**Energy recovery from thermal treatment of dewatered sludge in wastewater treatment plants**

Qingfeng Yang, Karla Dussan, Rory F. D. Monaghan and Xinmin Zhan

**ABSTRACT**

Sewage sludge is a by-product generated from municipal wastewater treatment (WWT) processes. This study examines the conversion of sludge via energy recovery from gasification/combustion for thermal treatment of dewatered sludge. The present analysis is based on a chemical equilibrium model of thermal conversion of previously dewatered sludge with moisture content of 60–80%. Prior to combustion/gasification, sludge is dried to a moisture content of 25–55% by two processes: (1) heat recovered from syngas/flue gas cooling and (2) heat recovered from syngas combustion. The electricity recovered from the combined heat and power process can be reused in syngas cleaning and in the WWT plant. Gas temperature, total heat and electricity recoverable are evaluated using the model. Results show that generation of electricity from dewatered sludge with low moisture content (< 70%) is feasible within a self-sufficient sludge treatment process. Optimal conditions for gasification correspond to an equivalence ratio of 2.3 and dried sludge moisture content of 25%. Net electricity generated from syngas combustion can account for 0.071 kWh/m³ of wastewater treated, which is up to 25.4–28.4% of the WWT plant’s total energy consumption.

**Key words** | energy recovery, gasification, sewage sludge, sludge treatment, thermal treatment, wastewater treatment plant

**INTRODUCTION**

Sludge is the residue produced in municipal wastewater treatment plants (WWTPs). On average, 90 g of dry sludge per person is generated every day from the treatment of urban wastewater (Fytildi & Zabaniotou 2008). Sewage sludge is a moisture-rich material (moisture content, YM > 90%), composed of a volatile carbon fraction, other organic components, including N and S, and inorganic materials (Sawai et al. 2013). Before disposal and transportation, sludge volume should be reduced by thickening, conditioning and dewatering (Metcalfe & Eddy 2014). When YM decreases from 98% to 60%, sludge volume reduces by ≤95%. State-of-the-art dewatering processes can reduce YM to between 60% and 80% (Werther & Ogada 1999; Neyens & Baeyens 2003; Cai et al. 2012; Li et al. 2014).

Dewatered sludge disposal methods include dumping at sea, land-filling, recycling as fertilizer and thermal treatment via combustion, also known as incineration (Werther & Ogada 1999; Stasta et al. 2006; Nipattummakul et al. 2010). The first three methods can lead to environmental problems due to the presence of toxic components and heavy metals in sludge. Sludge dumping to surface waters is prohibited in the European Union since the introduction of the Urban Wastewater Directive 91/271/EEC (EU 1991). Land-filling and recycling as fertilizer are banned or highly restricted in many countries due to concerns over soil and crop contamination (Petersen & Werther 2003). Thermal conversion processes, including combustion and gasification, are promising sludge disposal alternatives that can provide low-carbon energy to the WWTP.

In combustion, sludge is converted to a mixture of high-temperature oxidized gaseous species, known collectively as flue gas, which consists primarily of CO₂, H₂O, O₂ and N₂, as well as inorganic solids, known as ash (if solid) or slag (if molten). Through thermal conversion, waste volume is reduced by 80–90%, organic matter is fully converted to gas, and pathogens are fully eliminated, complying with disposal requirements. Furthermore, energy can be recovered as heat and/or electricity, usually via steam turbines (Marani et al. 2003). Emissions of NOₓ, SOₓ, heavy metals in fly ash and toxic gases such as PCDD/PCDF (chlorinated...
dioxins and dibenzofurans) are the main potential adverse environmental impacts of combustion (Fullana et al. 2004; Mininni et al. 2004; Zhu et al. 2015).

