fraction includes incombustible material which remains as process residue – ash from waste incinerator. The number of MSW processing hub *b* is determined based on the size of waste management network level.
This work determines the optimal allocation of MSW to each processing hub b via $F2_{b,j}$ (t/d). $F2_{b,j}$ is the flowrate allocation of MSW being processed into intermediates or product *j* in hub *b*. From the allocation of MSW, the existence of technology *i* in hub *j* is determined. Integrated waste management system that implements more than one MSW processing unit operation (both incineration and biogas digestion) is possible in each MSW processing hub. It shall be noted that none MSW processing technology achieves complete MSW conversion. The unprocessed waste or process residue from each technology is sent to landfill. The model considers the product's revenue, capital cost and ultimate waste disposal cost. It is optimised to achieve minimum MSW management cost after revenue.

3. Model formulation

MSW collected from source *a* is sent to possible processing hub *b* at flowrate $MSW_{a,b}$ (t/d) and its amount must not exceed its availability:

$$\sum_b MSW_{a,b} \leq \text{FW} \qquad \forall\, a \in A \qquad (1)$$

where FW is MSW generation rate of source *a* (t/d).
The amount of MSW sent to technology *i* at flowrate $F1_{b,i}$ (t/d) in each MSW processing hub *b* is constrained by its total availability from all source *a*:

$$\sum_a MSW_{a,b} \times MF_i = F1_{b,i} \qquad \forall\, b \in B, i \in I \qquad (2)$$

where MF_i is the digestable MSW fraction *X* for biogas digester and combustible fraction *Y* for waste incinerator.

MSW sent to possible hub b is processed into intermediates or final products j at flowrate $F2_{b,j}$ (t/d or MWh/d or m^3/d). The intermediate may be further processed into final products at flowrate $F4_{b,j}$ (t/d). The amount of electricity (EL) and heat (HT) generated at flowrate $F5_j$ (t/d) are required to fulfil the local area requirement of utilities RQ_j (MWh/d). Any deficit of EL and HT to fulfil the local requirement is to be topped up by external import of utilities EX_j (MWh/d):

$$F2_{b,j} = \sum_i F1_{b,i} \times CF_{i,j} \qquad \forall\, b \in B,\, j \in J \qquad (3)$$

$$F2_{b,j} \geq F3_{b,j} \qquad \forall\, b \in B,\, j \in BG \qquad (4)$$

$$F4_{b,j} = F2_{b,j} - F3_{b,j} \qquad \forall\, b \in B,\, j \in BG \qquad (5)$$

$$F4_{b,j} = F2_{b,j} + F3_{b,j} \times BF_j \qquad \forall\, b \in B,\, j \in EL, HT \qquad (6)$$

$$\sum_b F4_{b,j} + EX_j = F5_j \qquad \forall\, j \in EL, HT \qquad (7)$$

$$F5_j = RQ_j \qquad \forall\, j \in EL, HT \qquad (8)$$

where $CF_{i,j}$ is the conversion factor of MSW into intermediate or final product j in possible hub b through MSW processing technology i. Eq. 5 is the continuity equation for intermediate product – biogas (BG) produced is sent for further conversion into electricity (EL) and heat (HT) at flowrate $F3_{b,j}$ (m^3/d); BF_j is the EL and HT generation factor per unit weight of BG.
The unconverted MSW and processing residue in each hub b is sent for landfill at flowrate LAN_b(t/d):

$$LAN_b = \sum_a MSW_{a,b} - \sum_i F1_{b,i} + F2_{b,j} \qquad \forall\, b \in B,\, j \in AS \qquad (9)$$

where AS is the residue – ash generated from MSW incineration.
The capital costs (USD) of MSW processing unit operation in hub b – biogas digester (CDG_b) and MSW incinerator (CIN_b) is given by the following equation with a minimum processing capacity of a t/d:

$$CDG_b = \sum_i 51940 \times IA_{b,DIG} + 768965 \qquad \forall\, b \in B \qquad (10)$$

