YUCHENG CAO*, **, ARTUR PAWŁOWSKI**

ENERGY SUSTAINABILITY OF TWO PARALLEL SEWAGE SLUDGE-TO-ENERGY PATHWAYS: EFFECT OF SLUDGE VOLATILE SOLIDS CONTENT ON NET ENERGY EFFICIENCY

Previously, we conducted a preliminary evaluation on two parallel sewage sludge-to-energy pathways from the perspective of energy conversion efficiency. One pathway combined anaerobic digestion with fast pyrolysis while its counterpart was simplified to only use the pyrolysis. In this study, their energetic performances were evaluated as a function of the volatile solids (VS) content and in terms of net energy efficiency. Both pathways, when used to convert sludge with higher VS content, can achieve higher net energy efficiency. The combined pathway could achieve higher net energy efficiency than the simplified pathway, but its relative advantage is not impressive when converting sludge with low VS content; for example, the difference in normalized net energy production between the two pathways was only 0.76 MJ/kg for sludge with 50% VS content.

1. INTRODUCTION

There are increasing concerns over energy security and climate change. The long-term fossil fuels-based pattern in energy supply, production and consumption resulted in the fossil resources to be exhausted, and the Earth getting warmer. It is urgent to develop and deploy renewable energy as it can provide alternative energy to fossil energy and is believed to be carbon neutral.

Energy recovery from sewage sludge offers an opportunity for sustainable management of sewage sludge and energy [1–3]. Anaerobic digestion (AD) and fast pyrolysis are among the most promising and sustainable processes used to convert sewage sludge to usable energy. In our previous study [4], a preliminary energy efficiency evaluation has been carried out on two parallel sludge-to-energy pathways: a pathway combined AD with fast pyrolysis process (referred to as CP pathway), and a path-

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*School of Environment and Resource, Zhejiang Agricultural and Forestry University, Hangzhou 311300, China; e-mail: Cao.y@wis.pol.lublin.pl

**Faculty of Environmental Engineering, Lublin University of Technology, 20-618 Lublin, Poland.

way that was simplified to exclusively include the pyrolysis process (referred to as SP pathway). Based on a case study on two sludge feedstocks, we observed that the CP pathway can achieve higher energy conversion efficiency compared to the SP pathway but the result indicates the relative advantage strongly depends on volatile solids (VS) content of the sludge feedstock.

In this study, we focus our investigation on the effect of sludge VS content on the net energy efficiency of the pathways. The previous study [4] evaluated the two pathways in terms of energy conversion efficiency, by looking at their potential to convert sewage sludge into usable bioenergy products (biogas and bio-oil). This study expands the investigation to include the energy consumption throughout the process chains such as heat and electricity consumption by sludge drying, AD and pyrolysis operation.

2. TWO PARALLEL SLUDGE-TO-ENERGY PATHWAYS

Figure 1 presents the flowchart of the two parallel pathways for energy recovery from sewage sludge. For the CP pathway, liquid raw sewage sludge (RSS) is fed into the digestion tank for biogas production, simultaneously discharging digestate (anaerobically-digested sludge, ADS); the discharged ADS is processed via dewatering and drying for water removal, and then subjected to pyrolysis to produce bio-oil, biochar and pyrolytic gas (referred to as py-gas). For the SP pathway, the AD process is excluded, while the RSS (after water removal) serves as pyrolysis feedstock to produce bio-oil, biochar and py-gas.
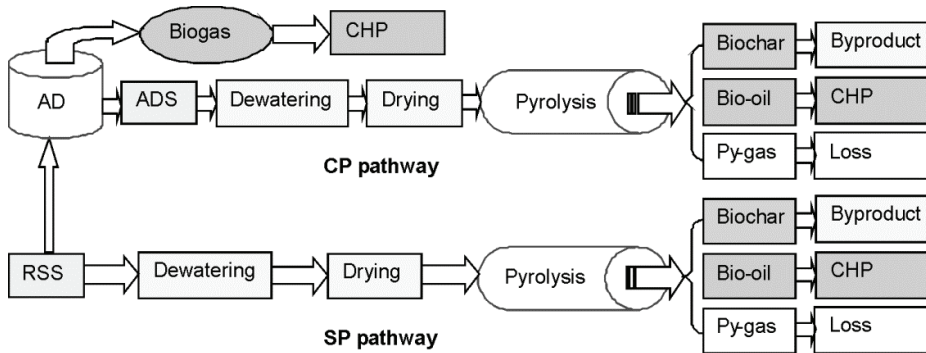

