Energy Recovery in Sludge Management Processes

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**ABSTRACT:** This work presented a preliminary analysis of the energy recovery efficiency of sludge management. Using literature data, this work compares energy recovery potential from several thermal processes, including incineration (with electricity production or sludge pre-drying), supercritical wet air oxidation, pyrolysis, and digestion.

INTRODUCTION

WASTEWATER comprises a mixture of organic and inorganic compounds, and associated water. The organic component of the sludge displays a heat value of approximately 25 MJ/kg-dried solids (ds). Considering the inert fraction in the sludge this value is reduced to 16–20 MJ/kg-ds for raw sludge, or 10–14 MJ/kg-ds for digested sludge [1]. These values can be considered the upper limits of energy recoverable from the sludge.

Thermal processes treat wastewater sludges at high temperatures, including oxygen-sufficient processes, such as incineration or wet air oxidation, or oxygen-deficient processes, such as the thermo-chemical conversion process [2,3]. Figure 1 schematically displays the pressure ($P$) versus enthalpy ($H$) diagram for water, and the corresponding operational “regimes” for some thermal processes. The sludge state must be brought to these regimes for reaction, by adding 2.6 MJ/kg-water for drying or supercritical wet air oxidation (WAO), 4.4 MJ/kg-water for incineration, or 1.3 MJ/kg-water for subcritical WAO process. From the first law of thermodynamics, treatment can not only recover the external energy input, but the entire energy content of wastewater sludge, regardless of its initial physical state. However, in practice this generally is not the case. Huge energy demands make high-temperature processes expensive, suitable only if the land for final disposal is limited and/or the environmental regulations to land applications are stringent. Thus differences exist between expectations and reality on the recovery efficiency of energy from sludge.

The second law of thermodynamics determines the upper limit for energy recovery from sludge, namely the availability or energy of the process streams in sludge treatment practice. Restated, expenditure is necessary to recovery. The process irreversibility further restricts our ability to recover waste heat from the sludge treatment, which depends on the real process pathway and the thermal efficiencies of the treatment units adopted. This presentation assesses the energy recovery efficiency of various sludge treatment processes, considering the irreversibilities of these processes.

ENERGY IN SLUDGE

Since sludge is initially a suspension, the large quantity of associated water makes it a low-density energy source. Energy must be gathered from sludge before this energy can be applied for useful purposes, meaning the sludge has a high entropy state. The sludge has opposite characteristics to fossil fuels, which are a high-density energy source (up to 40 MJ/kg-ds) in a low entropy state. The moisture in the sludge is bound with the solids phase by a certain binding strength [4]. This binding strength limits mechanical dewatering. The wastewater sludge from the clarifiers has a solids fraction of 1–5%. The “effective” heat value of this suspension is just 0.16–0.8 MJ/kg-sludge. This suspension is the feed for anaerobic digestion treatment or wet air oxidation. Chemical conditioning followed by mechanical dewatering are frequently applied to further remove
the free water from wastewater sludge. Following mechanical dewatering, the moisture content in the dewatered cake ranged from 70–85% w/w. For example, Figure 2(a) shows a mechanically dewatered cake from a wastewater sludge. The cake resembles a piece of chewed gum, soft to the touch and free of surface moisture. Figure 2(b) shows the same cake after thermal drying at 102°C. The cake volume is reduced by over 90%, indicating that the dewatered cake in Figure 2(a) contains over 85% moisture. In this regard, the dewatered sludge cake has an effective heat value of around 2.4–6.0 MJ/kg-wet cake. This cake is the raw material that undergoes further thermal processes, if any, such as drying, incineration, or thermal pyrolysis.

Mininni [3] reported electricity production capacity from a sludge incineration plant to range from 0.7–5.6 MJ/kg-ds. Mininni et al. (unpublished results) noted that when the wastewater cake was dewatered to a solids fraction of 40%, the electricity production equivalent to 2.17 MJ/kg-dried solids (ds) was yielded, representing approximately 12% of the upper limit for energy content in sludge (16–20 MJ/kg-ds). At a lower solid fraction of 30%, the electricity output becomes approximately 1 MJ/kg-ds. When the solids fraction of cake is below 20%, it can be assumed that the plant cannot produce electricity from sludge incineration. Mininni et al. [5] stated that the steam produced by waste incineration heat could thermally dehydrate the sludge cake from 21% to 45.9% w/w, with self-sustainable incineration being achievable at the latter solids fraction. However, no electricity could be produced in this case.