$$CIN_b = \sum_i 260000 \times IA_{b,INC} \qquad \forall\, b \in B \qquad (11)$$

$$F1_{b,i} \leq IA_{b,i} \qquad \forall\, b \in B,\, j \in AS \qquad (12)$$

where DIG and INC are the indexes for biogas digester and waste incinerator, respectively; $IA_{b,i}$ is integer variable to constrain the stepwise increment of equipment's processing capacity. These constrains are the unit operation's minimum capacity of 1 t/d for each installation of MWS processing unit operations.
The total MSW transportation cost, TTC (USD/d) is calculated based on the average MSW transportation distance, AD (km) of each level at NH, DT and TW:

$$TTC = \sum_{a,b} B1_{a,b} \times \mathrm{AD} \times \mathrm{TC} \qquad (13)$$

where $B1_{a,b}$ is binary variable that denotes the existence of transportation pathway from source a to hub b; TC is transportation cost per unit weight and distance delivered (USD/km-t).
The binary variable $B1_{a,b}$ is associated to the model through the following equation. It is assumed that a source of MSW will be sent to only one processing hub b:

$$MSW_{a,b} - B1_{a,b} \times \mathrm{FW} \leq 0 \qquad (14)$$

$$\sum_b B1_{a,b} = 1 \qquad (15)$$

The possible gate fee or waste collection fee, GTF (USD/d) that can be imposed at different levels of waste management capacity is calculated:

$$GTF = \sum_{b,i} \mathrm{GI} \times F1_{b,INC} + \mathrm{GD} \times F1_{b,DIG} \qquad (16)$$

$$CDP = \sum_b LAN_b \times \mathrm{GL} \qquad (17)$$

where GI, GD and GL are waste collection fees (USD/t) for waste processing through incineration, biogas disgestion and landfill; CDP is the total waste disposal cost through landfill (USD/d).
The gross revenue, REV (USD/d) and cost, COS (USD/d) of this MSW management network are defined as:

$$REV = \sum_{b,j} F4_{b,j} \times PR_j \qquad (18)$$

$$COS = 0.000137 \times (\sum_b CDG_b + CIN_b) + TTC + CDP \qquad (19)$$

where PR_j is the selling price of products (USD/t); 0.000137 is the averaging factor to average the capital cost based on 20 y and 365 d/y of operational lifespan.

This MSW management network is optimised for maximum economic function:

$$max\,(REV - COS) \tag{20}$$

4. Illustrative case study

A demonstrative case study is built to investigate the MSW management network. The case study proposed by Varbanov et al. (2012) is applied and extended with slight modification. MSW generation rate and local area heat and electricity requirement follow the previous case study. MSW produced from each HH is centrally collected at MSW dump sites that each site (source *a*) serves around 200 HHs. The flow diagram of the process is illustrated in Figure 2 and the case study parameters are listed in Table 1.

