Life-Cycle Modeling of Solid Waste Combustion and Combustion Residues

Thomas F. Astrup, PhD
Associate Professor

go.ncsu.edu/swolf

www.easetech.dk
Outline

• LCA of W-t-E – current status in literature
• Emission types and modeling approaches
• Emissions from residues
• Importance of energy substitution modeling
Solid Waste Systems
The WTE Process Model

Material Input
(Mg\textsuperscript{in})

Direct Emissions
(kg/Mg\textsuperscript{in})

Electricity and Heat
(energy/Mg\textsuperscript{in})

Capital Cost
($/Mg\textsuperscript{yr^{-1}}$)

Operating Cost
($/Mg\textsuperscript{in}$)

User Inputs

WTE Process Model

Recovered Metals:
Ferrous, Non-ferrous
(Mg\textsuperscript{out})

Ash
(Mg\textsuperscript{out})

User Inputs

- Waste composition
- Waste properties
- Combustion and APC technology
- Equipment cost and performance
The Composting Process Model

Incoming Waste Materials (Mg\text{in})

- Direct Emissions (kg/Mg\text{in})
- Equipment Fuel Use (L/Mg\text{in})
- Electricity Use (kWh/Mg\text{in})
- Capital Cost ($/Mg-yr\text{-1})
- Operating Cost ($/Mg\text{in})

Residual Contaminants (Mg\text{out}/ Mg\text{in})

Final Compost and Properties (Mg\text{out}/ Mg\text{in})

User Inputs

- Waste composition
- Waste properties
- Compost technology
- Equipment cost and performance

- C, N, P, K content
- Potential for beneficial use
Background and introduction

- 136 peer-reviewed journal articles were evaluated
- 250 individual LCA case studies
- Primary focus on mass-burn incineration
- Very few studies provided adequate description of: goal & scope, technologies, modelling approach, and assumptions.

Most studies (58 %) focused on treatment of a unit mass of waste
68 % of the studies either compared different WtE technologies or WtE technologies with other waste technologies
26 % of the studies included WtE as part of a system
Technology types addressed

- Most studies focused on mass-burn incineration
- Few studies addressed or specified the material and chemical composition of the input waste
- Many studies did not specify the origin of the inventory data used in the LCA
Modelling approach: Input = output?

- Modelling of waste specific emissions in many cases neglected
- Energy content of waste only reflected in some cases
- Use of transfer coefficients generally not implemented in LCA software
- Approaches poorly described
## Emission modeling

<table>
<thead>
<tr>
<th>Process specific emissions</th>
<th>Emissions are primarily governed by emission control systems rather than the contents of the fuel input itself</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input specific emission</td>
<td>Emissions are primarily governed by the contents of the fuel input, although emission control systems may remove a certain fraction of the components</td>
</tr>
</tbody>
</table>

The LCA modelling approach is critical for the results. If only process specific emissions are applied, no effects from changes in fuel input will be obtained.
Air-emission modeling

- Input-specific
- "Reality"
- Process-specific

mg Cd to air/ton waste

mg Cd/ton waste
Transfer coefficients

Input specific emissions are estimated by assuming that fixed ratios of the input are routed to specific outputs.

\[ M_{i,o} = M_t \times \sum_f (m_f \times C_{f,i} \times TS_f \times TFC_{f,i,o}) \]
## Critical air emissions from waste

### Daily average values based on on-line measurements:

<table>
<thead>
<tr>
<th></th>
<th>European Union(^a)</th>
<th>Germany(^b)</th>
<th>The Netherlands(^c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOC</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Dust</td>
<td>10</td>
<td>10</td>
<td>5</td>
</tr>
<tr>
<td>HCl</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>HF</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>SO(_2)</td>
<td>50</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>NO(_x)</td>
<td>200</td>
<td>200</td>
<td>70</td>
</tr>
<tr>
<td>CO</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>

### Average values (sampling period 0.5-8 hours):

<table>
<thead>
<tr>
<th></th>
<th>European Union(^a)</th>
<th>Germany(^b)</th>
<th>The Netherlands(^c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cd+Tl</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Hg</td>
<td>0.05</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>Sb+As+Pb+Cr+Co+Cu+Mn+Ni+V</td>
<td>0.5</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>As+Cd+Co+Cr+benzo(a)pyrene</td>
<td></td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>PCDD/F</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Carbon emissions: fossil or biogenic?

Figure 2. Results from long-term sampling at plant A, illustrating the annual variation in fossil CO$_2$ (f-CO$_2$) and biogenic CO$_2$ (b-CO$_2$). The results are provided as percentage of the total CO$_2$ emission during the sampling period. Each bar represents an averaged, monthly result. Uncertainties on results were $[1 \pm 5\%]$.

