Evaluating the quality of energy recovery from waste

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MatER
MatER point of view

BOTH material recovery AND energy recovery are essential for Sustainability

Sustainability

Integrated system:
1) Reduction
2) Re-use
3) Recovery
4) Inerts disposal

Material Recovery ↔ Energy Recovery

Reduction of waste production
To be sustainable, energy from waste must somehow lead to a lower use of non-renewable resources --> substitution/competition with fossil fuels.

Viewing WTE plants as power/thermal stations - rather than a disposal technology - is crucial to make WTE acceptable to the public opinion and legislators.

Waste = Resource
Directions for improvement

How can WTE "beat" fossil fuel-fired plants?

1) Decrease costs
   - simpler configuration
   - use less material
   - ease/decrease maintenance
   - other?

2) Increase efficiency
   - improve boiler efficiency
   - improve thermodynamic cycle efficiency
   - cogenerate heat & power

3) Adopt new/different technology?
   - fluidized bed?
   - gasification?

4) Generate additional outputs
   - recover materials from bottom ashes
   - other?
How can we measure "efficiency"?

Recovery of heat generated by combustion: boiler efficiency

\[ \eta_{\text{boil}} = \frac{\dot{Q}_{\text{useful}}}{\dot{m}_{\text{MSW}} \cdot \text{LHV}} \]

Production of electric power: electric efficiency

\[ \eta_{\text{e}} = \frac{\dot{E}}{\dot{m}_{\text{MSW}} \cdot \text{LHV}} = \frac{\dot{Q}_{\text{useful}}}{\dot{m}_{\text{MSW}} \cdot \text{LHV}} \cdot \frac{\dot{E}}{\dot{Q}_{\text{useful}}} = \eta_{\text{boil}} \cdot \eta_{\text{cycle}} \]

These two definitions are Ok when considering the production of heat only or of electricity only.

But what about the production of power + heat?
Energy content of waste (100)

Recovery process (waste incineration)

Recovered thermal energy (85)
Losses (15)

Heat recovered in the boiler can be used:

- as heat, to satisfy a heat demand
- as input of a thermodynamic cycle for the production of power+heat
- as input of a thermodynamic cycle for the production of power only
• The production of just heat dramatically simplifies the WTE plant --> dramatic reductions of Capex and Opex

• But unlike power, the transport of heat is difficult and very expensive - and can be done only within a very limited range (max 10-20 km)

• This is why all developed countries have a very pervasive, interconnected infrastructure for the transport and distribution of electricity but not for heat.

• District heating networks for the transport and distribution of heat are always "local" - as the term "district" itself implies - and are not interconnected
Energy recovery from waste to produce just heat is rare, either because of:

- **lack of infrastructure**: delivering all the heat generated by waste is challenging and expensive, or
- **lack of demand**: in the area where waste is generated and/or waste is disposed the heat demand is small (or zero)
- **heat demand varies throughout the year**: in many countries, a demand for residential heating exists only for up to 2000-3000 hrs / year

The production of power decouples the location of the WTE plant from the location of the energy demand. (The same applies to fossil fuel-fired plants).

The cogeneration of power and heat is an "intermediate" arrangement that can meet either local (thermal) demand and remote (power) demand.
Not only does the choice between production of heat and production of electricity impact on costs and logistics. It has an important impact on the amount of resources that energy recovery can save, ultimately on its sustainability.

Meeting 1 unit of heat demand generates a saving of primary energy DIFFERENT from meeting 1 unit of electric demand.

Even if all forms of energy are measured in the same unit (Joules), THEY ARE NOT THE SAME!

1 unit of "noble" energy like electricity is more valuable than 1 unit of "degraded" energy like low-temperature heat.
Converting heat into power

- From the thermodynamic point of view, the conversion factor between heat and electricity is given by the Carnot efficiency. Measuring temperatures in Kelvin:

\[
1 \text{ Joule of heat at } T_Q = \left(1 - \frac{T_{\text{amb}}}{T_Q}\right) \text{ Joules of electric energy}
\]

- The lower \( T_Q \), the lower the "thermodynamic value" of heat
- From the economic point of view, the sensitivity of cost to \( T_Q \) is weaker. Nonetheless, in nearly all circumstances electricity is much more valuable than heat
- One consequence of the conversion factor above is that 1 unit of electricity can generate more than 1 unit of heat - and the lower the temperature \( T_Q \) at which heat must be provided, the greater the amount of heat that can be produced by a single unit of electricity
Heat pump

1 J of electricity

Ideal cycle
- 4.39 J of heat @ 100°C (useful effect) vs. 1 J of electricity (input)
- COP: 4.39 (reverse Carnot cycle between 15°C and 100°C)

Real cycle
- 2.5 J of heat @ 100°C (useful effect) vs. 1 J of electricity (input)
- COP: 2.5