Gasification is a thermochemical conversion process in which oxygen, in air or pure O2, is reacted with sludge at high temperature to generate a synthetic gas (syngas) (Belgiorno et al. 2003) and ash/slag. H2O, present as injected water, steam or sludge moisture content, is also required for gasification. Air-blown sludge gasification usually takes place at atmospheric pressure and temperatures of 700–1,000 °C (Lumley et al. 2014), producing a syngas containing mainly CO, H2 and N2, with heating values of 4–7 MJ/Nm³ (Belgiorno et al. 2003; De Andrés et al. 2011), that can be burned in combined heat and power (CHP) processes (Dogru et al. 2002). Syngas is not an ideal fuel for CHP because of its relatively low heating value compared to natural gas (37 MJ/Nm³) (Williams 2005; Sun et al. 2015). However, diesel engines using dual-fuel injection or de-rated spark ignition engines can be modified to operate with low heating value gaseous fuels (Hagos et al. 2014). Similar to combustion, gasification reduces sludge volume, while it fixes the heavy metal in the ash, trapping toxic compounds (Dogru et al. 2002). Thus, gasification is considered to be a suitable technology for dewatered sludge disposal.

In this study, the technical feasibility of the thermal treatment of previously dewatered sludge by combustion/gasification is evaluated using a chemical equilibrium model. This process involves: (1) a drying stage in which sludge moisture content is reduced from 60–80% to 25–55%; (2) a gasification/combustion stage in which the chemical equilibrium driven by sludge composition and oxygen concentration defines the process temperature and gas composition; and (3) an energy recovery stage consisting of gas cooling and syngas-fuelled CHP. The purpose of the study is to evaluate the process conditions in the gasification/combustion stage, including dewatered and dried sludge moisture contents and sludge–air ratios, which lead to a self-sufficient sludge thermal treatment process, while providing electricity generation on site.

**METHODS**

The proposed self-sufficient thermal treatment process for dewatered sludge is presented in Figure 1. Wastewater enters the WWTP, producing concentrated sludge with a moisture content of $Y_{M,cs} = 94\%$ (Neyens et al. 2004; Wang et al. 2010). The concentrated sludge undergoes dewatering after sulfuric acid hydrolysis pre-treatment to obtain a dewatered sludge moisture content ($Y_{M,dew}$) of 60–80%. Sludge drying is performed to bring dried sludge moisture content ($Y_{M,dry}$) to acceptable ranges for thermal treatment (25–55%). For combustion, extremely low $Y_{M,dry}$ is desirable, while for gasification, which requires H2O, some amount of moisture is required. In order for the thermal treatment process to be energy self-sufficient, this sludge drying stage is performed using two sources of heat: (1) heat recovered from the desuperheating of syngas/flue gas (cooling from process temperature to 373 K) and (2) heat recovered from the combustion of syngas in a CHP system. Due to the fact that the latter source relies on the combustion of syngas, this is only considered for gasification. Besides the heat for sludge drying, the electricity consumption of the syngas cleaning system is also provided by the electricity recovered from the CHP process, to achieve a self-sufficient sludge thermal treatment system. The key step in the thermal
treatment process is the combustion/gasification step. The present work treats combustion and gasification as similar processes that are differentiated by the relative amounts of sludge and air present using an equivalence ratio (ER), which is described in Equation (1). The high-temperature gas produced is cooled (desuperheated) to 373 K, providing energy for sludge drying ($Q_j$). It is then sent for scrubbing to remove sulfurous compounds and other harmful emissions with a required electricity demand of $W_{scrubber}$. It is finally either released to the atmosphere (for combustion flue gas), or combusted in the presence of air in a CHP system (for gasification syngas). Electricity produced from syngas combustion ($W_2$) is supplied to the scrubber ($W_1$) and WWTP ($W_3$), while heat is recovered for sludge drying ($Q_2$).

**Feedstock properties and ER**

The proximate and ultimate analyses and the lower (LHV) and higher heating value (HHV) of dewatered sludge considered for thermal treatment are shown in Table 1 (ECN Phyllis 2).

The amount of air reacted with sludge is quantified by the ER, which is defined as the ratio of the stoichiometric air–fuel mass ratio to the actual air–fuel mass ratio used in the process. Stoichiometric refers to the air–fuel mass ratio such that the minimum amount of air is present to cause full oxidation (combustion) of the fuel. ER can be expressed as:

$$ER = \frac{AF_{stoi}}{AF}$$  \hspace{1cm} (1)

where $AF_{stoi}$ is the stoichiometric air–fuel mass ratio and $AF$ is the actual air–fuel mass ratio. In the present work, we define combustion as occurring at $ER \leq 1$, while gasification takes place when $ER > 1$.