Fig. 1. Flowchart of the two sludge-to-energy pathways:
RSS – raw sewage sludge, ADS – anaerobically digested sludge;
AD – anaerobic digestion; CHP – combined heat and power production

Anaerobic digestion of sewage sludge is commonly operated in the mesophilic (30–38 °C) or thermophilic (50–57 °C) temperature range. The mesophilic digestion

process consistently remains dominant in practical application. Table 1 lists its basic process parameters, which were adopted in this study to model mass and energy output (biogas and digested sludge) from the digestion process, as well as volatile solids content of the digested sludge. Details on the mass and energy balance are presented in Section 3.1.

T a b l e   1

Parameters used for mesophilic digestion

Parameter	Value	Origin
Total solids content of sludge, wt. %	5	[5]
Volatile solids content of sludge, wt. %	50–85	variable
Digestion tank configuration – cylindrical		
Work volume of digestion tank, m^3	1500	calculated
Ratio of diameter to side depth	2: 1	assumed, according to [5]
Ratio of M_{id} depth to side depth	1.2: 1	assumed, according to [5]
Digestion operating		
Solids retention time, d	15	[5]
Process temperature, °C	35	[5]
Volatile solids destruction during digestion, wt. %	56	
Specific biogas production, m^3/kg VS destroyed	1	averaged, according to [6]
Power of sludge mechanical mixing, W/m^3	8	[7]

Sludge pyrolysis can give rise to three products: bio-oil, biochar and py-gas. Their relative energy share achieved from sludge feedstock depends on specific pyrolysis process employed, particularly pyrolysis temperature and heating rate. Fast pyrolysis using a high heating rate (ca. 100 °C/min) and a moderate temperature (450–550 °C) can dominantly distribute sludge energy into bio-oil, which is commonly regarded as a priority energy product; as fossil fuel-based oil is being exhausted while biomass including organic waste is the only source of renewable energy that can produce oil. In this study, fast pyrolysis for bio-oil production was considered. As described in the previous study [4], the py-gas produced is considered energy unrecoverable and as a cause of energy loss, since it has low yield and low energy content. The biochar byproduct is not considered as an energy fuel, but considered to be used as soil amendment and used for carbon sequestration, since it has potential to enhance nutrient bioavailability, immobilize soil contaminants (e.g. heavy metals) and to deposit carbon into soil.

CHP (combined heat and power production) is an integrated energy production system that is fuelled by a single fuel source (such as biogas, natural gas and oil) to produce electricity, and simultaneously to recover heat from the exhaust. Installing CHP at a wastewater treatment pant is particularly feasible given that the electricity and heat produced can be used on-site. For example, the recovered heat can be used to warm the digester and to dry the digested sludge.

3. METHODS

To facilitate calculation, liquid raw sludge subjected to the two parallel pathways (the CP and SP) for energy recovery was assumed to have the flowrate of 100 m^3/d, as discharged from wastewater treatment units. Energy input and output throughout two parallel chains, from sludge pre-treating to the production of bioenergy, and up to heat and electricity cogeneration (CHP), were separately quantified based on mass and energy balance. For the CP pathway combined the AD process with fast pyrolysis, mass and energy output from the AD process associated with biogas and ADS, as well as VS content of the ADS, were calculated according to the VS content of the raw sludge and its reduction level by the AD. The biogas energy output was merged with the bio-oil energy production from the pyrolysis of the ADS remainder to determine the cumulative bioenergy output, and thereby to determine the heat and electricity output from the CHP system. The energy input was determined by taking into account the energy requirement (heat or electricity) for sludge pre-treating (dewatering and drying), AD operation (sludge mixing and heating, and heat loss) and pyrolysis operation (sludge heating, reaction heat and heat loss). Details regarding the mass and energy balance are presented in the subsections.

Two indicators including normalized net energy production (NNEP) and energy ratio (ER) were used to characterize the energetic performance of the sludge-to-energy approaches. The indicators are expressed as

$$ER = \frac{E_p}{E_c} \tag{1}$$

$$NNEP = \frac{E_p - E_c}{M_{sludge}} \tag{2}$$

where E_p (MJ) is the energy production (CHP) of the pathways, which calculated based on the mass yield and calorific value of the bioenergy (bio-oil and biogas by using a CHP energy efficiency of 85%, E_c (MJ) is the total heat and electricity consumption of the sludge-to-energy system, M_{sludge} (kg) are mass weight of pyrolysis feedstock (dry weight). The energy consumption excluded the energy content of feedstock sludge, given at the sludge feedstock can be identified as renewable biomass waste. Therefore, an ER value greater than 1 indicates energy bonus.