- 1.5 J of “free” heat @ 15°C
The "quality" of energy recovery

- How can we measure the "quality" of energy recovery from waste?
- One possible measure is the amount of primary energy saved - which is strictly related to the amount of avoided emissions.
- The energy recovery process that saves the most primary energy is NOT the process with the highest 1st Law efficiency --> referring to the sum of electricity+heat exported (starting point of BREF review) looks inappropriate.
- A proper evaluation must consider BOTH fundamental physical Laws that control the process:
  - conservation of energy (1st Law)
  - direction of physical processes (2nd Law)
- This requires that electricity and heat are properly weighed.
Indicator of energy efficiency introduced by EU Directive 2008/98/EC:

\[ R1 = \frac{E_P - (E_F + E_I)}{0.97 \times (E_W - E_F)} \]

- \( E_P = 2.6 \times E_{\text{gross}} + 1.1 \times \text{Heat} \)
- \( E_F = \text{energy of fuels that contribute to the generation of steam} \)
- \( E_W = \text{energy in waste (LHV)} \)
- \( E_I = \text{energy imported, } E_F \text{ and } E_W \text{ excluded} \)
Let's consider four cases

1) All the heat recovered in the boiler is used as heat at 90°C to meet the baseload heat demand of a district heating network

2) The energy recovered in the boiler feeds a backpressure steam cycle where all the heat discharged by the condenser is used as heat at 90°C to meet the baseload heat demand of a district heating network

3) The energy recovered in the boiler feeds a condensing-extraction steam cycle where steam bled along the turbine expansion is used as heat at 90°C to meet the seasonal heat demand of a district heating network. All the heat discharged at the condenser is wasted

4) The energy recovered in the boiler feeds a condensing steam cycle where all the heat discharged at the condenser is wasted and no useful heat is generated
Case 1: only heat

Energy content of waste (100)

Recovery process (waste incineration)

Recovered thermal energy (85)

Losses (15)

Heat to stack & ashes, unburned carbon, etc.

Auxiliaries (2.0)

Heat demand (85)

Net energy export = 83
Case 2: back-pressure Steam Cycle

Energy content of waste (100)

Recovery process (waste incineration)

Recovered thermal energy (85)
Losses (15)

Electrical energy import (0.3)
Heat to stack & ashes, unburned carbon, etc.
friction, leakages, electric losses, etc.

Auxiliaries (2.5)

Electrical energy (10)
Heat demand (72)
Losses (3)

Net energy export = 79.5
Case 3: condensing-extraction SC

Energy content of waste (100)

Recovery process (waste incineration)

Recovered thermal energy (85) Losses (15)

Auxiliaries (3.5)

Electricity import (0.3)

Electricity (27.5) Heat demand (32.5) Losses (25)

Net energy export = 56.5

Heat to stack & ashes, unburned carbon, etc.

friction, leakages, electric losses, etc. + heat discharged by condenser
Case 4: condensing Steam Cycle

Energy content of waste (100)

Recovery process (waste incineration)

Recovered thermal energy (85)
Losses (15)

Electricity (33)
Losses (52)

Net energy export = 29

Auxiliaries (4.0)

Electricity import (0.3)

Heat to stack & ashes, unburned carbon, etc.

friction, leakages, electric losses, etc. + heat discharged by condenser
### Supply of heat at 90°C

<table>
<thead>
<tr>
<th>Case</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste input</td>
<td>100,0</td>
<td>100,0</td>
<td>100,0</td>
<td>100,0</td>
</tr>
<tr>
<td>Heat recovery</td>
<td>85,0</td>
<td>85,0</td>
<td>85,0</td>
<td>85,0</td>
</tr>
<tr>
<td>Electric output, GROSS</td>
<td>0,0</td>
<td>10,0</td>
<td>27,5</td>
<td>33,0</td>
</tr>
<tr>
<td>Electric consumption on site</td>
<td>2,0</td>
<td>2,5</td>
<td>3,5</td>
<td>4,0</td>
</tr>
<tr>
<td>Heat lost in tdn cycle</td>
<td>-</td>
<td>3,0</td>
<td>25,0</td>
<td>52,0</td>
</tr>
<tr>
<td>Electric output, NET</td>
<td>-2,0</td>
<td>7,5</td>
<td>24,0</td>
<td>29,0</td>
</tr>
<tr>
<td>Heat to export, NET</td>
<td>85,0</td>
<td>72,0</td>
<td>32,5</td>
<td>0,0</td>
</tr>
<tr>
<td>Total Export</td>
<td>83,0</td>
<td>79,5</td>
<td>56,5</td>
<td>29,0</td>
</tr>
<tr>
<td>Ranking</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