**Mass conservation and chemical equilibrium**

In this model, $C_xH_yO_zN_mS_n$ is the elemental composition of the organic fraction of the sludge. The global sludge combustion/gasification reaction can be expressed as follows:

$$C_xH_yO_zN_mS_n + aH_2SO_4 + b(O_2 + 3.76N_2) + ch_2o = dCO + eCO_2 + fCH_4 + gH_2 + hH_2O + iH_2S + jN_2$$  \hspace{1cm} (2)

where $x, y, z, m, n$ are the mole fractions of the elements defined by the ultimate analysis of the sludge feedstock, and $a$ to $j$ are the stoichiometric coefficients in the global reaction. All the mass balance, chemical equilibrium and energy balance equations are referenced from Higman & Burgt (2011).

Gas product composition is determined assuming that chemical equilibrium is attained. Implicit in this assumption is that sufficient time is allowed to elapse for an equilibrium state to be reached. This is a valid limiting assumption in the case of a well-designed and well-sized thermal treatment system, and is a commonly used first step in process design.

The equilibrium constant $K_P(T)$ can be estimated using the Gibbs free energy of the reaction $\Delta G_R^0(T)$, the reaction temperature ($T$) and the universal gas constant ($R$):

$$K_P(T) = e^{\frac{\Delta G_R^0(T)}{RT}}$$  \hspace{1cm} (3)

For a particular reaction, $\Delta G_R^0(T)$ is determined by the standard-state Gibbs free energy of formation of reactants and products:

$$\Delta G_R^0(T) = \sum_{prod} v_i^0 g_{f_i}^0(T) - \sum_{react} v_i^0 g_{f_i}^0(T)$$  \hspace{1cm} (4)

where $i$ corresponds to species, $g_{f_i}^0(T)$ represents standard-state Gibbs free energy of formation of the pure species at $T$, and $v_i^0$ and $v_i^0$ represent stoichiometric coefficients of products and reactants, respectively. Empirical expressions for the estimation of $g_{f_i}^0(T)$ are taken from the literature and are presented as polynomials of the form shown in

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**Table 1** | Dewatered sludge proximate and ultimate analyses and heating values

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Value</th>
<th>Data range (ECN Phyllis 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture content</td>
<td>wt% a.r.</td>
<td>60.00, 70.00, 80.00</td>
<td></td>
</tr>
<tr>
<td>Ash content</td>
<td>wt% d.b.</td>
<td>35.00</td>
<td>26.15–54.50</td>
</tr>
<tr>
<td>Volatile matter</td>
<td>wt% d.b.</td>
<td>53.50</td>
<td>39.70–74.20</td>
</tr>
<tr>
<td>Fixed carbon</td>
<td>wt% d.b.</td>
<td>11.50</td>
<td>2.10–11.56</td>
</tr>
<tr>
<td>Ultimate analysis</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>wt% d.b.</td>
<td>34.00</td>
<td>23.10–40.75</td>
</tr>
<tr>
<td>H</td>
<td>wt% d.b.</td>
<td>4.90</td>
<td>2.60–5.82</td>
</tr>
<tr>
<td>O</td>
<td>wt% d.b.</td>
<td>20.01</td>
<td>10.01–26.26</td>
</tr>
<tr>
<td>N</td>
<td>wt% d.b.</td>
<td>4.70</td>
<td>1.40–6.22</td>
</tr>
<tr>
<td>S</td>
<td>wt% d.b.</td>
<td>1.30</td>
<td>0.50–2.90</td>
</tr>
<tr>
<td>LHV</td>
<td>MJ/kg d.b.</td>
<td>14.03</td>
<td>6.50–16.53</td>
</tr>
<tr>
<td>HHV</td>
<td>MJ/kg d.b.</td>
<td>15.10</td>
<td>7.20–18.20</td>
</tr>
</tbody>
</table>

a.r.: As received. d.b.: Dry basis.
Equation (5) (Syed Janajreh et al. 2011). The coefficient values \(A\) to \(G\) and the enthalpy of formation \(h_f^0\) at 298 K and 1 atm are tabulated in the literature (Probstein & Hicks 2006).