3.1. MASS AND ENERGY BALANCE FOR AD PROCESS

The yield of biogas (by volume) produced during AD process, and the amount of the remaining ADS and its VS content were calculated using the method similar to that provided by Metcalf and Eddy [5]. The calculations are formulated as

$$M_{\text{ADS}} = \frac{M_{\text{RSS}}\left(1 - VS_{\text{RSS}}\right)}{1 - VS} \tag{3}$$

$$VS_{\text{ADS}} = \frac{VS_{\text{RSS}}\left(1 - R_{\text{VS-AD}}\right)}{1 - R_{\text{VS-AD}}VS_{\text{RSS}}} \tag{4}$$

$$V_{\text{biogas}} = SBP_{\text{biogas}}M_{\text{RSS}}VS_{\text{RSS}}R_{\text{AD}} \tag{5}$$

where M_{RSS} (kg) and M_{ADS} (kg) are the weights (dry) of the raw sewage sludge (RSS) fed into digester and of the digested sludge (ADS), VS_{ADS} (wt. %) and VS_{RSS} (wt. %) are the VS contents in the ADS and RSS, $R_{\text{VS-AD}}$ (%) is the VS reduction percentage during the AD, V_{biogas} (m³) is the yield of the biogas produced, SBP_{biogas} is the specific biogas production (m³ biogas produced/kg VS degraded).

The weight of biogas obtained was used to calculate the energy output from the AD process. The calculation employed the value of 25.8 MJ/m³ as calorific value of the biogas produced. This value was calculated at standard temperature and pressure, assuming the biogas consists of 35% of CO_2 and 65% of CH_4 (the calorific value of CH_4 is 39.6 MJ/m³).

The energy consumption by the AD process was cumulatively quantified by taking into account (1) electricity demand for sludge mixing, (2) heat requirement to raise the influent sludge to the process temperature, and (3) heat loss through the walls, floor and cover of the digestion reactor. The energy consumption for mixing was calculated using a volume-specific electricity consumption factor of 8 W/m³ [7]. The energy required to heat the influent sludge, $E_{\text{h-AD}}$ (MJ/d), was assessed by

$$E_{\text{h-AD}} = Q_{\text{ls}}\Delta T\left(\text{MF}_{\text{AD-in}}C_{\text{pw}} + \left(1 - \text{MF}_{\text{AD-in}}\right)C_{\text{ps}}\right) \tag{6}$$

where Q_{ls} (kg/d) is the flowrate (as received) of the influent sludge, ΔT is the temperature difference between the temperature of the influent sludge (10 °C) and the process temperature (35 °C), C_{pw} and C_{ps} are the heat capacities of water and solids in sludge, respectively, and $\text{MF}_{\text{AD-in}}$ (wt. %) is the water fraction in the influent sludge. Q_{ls} was calculated based on the assumed flowrate by volume (100 m³/d), and the specific gravity of the influent sludge equal to 1.

The energy requirements to offset heat loss from the digester to the ambience (air, dry and moist earth) through the wall, cover and floor were separately calculated from

$$E_{\text{l-AD}} = UA\left(T_{\text{d}} - T_{\text{a}}\right) \tag{7}$$

where $E_{\text{l-AD}}$ (W) is heat loss from the digester, U (W/(m²·°C)) is the heat transfer coefficient, A (m²) is the surface area of the interfaces where the heat losses occur, T_{d} is the assumed digester temperature (35 °C), and T_{a} is the ambient temperature (°C).

Table 2 presents representative U and T_{a} values used for the calculation of the heat losses. Temperature data at one year scale in the literature [8] were used to estimate

the air temperature (aboveground). The estimation was carried out by averaging the absolute minimum monthly temperatures. A single cylindrical digester was considered to receive the liquid sludge. The wall of the digester was designed to be 1/4 underground.