Wet air oxidation (WAO) oxidises the wastewater sludge in pressurized water. The subcritical WAO process operates at 175–320°C and 2–20 MPa. Water becomes supercritical when P > 22 MPa and T > 374°C. Assuming a solids fraction of 10%, Modell and Tester [6] claimed that the supercritical WAO process at 500–650°C and 25 MPa could be operated at an energy demand of 0.5 MJ/kg-wet cake, or equivalently, 5 MJ/kg-ds. This value is just 30% of the energy content in wastewater sludge, with the remaining 70% energy recoverable from the waste stream. Bridle [7] commented on the use of their thermal pyrolysis plant for dried sludge, operated at 400–500°C and atmospheric pressure. The so-called ENERSLUDGE™ process can

![Figure 1. The schematics of the phase diagram of water. Regimes marked denote the operational conditions correspond to the thermal treatment processes. Incineration occurs at 850°C and atmospheric pressure.](image1)

![Figure 2. The appearances of dewatered cakes before or after thermal drying; (a) Cake containing 85% moisture, (b) cake dried at 102°C for 24 hrs.](image2)
produce pyrolyzed products equivalent to a net thermal energy output of 7.7 MJ/kg-ds, or 39–48% of the energy content of the raw sludge. Meanwhile, the anaerobic digestion process produces one Nm³ biogas for each kg of volatile solids destroyed, where each kg of volatile solids has a heat value of 22–25 MJ. Taking 5% w/w sludge as the substrate, with 70% volatile solids (VS) and a 50% destruction ratio of organic matters, then the energy recovery efficiency through biogas production is approximately 8 MJ/kg-ds.

This preliminary information can be used to calculate the energy recovery efficiencies from wastewater sludge processes, as follows: supercritical WAO > pyrolysis digestion > incineration (40% w/w dried cake with electricity production) > incineration (using recovered steam for cake dehydration). Especially in the last case, energy recovery credit appears to be zero. The following section explores this point further, remembering that the comparison is unfair if overall efficiency is considered.

**ENERGY RECOVERY FROM PROCESSES**

For comparison, this work takes the wastewater sludge from the gravity thickener at a weight percent of 5% as the starting material. This sludge is a suspension and can be dehydrated to 20% w/w dried solids using mechanical dewatering. The physical properties were assumed to be identical to those described by Mininni [3]. We neglect the energy demand by mechanical dewatering. Take one kilogram of dried solids (72% VS, equivalent heat value of 18 MJ/kg-ds) as a basis for further calculation. A sludge cake of 5% or 20% w/w ds at 25°C then would contain 19 kg or 4 kg water. For simplicity, we consider only the heat duties for the main reactor and the heat exchange units. Since all other process irreversibilities are ignored the results reported here can only be considered preliminary.

**Incineration**

The incinerator receives the dewatered cake at 20% w/w ds. The solids is heated to 850°C, which requires 1 kg \times 2000 \text{kJ/kg}^°C \times (850 – 25°C) = 1.65 \text{MJ}. Complete moisture evaporation requires 2.6 MJ/kg, while bringing the water to the combustion temperature of 850°C requires another 1.8 MJ/kg (Figure 1). Consequently, the water absorbed energy would be 4.4 MJ/kg \times 4 \text{kg} = 17.6 \text{MJ}. Take 40% excess air, or 7 kg, being fed into the incinerator during sludge combustion. The energy required to heat this air then is 7 kg \times 1320 \text{kJ/kg}^°C \times (850–25°C) = 7.6 \text{MJ}, and the theoretical heat demand becomes (7.6 + 17.6 + 1.7) = 26.9 MJ. Moreover, the energy content in the wastewater sludge then is released to the flue gas during burning. The external heat demand then is (26.9 – 18) = 8.9 MJ/kg-ds. The ash (0.28 kg) was discharged directly to the surroundings, losing residual energy of 0.46 MJ. If the flue gas (at 850°C) was discharged directly to the surroundings, then the entire energy (26.9 – 0.46 = 26.4 MJ) was
lost into entropy. Figure 3 illustrates this process. B is the (entropy generation, net work production) vector. In all cases vector B points toward the lower half of the plane since real applications produce entropy. A vertically downward B indicates no net work production with all available energy being lost to entropy, representing the worst thermal management scenario.

If the flue gas were used in a boiler to produce high-pressure steam at 450°C and 8 MPa ($H = 3.3$ MJ/kg-steam), the minimum temperature for the flue gas leaving the boiler is 450°C. The heat capacities of all components in the flue gas are assumed to be constant. The maximum energy recoverable in the boiler from the flue gas then is $7.5 \times 1,320 \text{ J/kg} \cdot \text{°C} \times (850 - 450) + 1.4 \times (4.4 - 3.3 \text{ MJ/kg}) = 5.6$ MJ. Therefore, the maximum steam yield is $5.6/3.3 = 1.7$ kg. When fed into a turbine, the electricity produced by this steam is reported to be 2.17 MJ, representing an efficiency of 38%, which is a common value for electricity generation. The total loss work thus is $(26.9 - 2.17) = 24.7$ MJ/kg-ds, indicating 8.2% (2.17/26.4) recovery from the flue gas, or 24.3% recovery based on external heat demand (2.17 MJ/8.9 MJ). Consequently, the pre-dryer has a thermal efficiency of around (6.5 + 0.53)/11 = 64%. Although using steam to pre-dry sludge produces no electricity, the lost work is 18 MJ/kg-ds, just 67% of that discussed in the previous electricity-producing scheme. Figure 4 illustrates this situation. Notably, although no net work is produced in this case, entropy generation is lower than in Figure 3, indicating less loss work during processing.