\[
\hat{g}_{fi}(T) = h_{fi}^0 - AT\ln(T) - BT^2 - \left(\frac{C}{2}\right)T^3 - \left(\frac{D}{3}\right)T^4
+ \left(\frac{E}{2T}\right) + F + GT
\]

(5)

**Energy balance during thermal conversion**

The process is considered to be adiabatic and at constant pressure (1 atm) under steady-state operation. The energy balance for thermal conversion is shown in Equation (6).

\[
\sum_{i=\text{reactants}} y_i \left(h_{fi}^0 + h_{s,i}(T)\right) = \sum_{j=\text{products}} y_j \left(h_{f,j}^0 + h_{s,j}(T)\right)
\]

(6)

where \(y_i, y_j\) are the mass fractions of reactants and products, \(h_{fi}^0, h_{f,j}^0\) are the specific enthalpies of formation of reactants and products, and \(h_{s,i}(T), h_{s,j}(T)\) are the sensible enthalpies at temperature \(T\). The sensible enthalpies \(h_s(T)\) can be estimated as follows:

\[
h_s(T) = \int_{T_0}^{T} C_p,i dT
\]

(7)

where \(C_p,i\) is the specific heat capacity of component \(i\) at \(T\) and it can be determined by empirical expressions as a function of temperature (Shi et al. 1996). Specific heat capacity (Seggiani 1998), latent heat of melting (Vargas et al. 2001) and temperature- and composition-dependent viscosity (Monaghan & Ghoniem 2012a, 2012b) of ash are all considered in this model.

The enthalpy of formation of sludge \(h_{f,\text{sludge}}^0\) can be calculated following the Hess Law (Negi & Anand 1985) for the following overall reaction:

\[
C_xH_yO_zN_mS_n + \left(x + \frac{y}{4} + m + n - \frac{z}{2}\right)O_2
= xCO_2 + \frac{y}{2}H_2O + mNO_2 + nSO_2
\]

(8)

\[
h_{f,\text{sludge}}^0 = x \cdot \Delta h_{f,CO_2} + \frac{y}{2} \cdot \Delta h_{f,H_2O} + m \cdot \Delta h_{f,NO_2}
+ n \cdot \Delta h_{f,SO_2} + \text{LHV}_{\text{sludge}}
\]

(9)

where the \(\Delta h_f\) terms represent the enthalpies of formation of product species, \(\text{LHV}_{\text{sludge}}\) is the known LHV of sludge, and the coefficients \(x, y, m, n\) are defined from mass conservation.

**Cold gas efficiency and energy recovery**

The performance of gasification is often expressed in terms of its cold gas efficiency (CGE):

\[
CGE = \frac{F_{\text{gas}} \times \text{LHV}_{\text{gas}}}{\text{LHV}_{\text{sludge}} + F_{\text{H}_2\text{SO}_4} \times \text{LHV}_{\text{H}_2\text{SO}_4}}
\]

(10)

where \(\text{LHV}_{\text{gas}}\) corresponds to syngas LHV and can be estimated by the LHV of CO, H\(_2\), and CH\(_4\) in the gas (kJ/m\(^3\)) (Basu 2006). \(\text{LHV}_{\text{H}_2\text{SO}_4}\) represents sludge LHV (kJ/kg) and \(\text{H}_2\text{SO}_4\) LHV (0 kJ/kg). \(F_{\text{gas}}\) is syngas volumetric flow rate (m\(^3\)/s), \(F_{\text{sludge}}\) and \(F_{\text{H}_2\text{SO}_4}\) are sludge and \(\text{H}_2\text{SO}_4\) mass flow rates (kg/s).