Table 2

U and T_a values used for calculation of the digester heat loss

Parameter[a]	From digester to aboveground		From digester to underground	
	Cover	Wall	Wall	Floor
U, W/(m²·°C)	1.4 (100 mm thick fixed concrete with insulation)	0.7 (300 mm thick concrete with insulation)	1.0 (concrete surrounded by dry and moist soil)	2.85 (300 mm thick concrete, surrounded by moist soil)
T_a, °C	−7		0	5

[a]U is the heat transfer coefficient, , and the data was adopted from the literature [5]. T_a is the ambient temperature; the aboveground temperature was calculated by averaging absolute minimum monthly temperatures reported by [8], while the rest data were derived from the literature [5].

3.2. ENERGY CONSUMPTION BY SLUDGE PRETREATMENT

The energy requirement for sludge dewatering was calculated by using an empirical value of 144 kJ/kg of sludge (dry matter basis) according to the survey findings reported previously [6]. The dry matter content of sludge after dewatering is assumed to reach 30%. The heat consumption by drying the dewatered sludge was calculated from

$$E_{\text{drying}} = M_{\text{de−s}} WF_{\text{de−s}} \left(C_{\text{pw}} \Delta T + \Delta H_v \right) + \left(M_{\text{de−s}} \left(1 - WF_{\text{de−s}} \right) \right) C_{\text{ps}} \Delta T \tag{8}$$

where E_{drying} (MJ/d) is the energy consumption for sludge drying, $M_{\text{de−s}}$ (kg) is the amount (by wet weight) of the dewatered sludge, $WF_{\text{de−s}}$ (wt. %) is the water fraction in the dewatered sludge, ΔH_v is the latent heat of vaporization of water (2257.9 kJ/kg), C_{pw} is the heat capacity of water, 4.18 kJ/(kg·°C), C_{ps} is the heat capacity of solids in sludge, 1.95 kJ/(kg·°C) [9], and ΔT (°C) is the temperature difference between the temperature of incoming sludge and drying temperature (105 °C). It is assumed that the temperature of incoming sludge was 10 °C. After drying, the dry matter content in sludge was assumed to reach 92%.

3.3. MASS AND ENERGY BALANCE FOR SLUDGE PYROLYSIS

The bio-oil production from the raw sludge (the SP pathway) and from the digested sludge (the CP pathway) was determined by using a mathematical correlation between sludge VS content and bio-oil yield. Details on the correlation are presented in our previous study [4]. Briefly, the correlation, which was established based on the

experimental results of fast pyrolysis of both raw and digested sludge under the uniform pyrolysis conditions, can be expressed as

$$Y_{\text{bio-oil}} = 63.684 \text{VS}_{\text{sludge}} - 11.34 \left(R^2 = 0.9982 \right) \tag{9}$$

where $Y_{\text{bio-oil}}$ is the yield (wt. %) of bio-oil, and $\text{VS}_{\text{sludge}}$ is the volatile solids content of sludge (wt. %). The bio-oils produced were found to have similar calorific values around 37 MJ/kg, regardless of how much VS fraction the feedstock has, as described in the previous study [4]. This value was used as a reference value to calculate the energy yield of bio-oil.

The energy consumption by the pyrolysis was evaluated by taking into account (1) the energy requirement to raise the incoming dried sludge to the final pyrolysis temperature, (2) reaction heat resulting from endothermic pyrolysis processes, and (3) heat loss through pyrolysis reactor. The first item was calculated using

$$E_{\text{h-py}} = M_{\text{py-in}} C_{\text{ps}} \left(T_{\text{end}} - T_{\text{ds}} \right) \tag{10}$$

where $E_{\text{h-py}}$ (MJ/d) is the energy consumption to heat the sludge feedstock in the pyrolyzer, $M_{\text{py-in}}$ (kg/d) is the weight of the dried feedstock fed to pyrolysis, T_{end} is the end pyrolysis temperature (500 °C), and T_{ds} is the feedstock temperature which was considered to be 105 °C, assuming the sludge after drying is instantly fed to the pyrolyzer. The reaction heat for pyrolysis was assumed to be 0.3 MJ/kg [9], while the heat loss during pyrolysis was considered 10% of the sum of $E_{\text{h-py}}$ and the reaction heat.

4. RESULTS AND DISCUSSION

The net energy efficiency of the two parallel sludge-to-energy pathways as a function of VS content of its feedstock is shown in Fig. 2, characterized by energy ratio (ER) and normalized net energy production (NNEP). For comparison, it was assumed that the weight of dry matter of sludge feedstock remains constant while the relative content of VS fractions ranges from 50–85%, and that the VS reduction by the AD process has a uniform level (56%). To facilitate discussion, normalized energy consumption (NEC) and production (NEP) varying with the VS content were also plotted for the two pathways (Fig. 3). The NEC and NEP were calculated by dividing the total energy consumption and total energy production, respectively, by the weight of the sludge feedstock (dry).