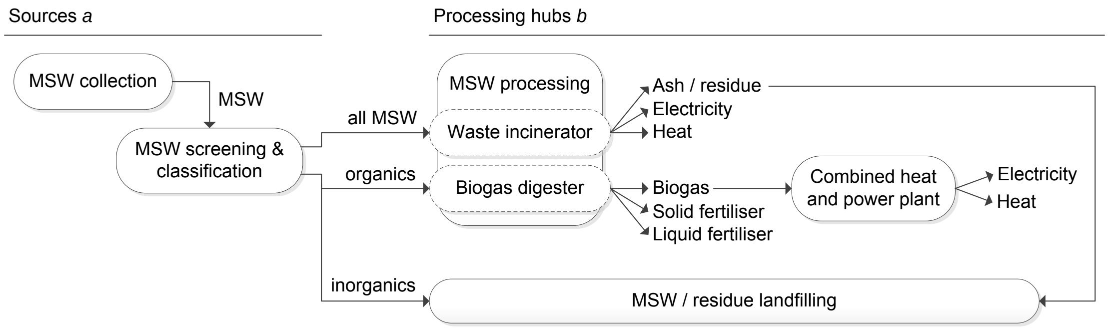

Figure 2: Case study MSW management flow diagram

Table 1: Case study parameters

Parameters	HH	NH	DT	TW
Number of MSW sources *a* (200 HH / source *a*)		125		
Number of MSW processing hub *b*	125	11	3	1
Average distance from source *a* to hub *b*, AD (km)	0	10	20	30
Transportation cost, *TC* (USD/t-km)		9		
Landfill gate / waste collection fee, *GL* (USD/t)		60		
Product price, PR_j				
Biogas (USD/m^3)		0.35		
Electricity (USD/MWh)		242		
District heating (USD/MWh)		50		
MSW fraction send to technology *i*, MF_i				
Biogas digester fraction, *X*		0.67		
Waste incineration fraction, *Y*		1.00		
MSW conversion factor, $CF_{i,j}$				
Waste incinerator ash production (t/t MSW)		0.20		
Waste incinerator electricity production (MWh/t MSW)		0.67		
Waste incinerator heat production (MWh/t MSW)		2.00		
Biogas digester biogas production (m^3/t MSW)		303.60		
Biogas digester liquid fertilizer production (t/t MSW)		1.69		
Biogas digester solid fertilizer production (t/t MSW)		0.45		
Biogas conversion factor, BF_j				
Biogas electricity production (MWh/m^3)		0.0024		
Biogas heat production (MWh/m^3)		0.0025		

A mixed-integer linear programming (MILP) model is formulated and optimised using the modelling software General Algebraic Modelling System (GAMS, 2013). MSW management network optimisation is performed at four levels: HH, NH, DT and TW. The model results are plotted in Figure 3.

There is significant reduction of capital cost when the MSW management network moves from HH scale to NH scale. This is resulted from the saving of centralised MSW processing facilities. From HH scale to TW scale, the transportation distance increases and therefore, the transportation cost. Transportation cost may act as an indicator to the resulted transportation carbon footprint as both transportation cost and emission go proportionally with carbon footprint. The gross revenue – cost, which is calculated based on the sales revenue of BG, EL and HT with deduction of *TTC*, *CAP* and *CDP*, shows its highest value at NH level. MSW management network shows the highest economic attractiveness in NH level. This result matches the analysis carried out by Varbanov et al. (2012) that WTE facilities at NH scale may be optimal.

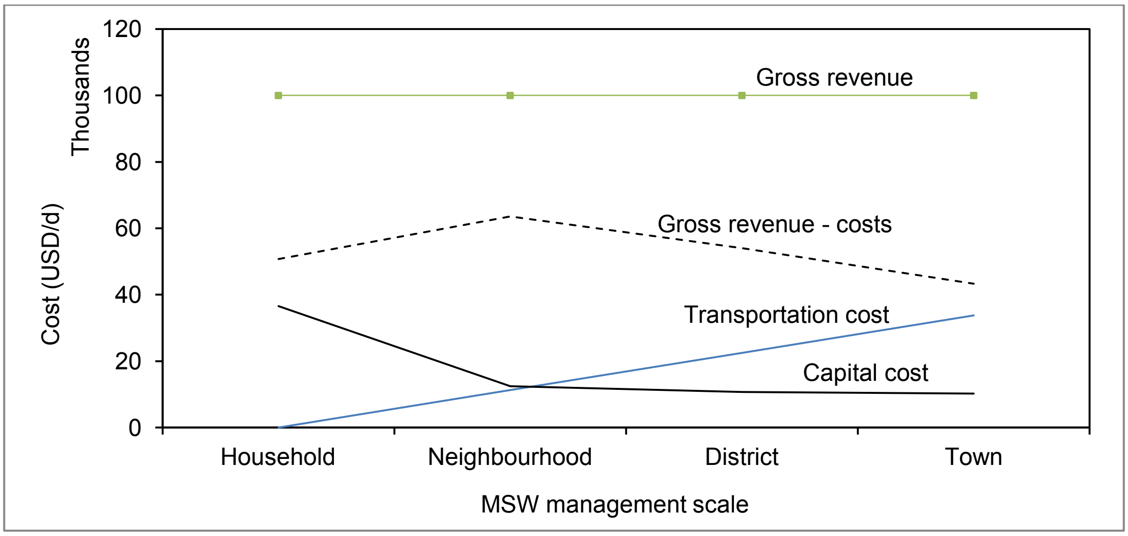

Figure 3:Costs comparison of MSW management network at different scales

An inverse relationship between transportation and WTE facilities scales is observed. Transportation cost and therefore, the transportation carbon footprint increases with increasing MSW management scale; whereas, WTE facilities capital cost decreases with increasing centralised MSW management. The transportation cost may be offset through the reduced capital cost at larger MSW management scale. MSW management scale at NH level may be the most optimal level as it accrues relatively low WTE facilities capital cost and moderately low transportation cost.