Wet Air Oxidation

Another two thermal treatment processes considered here are the supercritical WAO process at 450°C, 25 MPa, and the “dry” pyrolysis process at the same temperature and atmospheric pressure. The former assumes the sludge to be a 5% w/w suspension, while the later uses a dried cake as the feed.

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**Figure 4.** Enthalpy versus entropy diagram for treatment process using recovered energy to pre-dry sludge for self-sustainable incineration. H: heat exchanger.
Based on one kg dried solids, a sludge of 5% w/w ds contains 19 kg of water. The reactor heats the solids to 450°C by adding sensible heat at 1 kg × 2,000 kJ/kg-°C × (450 − 25°C) = 0.85 MJ. Notably, the H value for water at 450°C and 25 MPa is 3.1MJ/kg-water. Consequently, the enthalpy change for water heating is 19 kg × 3.1MJ/kg = 58.9 MJ. However, if the process could be operated at 550°C and 25 MPa with 10% w/w ds, the corresponding H value is 3.3MJ/kg-water and the heat required for water heating is 9 kg × 3.3 MJ/kg = 29.7 MJ. Assuming the provision of stoichiometric, pure oxygen (approx. one kg O₂), the heat demand is 1kg × 2,000 kJ/kg-°C × (550 − 25°C) = 0.43 MJ or 1kg × 1,020 J/kg-°C × (550 − 25°C) = 0.53 MJ. The theoretical heat demand thus is (0.85 + 58.9 + 0.43) = 60.1 MJ for 5% sludge, or 31.5 MJ for 10% ds sludge. Given complete oxidation, then the external heat demand is (60.1 − 18) = 42.1 MJ/kg-ds for 5% sludge, or 13.4 MJ/kg-ds for 10% sludge. The ash (0.28 kg) was directly discharged to the surroundings with residual energy of 0.46 MJ. If the spent liquor is discharged directly into the surroundings, the loss work is 60.1 or 31.5 MJ. However, if the pressurized water at 25 MPa is throttled isentropically to a high-pressure steam at 8 MPa, the corresponding temperatures of sludge are 400°C and 480°C, respectively. This steam can produce electricity of 24.2 MJ or 12.6 MJ, respectively, assuming 40% conversion efficiency. The total loss work is 35.9 MJ (= 60.1 − 24.2 MJ) or 18.9 MJ (= 31.5 − 12.6 MJ).

Pyrolysis and Digestion

Given pyrolysis process at 450°C and atmospheric pressure, the 20% sludge is fully dehydrated before processing. For one kg of dried solids, vaporizing 4-kg water requires 10.4 MJ, and the sensible heat for solids is estimated as 1 kg × 2,000 kJ/kg-°C × (450 − 25°C) = 0.85 MJ. The sludge absorbed pyrolysis energy, thus yielding pyrolyzed products. Bridle and Mantele [7] demonstrated a net thermal energy output of 7.7 MJ/kg-ds after drying energy was provided. The external heat demand thus is −7.7MJ. If the pyrolyzed product were used as fuel for sludge drying, then assuming 60% efficiency, the energy transfer is 4.6MJ, with a loss work of 3.1 MJ. If these fuels were used for electricity production, the outcome would become 3.1MJ, with loss work of 4.6MJ.

Another energy recovery system that also can be discussed is the anaerobic digestion system, which operates at 35°C with atmospheric pressure. With 50% destruction of organic matter in the 3.5% sludge, the methane yield is roughly 0.23Nm³/kg-ds, corresponding to a heat value of 8.4 MJ/kg-ds. Taking 25°C as the reference state, the energy demand for sludge heating is roughly 1.2 MJ. Consequently, the net thermal output is 7.2 MJ, comparable to the pyrolysis process. If biogas were used to produce electricity, the yield would be 2.9MJ, with loss work of 4.3MJ. However, anaerobic digestion cannot be considered the final disposal option for sludge, and the digested liquor must be treated further.