4.1. EFFECT OF VS CONTENT OF SLUDGE: THE CP PATHWAY

As shown in Fig. 2, the CP pathway experienced a gradual increase in the ER and NNEP with the increasing sludge VS content. This indicates that the energy recovery

from a higher VS content of sludge feedstock is not only more energy beneficial but also more energy efficient. Figure 2 also shows that if sewage sludge contains volatile fractions higher than 55%, the approach via the CP pathway to energy recovery from the sludge can achieve appreciable positive net energy yield. In developed countries, raw sewage sludge produced from wastewater treatment plants commonly has VS fractions ranging from 65–80%. In such cases, a substantial energy benefit can be achievable from sludge with the application of the CP option.
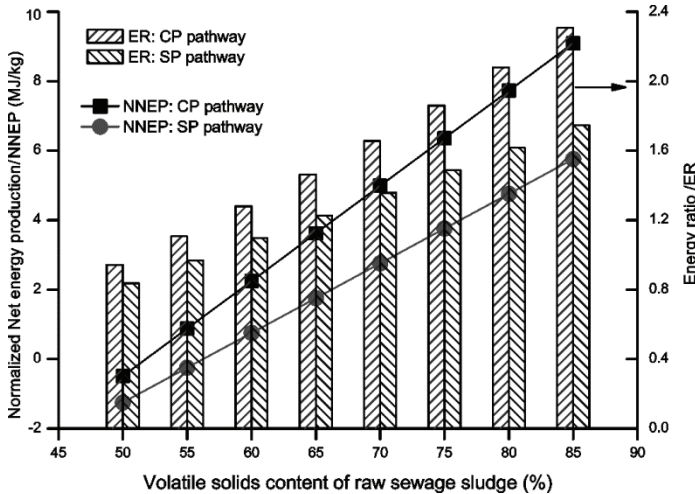

Fig. 2. Net energy efficiency in function of volatile solids content in raw sewage sludge
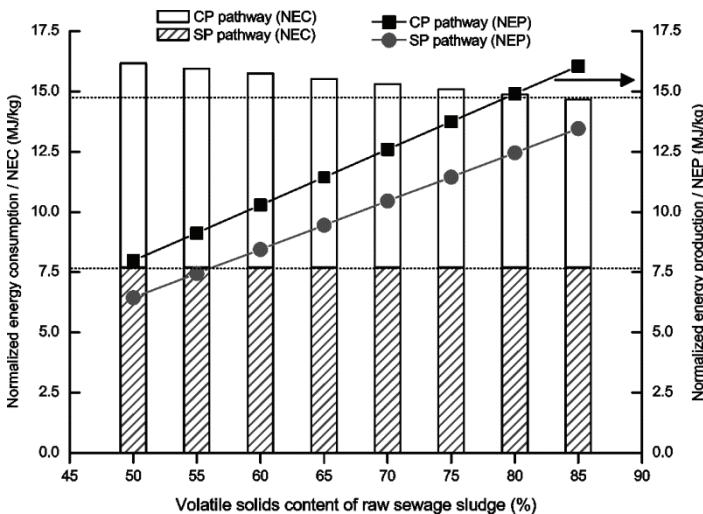

Fig. 3. Normalized energy consumption and production
as a function of volatile solids content in raw sewage sludge

On the other hand, the result similarly indicates that, if sludge feedstock contains low content of VS, its energy recovery potential and efficiency could be low and even passive. As shown in Fig. 2, the CP pathway gave NNEP values below zero and ER values below 1 with respect to the sludge VS content lower than 50%, indicating that the net energy yield (energy production minus energy consumption) was negative. It should be noted that these results and discussion do not argue against the approach to extract energy from sludge with a low VS content, given the facts that sewage sludge itself generally requires a series of energy-consuming processing such as dewatering, aerobic stabilization and drying, and that conventional sludge disposal methods (e.g. landfill and land spread) pose risks to the environment and public health.