Fuel properties: emissions and residues

Waste input | Furnace operation
---|---
Automobile Shredder Residue | Oxygen level
PVC waste | Furnace air distribution
Impregnated wood | 
Batteries | 
NaCl | 
Shoes | 

Astrup et al. (2011): Incinerator performance: effects of changes in waste input and furnace operation on air emissions and residues. Waste Management & Research, 29, S57-S68.
Air emissions

Astrup et al. (2011): Incinerator performance: effects of changes in waste input and furnace operation on air emissions and residues. Waste Management & Research, 29, S57-S68.
Transfer coefficients

Astrup et al. (2011): Incinerator performance: effects of changes in waste input and furnace operation on air emissions and residues. Waste Management & Research, 29, S57-S68.
Air emissions and control systems

![Graph showing air emissions and control systems](image)

<table>
<thead>
<tr>
<th>APC-technology</th>
<th>APC 1</th>
<th>APC 2</th>
<th>APC 3</th>
<th>APC 4</th>
<th>APC 5</th>
<th>APC 6</th>
<th>APC 7</th>
<th>APC 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle removal</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Scrubbing</td>
<td>No</td>
<td>No</td>
<td>Dry</td>
<td>Wet</td>
<td>Dry</td>
<td>Wet</td>
<td>Dry</td>
<td>Wet</td>
</tr>
<tr>
<td>Dioxin filter</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Flue gas condensation</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Damgaard et al. (2010): Life-cycle-assessment of the historical development of air pollution control and energy recovery in waste incineration. *Waste Management, 30, 1244-1250*
Incineration residues

- Grate siftings
- Boiler ash (5 kg)
- Bottom ash (150-300 kg)
- Dry / semidry system
- Fly ash (10-30 kg) + neutralization products (15-60 kg)
- Wet system
- Wastewater
- Sludge (1-5 kg)
Ash disposal options

Waste bottom ashes (non-hazardous waste):
• Substitute for natural aggregates (e.g. gravel) in road construction
• Filler materials for embankments, ramps, etc.
• Aggregate in concrete

Waste fly ash / APC residues (hazardous waste):
• (currently no real utilization, landfilling only after treatment/stabilization)
• Refilling of mines with APC ashes (Germany)
• Neutralization of waste acid with APC ashes (Norway)
Emissions via leaching

Further info:
Fruergaard, T, Hyks, J & Astrup, T 2010, 'Life-cycle assessment of selected management options for air pollution control residues from waste incineration' Science of the Total Environment, 408, 4672-4680.

Hyks, J & Astrup, T 2009, 'Influence of operational conditions, waste input and ageing on contaminant leaching from waste incinerator bottom ash: A full-scale study' Chemosphere, 76, 1178-1184.
Table 2
Overview of energy recovery efficiencies in case-studies reporting such data. Average and standard deviation (st.dev.) is provided when more than two case-studies was available. Gasification and pyrolysis efficiencies are based on gas-electricity and gas-heat conversions only.

<table>
<thead>
<tr>
<th>Energy Recovery Method</th>
<th>N. case-studies</th>
<th>Range (%)</th>
<th>Average ± st.dev. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross electricity efficiency</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incineration</td>
<td>61</td>
<td>0–34</td>
<td>21 ± 7.0</td>
</tr>
<tr>
<td>Co-combustion in cement-kilns</td>
<td>1</td>
<td>4.38</td>
<td>–</td>
</tr>
<tr>
<td>Co-combustion in power plants</td>
<td>2</td>
<td>34–40</td>
<td>–</td>
</tr>
<tr>
<td>Gasification</td>
<td>2</td>
<td>33–34</td>
<td>–</td>
</tr>
<tr>
<td>Pyrolysis</td>
<td>1</td>
<td>18.0</td>
<td>–</td>
</tr>
<tr>
<td>Pyrolysis-gasification</td>
<td>1</td>
<td>35.0</td>
<td>–</td>
</tr>
<tr>
<td>Net electricity efficiency</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incineration</td>
<td>87</td>
<td>–2–30</td>
<td>19 ± 7.5</td>
</tr>
<tr>
<td>Co-combustion in cement-kilns</td>
<td>0</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Co-combustion in power plants</td>
<td>2</td>
<td>34.0</td>
<td>–</td>
</tr>
<tr>
<td>Gasification</td>
<td>5</td>
<td>14.5–27.2</td>
<td>20 ± 5.3</td>
</tr>
<tr>
<td>Pyrolysis</td>
<td>1</td>
<td>15.25</td>
<td>–</td>
</tr>
<tr>
<td>Pyrolysis-gasification</td>
<td>0</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Net heat efficiency</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incineration</td>
<td>68</td>
<td>0–87.7</td>
<td>44 ± 28.4</td>
</tr>
<tr>
<td>Co-combustion in cement-kilns</td>
<td>0</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Co-combustion in power plants</td>
<td>3</td>
<td>26–40</td>
<td>31 ± 8.1</td>
</tr>
<tr>
<td>Gasification</td>
<td>2</td>
<td>33–45.5</td>
<td>–</td>
</tr>
<tr>
<td>Pyrolysis</td>
<td>1</td>
<td>70.3</td>
<td>–</td>
</tr>
<tr>
<td>Pyrolysis-gasification</td>
<td>1</td>
<td>40.0</td>
<td>–</td>
</tr>
</tbody>
</table>
Modelling approach: energy substitution

- Although included in most studies, modelling and/or description of energy substitution was poor.
- Critical for outcome of the LCA.
### Examples of substitution

<table>
<thead>
<tr>
<th>Energy type</th>
<th>Present</th>
<th>Future</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>Marginal electricity production = coal or natural gas</td>
<td>Marginal electricity production = biomass = wind power</td>
</tr>
<tr>
<td>Heat</td>
<td>Local &quot;responding&quot; heat production = coal, natural gas = biomass</td>
<td>Local &quot;responding&quot; heat production = natural gas = biomass</td>
</tr>
<tr>
<td>Transport</td>
<td>= diesel = gasoline</td>
<td>= diesel = gasoline = natural gas = biofuels</td>
</tr>
</tbody>
</table>

*Important: test the sensitivity of your assumptions on the results*
Thanks for your attention

go.ncsu.edu/swolf

www.easetech.dk