MASS BALANCE AND ENERGY ANALYSIS OF A WASTEWATER SLUDGE ANAEROBIC DIGESTION SYSTEM FOR ENERGY RECOVERY

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***Summary**: In wastewater treatment plant (WWTP), energy optimization is a big concern whilst sludge stabilization and energy recovery by anaerobic digestion implementation have recently gained importance. The mass balance and energy balance calculations in a case study of the urban district of Long Bien, Hanoi city with 352,000 populations showed that from 0 to 42.1% of total energy of 39,750kWh per day required for WWTP operation could be supplied from biogas production depending on application of anaerobic digestion process for sewage sludge treatment. The mesophylic anaerobic digestion at the studied WWTP with a capacity of 75,000m^3/day could generate 3,710m^3/day of biogas, equal to 8,394kWh of power and 13,919kWh of heat per day. In the other scenario, a conventional treatment process with centrifugal dewatering and dumping of sludge at landfill required 1,309kWh of energy per day for sludge treatment and disposal while total energy requirement for the WWTP was 41,051kWh/day. The results from this case study demonstrated the potential application of anaerobic digestion for sewage sludge treatment and energy recovery which could bring more benefits than conventional sewage sludge treatment options.*

***Keywords**: Anaerobic digestion; biogas; energy; resource recovery sewage sludge treatment .*

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1. Introduction

Energy consumption in wastewater treatment plant (WWTP) depends on various factors (i.e. size, design and operation of the plant; the characteristics of wastewater; and other local aspects); but it is generally estimated at 108,000 - 216,000kJ/person per year [1]. Recently, municipal wastewater is being looked at more as a renewable resource that can recover energy than as a waste [2]. The optimization of energy at WWTP is now widely implemented in developed countries. In this respect, anaerobic digestion has shown its efficacy on conversion of waste to energy [3]. Several researchers have pointed out that anaerobic digestion for stabilization of sludge generated at WWTPs can produce biogas which can be used as fuel for thermal energy and power generation and by this way part of energy demand in the wastewater treatment plants can be met, but the target of energy self-sufficiency hardly achievable [4]. In Vietnam, around 17% of urban wastewater is centrally treated, where most of sewage sludge is currently being treated by conventional method (dewatering followed by dumping), requiring high energy consumptions (adapted from [5]). Applying anaerobic digestion of sewage sludge can be a potential solution to minimize amount of waste dumped in landfills, increase biogas production, optimize the utilization of built urban engineering infrastructure components, and, hence, increase economic and environmental efficiency of the waste management systems.

In perspective of potentially applicable waste management approach, Long Bien - a Hanoi urban district has been selected as a case study. The investigation site has geographical boundary relatively separated from other districts and can represent a typical fast growing urban area. The objective of this study is to demonstrate the potential benefits of anaerobic digestion as a sewage sludge treatment option in terms of energy recovery compared with conventional dewatering and dumping sludge treatment option.

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2. Materials and Methods

2.1 Study site description and sludge management solutions as scenarios

In this research, Long Bien - an urban district of Hanoi was investigated for a sewage sludge (sludge generated at WWTP) management solution. As forecast up to 2030, the study site has a total area of 6,038.24 ha, with approximately 352,000 people of population and besides living areas; the land use plan has 157.87 ha for public and service purposes, 341.53 ha for industrial zones, handicraft villages, and reserve lands [6]. The current sewerage and drainage system in Long Bien district was combined sewerage system.

Estimating about 80% of urban wastewater and 100% of industrial wastewater would be collected, the capacity of WWTP in Long Bien district was calculated as 75,000m^3/day. Wastewater was being treated in primary, secondary and tertiary steps for solids, organics and nutrients removal aiming at achieving Vietnamese effluent standard QCVN 40:2011/BTNMT [7]. Calculation of sludge production in each step followed was mentioned in Vietnamese Drainage and Sewerage System Design Standard TCVN 7957:2008 and it was resulted in about 630.35 tons/day [8]. Two scenarios were proposed for sludge treatment. In scenario 1, sludge was digested in mesophylic anaerobic reactor. Digested sludge was dewatered and then dried using heat from collected biogas. Dried sludge was finally brought to incineration outside the treatment complex. Incineration residue as ash would be utilized for making construction materials (bricks…). In scenario 2, sludge was dewatered by centrifuge and after that, dumped at the city's landfill.