**RESULTS AND DISCUSSION**

**Flue gas/syngas temperature**

Combustion/gasiﬁcation temperatures below 1,023 K lead to very slow reaction rates, requiring extremely long residence times and impractically large reactors (Manyà et al. 2005; De Andrés et al. 2011). In this study, only operational conditions that lead to gas equilibrium temperatures \(T_{\text{gas}}>1,023\) K are considered. Figure 2 presents \(T_{\text{gas}}\) as a function of \(ER\) and \(Y_{M,\text{dry}}\) during the thermal treatment process. When \(ER=1\) (complete combustion) and \(Y_{M,\text{dry}}=25\%\), \(T_{\text{gas,max}}=1,891\) K, while \(T_{\text{gas,min}}=1,023\) K is attained at \(ER=1.8\) for \(Y_{M,\text{dry}}=45\%\), and at \(ER=2.3\) for \(Y_{M,\text{dry}}=25\%\). Oxidation reactions in combustion are exothermic (heat of reaction, \(\Delta h_R<0\)), providing thermal energy.
required for the endothermic reactions ($\Delta_h^o > 0$) in the gasification process. Table 2 shows the heat of reaction values of key reactions considered. Thus, when $ER \approx 1$ (complete combustion), oxidation reactions predominate and temperature is higher than that observed when $ER > 1$ (gasification). High-moisture sludge contains more liquid water than dry sludge, which must be evaporated prior to thermal treatment. This requires thermal energy that ultimately lowers the sludge, which must be evaporated prior to thermal treatment. This requires thermal energy that ultimately lowers the achieved $T_{\text{gas}}$. In lean combustion ($ER < 1$), even though reaction equilibrium is mainly limited by the sludge feed, excess air leads to lower temperatures due to the presence of large quantities of nitrogen that is mostly chemically inert and serves only to absorb heat.

### Heat and electricity recovery within the self-sufficient sludge thermal treatment process

Thermal energy recovery is accomplished in two stages (Figure 1): (1) the gas desuperheating prior to gas cleaning ($Q_1$); and (2) heat recovery from the syngas-fuelled CHP process ($Q_2$). A heat transfer efficiency of 80% is considered for gas desuperheating. CHP thermal efficiency of 35% based on syngas LHV is assumed for the estimation of $Q_2$ (Lantz 2012). Figure 3 presents the available thermal energy in the syngas ($Q_1 + Q_2$, kJ/kg dry sludge) as a function of $ER$ and $YM_{\text{dry}}$. As previously shown in Figure 2, higher $T_{\text{gas}}$ is achieved for $ER \leq 1$. Consequently, more thermal energy is recovered from the desuperheating of the flue gas ($Q_1 = 7,902$–$9,596$ kJ/kg dry sludge), than from the syngas ($Q_2 = 2,379$–$8,272$ kJ/kg dry sludge). Syngas, however, benefits from the capture of $Q_2$ (418–3,268 kJ/kg dry sludge), which increases its feasibility.

The thermal energy recovered can be compared with the energy required for the drying stage that reduces $YM_{\text{dew}}$ to $YM_{\text{dry}}$. The required drying energy ($Q_{\text{drying}}$) is directly dependent on both $YM_{\text{dew}}$ and $YM_{\text{dry}}$. For example, when $YM_{\text{dew}}$ is 60%, $Q_{\text{drying}} = 1,233$–$3,275$ kJ/kg dry sludge, and when $YM_{\text{dew}}$ is 80%, $Q_{\text{drying}} = 7,664$–$9,757$ kJ/kg dry sludge, with ranges depending on $YM_{\text{dry}}$. Available thermal energy ($Q_1 + Q_2$) and $Q_{\text{drying}}$ are compared via the drying heat ratio ($\theta$), which is defined as follows:

$$\theta = \frac{Q_1 + Q_2}{Q_{\text{drying}}}$$

(11)

When $\theta \geq 1$, $Q_1 + Q_2$ is enough to provide for $Q_{\text{drying}}$, and the sludge drying operation is self-sufficient. Drying heat ratio is shown in Figure 4 as a function of $ER$ and $YM_{\text{dry}}$ with values of $YM_{\text{dew}}$ of 60% (Figure 4(a)) and 70% (Figure 4(b)).