MINIMIZING ENTROPY PRODUCTION

Not all energy in sludge can be transferred to useful work. The maximum work recoverable from a fluid based on Carnot cycle is bounded by the temperatures of both the hot and cold ends. The theoretical thermal efficiency is \( \eta_{\text{max}} \leq 1 \). For instance, if a reversible cycle is operating between the flue gas from the sludge incinerator (850°C) and the surroundings (25°C) to recover energy, \( \eta_{\text{max}} \geq 73\% \). Moreover, given total energy input Q, then \( W_{\text{max}} = \eta_{\text{max}} Q \) and the loss work is \( (1 − \eta_{\text{max}})Q \). Each process unit has its irreversibility, characterized by its efficiency, \( \eta(1) \). The net work output then becomes \( W_{\text{max}} = \eta_{\text{max}} \eta Q \), and the loss work, \( (1 − \eta_{\text{max}} \eta)Q \), and so on. The above provides some guidelines for minimizing entropy production, as follows: (1) Less work would be lost if the recovered energy was converted by fewer steps to its final form. (For example, producing steam from flue gas and then producing electricity from this steam is a thermodynamically poor option. However, technical difficulties exist in using the flue gas directly for power generation.) (2) More work could be recovered if energy could be extracted from the loss work stream. The post-recovery hot stream also should be recovered if possible. (3) The difference in driving forces in contacting streams should be minimized whenever feasible to reduce external irreversibility. (4) Thermal process unit efficiency should be enhanced whenever possible to reduce internal irreversibility. Where multiple options exist, that with the highest efficiency should be selected. Other guidelines include increasing the heat value of the raw materials, such as appropriate conditioning followed by sufficient dewatering to reduce the moisture content, or using sludge hydrolyzation to remove inorganic compounds.

Table 1 lists the sample calculations conducted in this section. (Note: these processes are not considered to be optimal. Process integration and adopting treatment
units of higher thermal efficiency undoubtedly could improve energy recovery.) Notably, the trend observed differs from that based on electricity production or the heat value of pyrolyzed product. One key concern is external heat input and its recovery. The following trend is noted for the recovery ratio of the external heat input:

<table>
<thead>
<tr>
<th>Process</th>
<th>Inc1</th>
<th>Inc2</th>
<th>SupWAO</th>
<th>SupWAO</th>
<th>Pyrolysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input solids fraction</td>
<td>20%</td>
<td>20%</td>
<td>5%</td>
<td>10%</td>
<td>20%</td>
</tr>
<tr>
<td>P, MPa</td>
<td>0.1</td>
<td>0.1</td>
<td>25</td>
<td>25</td>
<td>0.1</td>
</tr>
<tr>
<td>T, °C</td>
<td>850</td>
<td>850</td>
<td>450</td>
<td>550</td>
<td>450</td>
</tr>
<tr>
<td>External heat input, MJ/kg-ds</td>
<td>8.9</td>
<td>0.0</td>
<td>42.5</td>
<td>13.4</td>
<td>0.0</td>
</tr>
<tr>
<td>Maximum loss work, MJ/kg-ds</td>
<td>26.9</td>
<td>18.0</td>
<td>60.5</td>
<td>31.4</td>
<td>18.0</td>
</tr>
<tr>
<td>Recovered fuel, MJ/kg-ds</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>7.7</td>
</tr>
<tr>
<td>Recovered electricity, MJ/kg-ds</td>
<td>2.17</td>
<td>0.0</td>
<td>24.2</td>
<td>12.6</td>
<td>3.1</td>
</tr>
<tr>
<td>Loss work production if electricity were generated, MJ/kg-ds</td>
<td>24.7</td>
<td>18.0</td>
<td>36.3</td>
<td>18.8</td>
<td>14.9</td>
</tr>
</tbody>
</table>

1Incineration with electricity production (Mininni et al., unpublished results).
2Incineration with sludge pre-drying (Mininni et al., unpublished results).
3Modell and Tester [6].
4Efficiency for electricity production is 40%.
5Bridle and Mantele [7].
6With no electricity production.

Figure 5 schematically illustrates a sludge treatment process involving both power production and pre-heating/drying stages. Regardless of the efficiencies of each operating unit, this process should display a high energy recovery because of point (2) above. The thermal efficiency for sludge drying through indirect heat exchange normally ranges from 55–80%, while that for electricity production using steam is approximately 40%. This observation [point (4)] interprets why sludge pre-drying is more efficient than that involving power generation. (This trend definitely can be reversed when more efficient combined cycles are adopted for power generation, and the heat exchanger is poorly designed and operated.) Nonetheless, we have [8].

\[ W = (Q_f - Q_0) + (\Sigma m_r H_r - \Sigma m_p H_p) \]  

The energy recovery should attempt to maximize \( W \) without at the cost of increased \( Q_f \). Restated, the target should be the recovery of energy content in the sludge, \( (\Sigma m_r H_r - \Sigma m_p H_p) \), during the processing. Inputting a vast amount of energy and only recovering a fraction is not an optimal solution.

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REFERENCES