5. Error analysis of model

Assumptions were made in evaluating the model practicability:

a) Constant supply of material that there is no fluctuation of MSW supply and delivery. However, this can be overcomed by proper arrangement of inventory storage.
b) Two common MSW processing technologies are considered instead of all technologies, such as composting, pelletisation, pyrolysis, gasification, etc.
c) The model assumed for no leakage emission and material loss from logistic activity.
d) The efficiencies of MSW processing technologies are not considered.
e) The operation cost and utility consumption for MSW processing is not considered.

These assumptions reduced the MSW management network's realism, however, the main objective of this work is to investigate the practicability of MSW management at different levels / scales.

6. Conclusions and Future Work

This work presented a study of MSW management network at four scales/levels. The network is optimised based on economic criteria. The offset of MSW processing capital cost with transportation cost is significant at NH level when the model switch to centralised WTE facilities at NH level as compared to distributed WTE facilities at HH level. NH level MSW management network shows the most attractive economic potential yet relatively lower transportation footprint. In future work, the model should be developed in detail which considers exact locations of sources and facilities, since the exact location and transportation pathway affect the location of processing hub significantly. Other MSW processing technologies and its operation costs should be considered for a more complete framework – for example downstream processing to methanol (Manenti et al., 2013) or other liquid wnwegy carriers. The efficiencies of each technologies at different scales should be assessed as this is predicted to be able to further distinct the network performance at different scales.

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Nomenclature

a: MSW collection source
AD: average MSW transportation distance (km)
AS: index for residue – ash generated from MSW incineration
b: MSW processing hub
$B1_{a,b}$: binary variable that denotes the existence of transportation pathway from source a to hub b
BF_j: electricity (EL) and heat (HT)generation factor per unit weight of biogas (MWh/t)
BG: index for biogas
CDG_b: capital cost of MSW processing unit operation in hub b – biogas digester (USD)
CDP: total waste disposal cost through landfill (USD/d)
$CF_{i,j}$: conversion factor of MSW into intermediate/final product j through processing technology i (1)
CIN_b : capital cost of MSW processing unit operation in hub b – MSW incinerator (USD)
COS: cost of MSW management network (USD/d)
DIG: index for biogas digester
EL: index for electricity
EX_j: flowrate of external importation of utilities EL and HT (MWh/d)
$F1_{b,i}$: flowrate of MSW sent to technology i in each MSW processing hub b (t/d)
$F2_{b,j}$: flowrate of intermediates or products j produced through technology i (t/d or MWh/d or m^3/d)
$F3_{b,j}$: flowrate of intermediates j for further processing in hub b (m^3/d)
$F4_{b,j}$: flowrate of product j (total EL and HT) generated in hub b (MWh/d).
$F5_j$: flowrate of total EL and HT after external utilities top-up (MWh/d)
FW: MSW generation rate per NH or DT or TW (t/d)
GD: waste collection fees for waste processing through biogas digestion (USD/t)
GI: waste collection fees for waste processing through incineration (USD/t)
GL: waste collection fees for waste processing through landfill (USD/t)
GTF: possible gate fee or waste collection fee (USD/d)
HT: index for heat
i: MSW processing technology i
$IA_{b,i}$: integer variable to constrain the stepwise increment of equipment’s processing capacity
INC: index for waste incinerator
j: products after MSW processing technology i
LAN_b : flowrate of unconverted MSW and processing residue in each hub b sent to landfill (t/d)
MF_i: fraction of MSW sent to technology i (1)
$MSW_{a,b}$: flowrate of MSW from source a to hub b (t/d)
PR_j: selling price of products (USD/t)
REV: gross revenue (USD/d)
RQ_j: local area requirement of utilities (MWh/d)
TC: transportation cost per unit weight and distance delivered (USD/km-t)
TTC: total MSW transportation cost (USD/d)

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