Electricity is recovered from the combustion of syngas in a CHP system. Electrical efficiency of a syngas-fuelled CHP system is assumed at 30% (Lantz 2012). Figure 5 presents the electricity production, also the available electricity for gas scrubbing (kWh/m³ of wastewater treated), attained from a CHP system that uses syngas generated from sludge gasification in a facility of the scale of the Ringsend WWTP in Dublin, Ireland. This plant has a wastewater treatment capacity of 150 Mm³/year and produces on average 17,260 tonnes/year of dry sludge, using sequencing batch reactors as the wastewater treatment process (EPA 2013). As expected from the LHV $\text{syn GAS}$, the maximum electricity generation of 0.090 kWh/m³ wastewater treated is attained when $ER = 2.3$ and $YM_{\text{dry}} = 25%$.

### Table 2 | Chemical reactions and their heats of reaction of importance to combustion and gasification

<table>
<thead>
<tr>
<th>Combustion</th>
<th>Reaction</th>
<th>$\Delta_h^o$ ($\text{kJ/mol}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C + O₂ = CO₂</td>
<td>$-393.77$</td>
<td></td>
</tr>
<tr>
<td>H₂ + ½O₂ = H₂O</td>
<td>$-241.80$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Gasification</th>
<th>Reaction</th>
<th>$\Delta_h^o$ ($\text{kJ/mol}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water-gas reaction C + H₂O = CO + H₂</td>
<td>$+131.38$</td>
<td></td>
</tr>
<tr>
<td>Boudouard reaction CO₂ + C = 2CO</td>
<td>$+172.58$</td>
<td></td>
</tr>
<tr>
<td>Shift reaction CO + H₂O = CO₂ + H₂</td>
<td>$+41.98$</td>
<td></td>
</tr>
</tbody>
</table>

---

*Figure 3 | Heat available for sludge drying ($Q_1 + Q_2$) as a function of $ER$ and moisture content ($YM_{\text{dew}}$).*

*Figure 4 | Heat available for sludge drying ($Q_1 + Q_2$) as a function of $ER$ and moisture content ($YM_{\text{dew}}$).*
The electrical energy recovered can be compared with the electricity required for the syngas cleaning stage. As a conservative estimate of scrubber performance, the required electrical energy for syngas cleaning at a coal-fed gasification plant of 95 kJ/kg (Monaghan et al. 2014) was increased by a factor of two to 186 kJ/kg. The maximum required electricity for scrubbing is therefore 0.067 kWh/m³ of wastewater treated at $ER = 0.5$, $Y_{M,dry} = 55\%$, and is 0.018 kWh/m³ at $ER = 2.3$, $Y_{M,dry} = 25\%$. The available electrical energy ($W$, shown in Figure 5) and $W_{scrubber}$ are compared via the scrubber electricity ratio ($\phi$), which is defined in Equation (12) and shown in Figure 6:

$$\phi = \frac{W}{W_{scrubber}} \quad (12)$$

When $\phi \geq 1$, $W$ is enough to provide for $W_{scrubber}$, and the gas cleaning stage is self-sufficient.

In this study, only operating conditions in which $\theta \geq 1$ and $\phi \geq 1$ are considered suitable for the process. Figures 4 and 6 present $\theta$ and $\phi$ as functions of $ER$ and $Y_{M,dry}$ for two sludge feedstocks ($Y_{M,dew} = 60\%$, 70%) for which both thermal and electrical conversion are feasible. When $Y_{M,dew}$ is low (60%), $\theta$ increases from 1.73 ($ER = 2.3$, $Y_{M,dry} = 25\%$) to 4.89 ($ER = 1.4$, $Y_{M,dry} = 55\%$). However, with the increase of $Y_{M,dew}$, the drying energy required for the process increases and $\theta$ reduces significantly. For $Y_{M,dew} = 70\%$, $\theta$ varies from 1.04 ($ER = 2.3$, $Y_{M,dry} = 25\%$) to 1.80 ($ER = 1.3$, $Y_{M,dry} = 52.5\%$). Scrubber electricity ratio $\phi$ increases from 1.01 ($ER = 1.3$, $Y_{M,dry} = 52.5\%$) to 4.85 ($ER = 2.3$, $Y_{M,dry} = 25\%$) regardless of $Y_{M,dew} = 60\%$ or 70%. For $Y_{M,dew} = 80\%$, the thermal and electrical...
conversion processes are found to be unfeasible with \( \theta < 1 \) and \( \varphi < 1 \).