- **1**: only heat
- **2**: back-pressure SC
- **3**: condensing-extraction SC
- **4**: condensing SC

**Electric equivalent to heat, NET**

<table>
<thead>
<tr>
<th>Case</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>17,6</td>
<td>14,9</td>
<td>6,7</td>
<td>0,0</td>
<td></td>
</tr>
<tr>
<td>Total El equivalent, NET</td>
<td>15,6</td>
<td>22,4</td>
<td>30,7</td>
<td>29,0</td>
</tr>
<tr>
<td>Ranking</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

- **E_p** = \(2.6 \times E_{\text{gross}} + 1.1 \times \text{Heat}_{\text{export}}\)

<table>
<thead>
<tr>
<th>Case</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>93,5</td>
<td>105,2</td>
<td>107,25</td>
<td>85,8</td>
<td></td>
</tr>
<tr>
<td>(E_F)</td>
<td>1,0</td>
<td>1,0</td>
<td>1,0</td>
<td>1,0</td>
</tr>
<tr>
<td>(E_I)</td>
<td>2,0</td>
<td>0,3</td>
<td>0,3</td>
<td>0,3</td>
</tr>
<tr>
<td>(E_W)</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>(R1, %)</td>
<td>94,2</td>
<td>108,2</td>
<td>110,3</td>
<td>88,0</td>
</tr>
<tr>
<td>Ranking</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>
### Supply of heat at 150°C

<table>
<thead>
<tr>
<th>Case</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste input</td>
<td>100,0</td>
<td>100,0</td>
<td>100,0</td>
<td>100,0</td>
</tr>
<tr>
<td>Heat recovery</td>
<td><strong>82,0</strong></td>
<td><strong>82,0</strong></td>
<td>85,0</td>
<td>85,0</td>
</tr>
<tr>
<td>Electric output, GROSS</td>
<td>0,0</td>
<td><strong>7,5</strong></td>
<td><strong>26,0</strong></td>
<td>33,0</td>
</tr>
<tr>
<td>Electric consumption on site</td>
<td>2,0</td>
<td>2,5</td>
<td>3,5</td>
<td>4,0</td>
</tr>
<tr>
<td>Heat lost in tdn cycle</td>
<td>-</td>
<td>3,0</td>
<td>25,0</td>
<td>52,0</td>
</tr>
<tr>
<td>Electric output, NET</td>
<td>-2,0</td>
<td>5,0</td>
<td>22,5</td>
<td>29,0</td>
</tr>
<tr>
<td>Heat to export, NET</td>
<td><strong>82,0</strong></td>
<td><strong>71,5</strong></td>
<td><strong>34,0</strong></td>
<td>0,0</td>
</tr>
<tr>
<td>Total Export</td>
<td>80,0</td>
<td>76,5</td>
<td>56,5</td>
<td>29,0</td>
</tr>
<tr>
<td>Ranking</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>E equivalent to heat, NET</td>
<td>26,2</td>
<td>22,8</td>
<td>10,8</td>
<td>0,0</td>
</tr>
<tr>
<td>Total El equivalent, NET</td>
<td><strong>24,2</strong></td>
<td><strong>27,8</strong></td>
<td><strong>33,3</strong></td>
<td><strong>29,0</strong></td>
</tr>
<tr>
<td>Ranking</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>$E_p = 2.6<em>E_{\text{gross}} + 1.1</em>Heat_{\text{export}}$</td>
<td>90,2</td>
<td>98,2</td>
<td>105,0</td>
<td>85,8</td>
</tr>
<tr>
<td>$E_F$</td>
<td>1,0</td>
<td>1,0</td>
<td>1,0</td>
<td>1,0</td>
</tr>
<tr>
<td>$E_I$</td>
<td>2,0</td>
<td>0,3</td>
<td>0,3</td>
<td>0,3</td>
</tr>
<tr>
<td>$E_W$</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>$R1, %$</td>
<td><strong>90,8</strong></td>
<td><strong>100,9</strong></td>
<td><strong>108,0</strong></td>
<td><strong>88,0</strong></td>
</tr>
<tr>
<td>Ranking</td>
<td>3</td>
<td>2</td>
<td>1</td>
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</tr>
</tbody>
</table>

1: only heat  
2: back-pressure SC  
3: condensing-extraction SC  
4: condensing SC
1) The future of WTE depends on the actual sustainability of the energy recovery process

2) The "certification" of the "quality" of energy recovery from waste is needed for a number of reasons:
   - permitting
   - access to incentives
   - overcome ideological opposition (possibly ...)

3) To this end, an appropriate indicator is needed. Such indicator must account for the fundamental physical laws underlying the energy recovery process

4) The mere "1st-Law efficiency" is inadequate, and can lead to incorrect conclusions.

5) While working at a better definition, should we start with using R1 ?
Thank you for your attention!

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