As indicated in Fig. 3, the achievement that the energy recovery from sludge with higher VS content is more energy efficient was not only because it produced more energy, but also because it consumed less energy. The underlying reason for the less energy consumption is that, with an identical VS reduction level, the AD process fed with higher VS content of sludge can discharge less mass amount of ADS, contributing to more energy savings associated with the subsequent sludge processing such as sludge dewatering and drying.

4.2. EFFECT OF VS CONTENT OF SLUDGE: THE SP PATHWAY

Similarly to the CP pathway, the net energy efficiency of the SP pathway also strongly depends on VS content of the sludge feedstock (Fig. 2), exhibiting an incremental trend with the increasing VS value. The total energy consumption consistently remained unaltered with varying VS content of the sludge, with an identical NEC value of 7.7 MJ/kg (Fig. 3). Therefore, the consequence that converting sludge containing more VS matter had higher net energy efficiency is totally attributed to that the conversion yielded more energy, instead of requiring less energy input. On the other hand, when the VS content is lower than 55%, the SP pathway used for energy recovery from sludge cannot achieve positive net energy yield (see Fig. 2), as a result of more energy consumed than produced (see Fig. 3).

Except for the bioenergy product (bio-oil), the sludge-to-energy pathway can form another useful product, biochar. The VS content of the feedstock also has a significant effect on yield and energy content of the biochar, as described in the previous study [4]. It is worth noting that, the biochar derived from sewage sludge has been found to have several benefits such as soil quality improvement, crop yield increase and carbon sequestration [10, 11]. The potential benefits from the biochar byproduct increase the feasibility and applicability of the sludge-to-energy approach. It should be mentioned that unlike plant-biomass derived biochar, sludge biochar more or less contains heavy metals, raising the concern about its risk to the environment and human health if applied into land [12]. However, this does not necessarily suggest that sludge biochar cannot used as soil amendment, when considering the facts that (1) heavy metals re-

tained in sludge biochar are highly stabilized [13], (2) the potential risk to the environment and human health by soil application of sludge biochar is much lower compared to the currently dominant sludge treatment methods (landfilling and direct agricultural utilization).

4.3. EFFECT OF VS CONTENT OF SLUDGE: THE CP PATHWAY VERSUS THE SP PATHWAY

As shown in Figure 2, the CP pathway consistently achieved higher net energy efficiency than the SP pathway in the case of converting sludge feedstock with VS content ranging from 50% to 85%. Furthermore, the CP approach grew faster in net energy efficiency with the increase of the VS content, as compared to the SP approach. For example, the difference in the NNEP between the two pathways was 0.76MJ/kg for the VS content of 50%, but was increased to 3.34 MJ/kg when the VS content increased to 85%.

Figure 2 also shows that, when converting sludge feedstock with low VS content, the energetic superiority of the CP pathway over the SP was not impressive and even overturned, as extrapolated from Fig. 2. Such consequence, as seen from Fig. 3, is attributable to that the CP pathway consumes more energy than the SP pathway, rather than the SP pathway could yield more bioenergy. It should be noted that the current study assumed that the VS removal by the AD is 56% for all sludge feedstocks with different VS contents. In practice, however, sewage sludge with low VS content generally has poor biodegradability, and its achievement for a desirable VS removal by the AD (e.g. 56% in the current study) requires longer sludge retention time, indicating more energy requirement for the AD operation (sludge heating and heat loss). Therefore, the SP option that is based on an exclusive pyrolysis appears to be energy competitive for energy extraction from sludge with relative low VS content. In developing countries, particularly in China, the organic matter fraction of undigested sludge (primary or waste activated sludge) from municipal wastewater treatment plants is rather low, typically below 50% [14]. In such cases, the commercialized application of the SP pathway could be especially potential.

5. CONCLUSIONS

The net energy efficiencies of two sewage sludge-to-energy pathways were evaluated as a function of sludge VS content. The two pathways evaluated are a pathway combined anaerobic digestion with fast pyrolysis, and a simplified pathway that only relies on the pyrolysis process for energy conversion. The target bioenergy products are biogas from AD process and bio-oil from pyrolysis process.

The results show that higher net energy efficiency can be achieved for both pathways when converting sludge feedstock containing higher VS matter. The combined

pathway can consistently achieve higher net energy efficiency than the simplified pathway with regard to the sludge feedstock with VS content ranging from 50% to 85%, and its energetic relative advantage is enlarged with the increase of the sludge VS content. However, the results also indicate that the difference in energetic performance between the two pathways tends to inappreciable, when sewage sludge with VS content lower than 55%.

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