**Electricity reused in WWTP**

As mentioned above, the maximum electricity generation from the CHP process is 0.090 kWh/m\(^3\) wastewater treated. Net electricity generated from syngas combustion (gross CHP generation minus scrubber electricity consumption) can total 0.071 kWh/m\(^3\) of wastewater treated, as illustrated in Figure 7. Conventional WWTPs consume 0.25–0.28 kWh/m\(^3\) wastewater treated (Metcalf & Eddy 2014), so the proposed system could provide 25.4–28.4% of WWTP electricity, assuming that a dewatered sludge with low \( Y_{M,\text{dew}} \) is produced in the WWTP (\( \leq 70\% \)). As mentioned previously, the generation of electricity through the proposed process becomes unfeasible when a dewatered sludge of \( Y_{M,\text{dew}} = 80\% \) is used, since additional thermal or electrical energy would be required.

**Comparison of model result with existing plants**

In order to evaluate the model, the key results are compared with the data obtained from the demonstration plant in Balingen, Germany, and the pilot plant in Mannheim, Germany. The plant in Balingen, built in 2002, is the first demonstration plant of sludge gasification. Six surrounding wastewater plants deliver their sludge to Balingen for drying and gasification. The pilot plant in Mannheim was subsequently built in 2010 (Judex et al. 2012). As shown in Table 3, the model results (gasification temperature, syngas LHV and CGE) are in ranges similar to those obtained in the two demonstration plants.

<table>
<thead>
<tr>
<th>Model results</th>
<th>Balingen</th>
<th>Mannheim</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Population equivalent</td>
<td>2,50,000</td>
<td>6,00,000</td>
<td>1,700,000</td>
</tr>
<tr>
<td>Throughput (t/a dry solids)</td>
<td>1,955</td>
<td>5,000</td>
<td>17,260</td>
</tr>
<tr>
<td>Gasification temperature (K)</td>
<td>1,123 – 1,173</td>
<td>1,145 K (( ER = 2.1 ), ( Y_{M,\text{dew}} = 70% ), ( Y_{M,\text{dry}} = 25% ))</td>
<td></td>
</tr>
<tr>
<td>Syngas LHV (MJ/Nm(^3))</td>
<td>3.2</td>
<td>4.7</td>
<td>2.9 (( ER = 2.3 ), ( Y_{M,\text{dew}} = 70% ), ( Y_{M,\text{dry}} = 25% ))</td>
</tr>
<tr>
<td>CGE</td>
<td>66%</td>
<td>70%</td>
<td>66.6%</td>
</tr>
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</table>

LHV and CGE are in ranges similar to those obtained in the two demonstration plants.

**CONCLUSIONS**

The present study evaluates the effect of three process variables: (1) moisture content of dewatered sludge (\( Y_{M,\text{dew}} \)), (2) moisture content of dried sludge (\( Y_{M,\text{dry}} \)), and (3) \( ER \), on the performance of a proposed self-sufficient thermal treatment process for wastewater sludge. The impact of these variables on key process performance indicators, including combustion/gasification temperature (\( T_{\text{gas}} \)), the quantities of heat (\( Q_1 + Q_2 \)), net CHP electricity generation (\( W \)) recoverable for use, and the fractions of sludge drying energy (\( \theta \)) and scrubber electricity consumption (\( \varphi \)) that can be provided by the process, are studied. The use of dewatered sludge with low \( Y_{M,\text{dew}} \) (\( \leq 70\% \)) allows for the self-sufficient thermal treatment of sludge to recover both heat and electricity. In this context, processes using sludge materials with high \( Y_{M,\text{dew}} \) (\( \geq 80\% \)) would rely on external heat/electricity sources. \( ERs \) around 2 and low \( Y_{M,\text{dry}} \) (~25%) are preferable when energy recovery as electricity is desired. Under these gasification conditions, the produced syngas can contain up to 2.9 MJ/Nm\(^3\), corresponding to a CGE of 66.6\%. Likewise, the net electricity derived from CHP can account for up to 0.071 kWh/m\(^3\) wastewater treated, providing potentially up to 25.4–28.4% of the energy consumption in a conventional WWTP.

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