2.2 STAN application for the mass balance calculation

STAN (subSTance flow Analysis) software was applied to model mass balance and energy analysis of the case study. This tool performs material flow analysis according to the Austrian standard S 2096 (Material flow analysis - Application in waste management) [9]. After building a graphical model with predefined components (i.e. processes, flows, system boundary, text fields), the known data (i.e. mass flows, stocks, concentrations, transfer coefficients) for different layers (i.e. mass, energy) and periods would be inserted for further calculations.

2.3 Energy calculations

In both scenario 1 and scenario 2, energy demand for wastewater treatment plant was calculated as given in equation (1) [10]:

$$E_{WWTP} = Q.e_{wwtp}, \quad kWh/day \tag{1}$$

in which, Q is capacity of WWTP (as calculated of 75,000 m^3/day) and e_{wwtp} is unit energy demand for WWTP; value of 0.4 kWh/m^3 [10].

2.3.1 Energy calculation for mesophylic anaerobic digestion (in scenario 1)

In scenario 1, energy demand (E_{input}) of the mesophylic anaerobic digestion system was for pumping, grinding, stirring, as demonstrated in equations from (2) to (6). Heat exchanger was used to utilize heat of the outflow sludge for temperature increasing of the inlet sludge [10, 11, 12, and 13].

$$E_{input} = E_{electricityin} + E_{sludgeheat} \tag{2}$$

$$E_{electricityin} = E_{pumping} + E_{stirring} \tag{3}$$

$$E_{pumping} = Q.\theta \tag{4}$$

$$E_{stirring} = V.\omega \tag{5}$$

$$E_{sludge\ heat} = Q.\rho.\gamma.(T_d - T_{SS}).(1-\varphi).(1+\epsilon) \tag{6}$$

Energy generation (output) was the amount produced from the anaerobic fermentation system including both heat and electricity of Combined Heat and Power (CHP) from burning biogas, was calculated in equation (7) and (8). In sum, the energy (E) produced from the system was expressed in equation (9).

$$E_{output} = E_{electricityCHP} + E_{heatCHP} \tag{7}$$

$$E_{output} = P_B.V.\alpha.\pi + P_B.V.\alpha.\beta \tag{8}$$

$$E_{surplus} = E_{output} - E_{input} \tag{9}$$

The meanings and values of the symbols in equations from (1) to (8) are indicated in Table 1.

Table 1. *Meanings and values of coefficients used in energy calculations*

Symbols	Meanings	Values	Source
E_i	Energy consumption for process of i, kJ/day	-	Calculated by authors based on equation (2) to (9)
Q	Flow of the inlet sludge flow, m^3/day	630.65	Calculated by authors based on TCVN 7957:2008
θ	Electricity for pumping, kJ/m^3 unit of tank/day	1.8×10^3	Lu et al., 2008
V	Working volume of the digesters, m^3	9,460	Calculated by authors based on TCVN 7957:2008
ω	Electricity for stirring, kJ/m^3	3.10^2	Lu et al., 2008
ρ	Specific weight of sludge, kg/m^3	1,000	Metcalf and Eddy, 1991
γ	Specific heat capacity of sludge, kJ/kg.^{o}C	4.18	Metcalf and Eddy, 1991
T_d	Temperature of digester, ^{o}C	20	Assumed
T_{SS}	Temperature of the inlet sludge, ^{o}C	37	Mesophylic condition
φ	Heat recovery ratio from the outflow and the inflow through heat exchanger	0.85	Lu et al., 2008
∈	Heat loss ratio	0.08	Lu et al., 2008
P_B	Biogas yield, m^3 biogas/ m^3 digester/day	3,710	Calculated by authors based on [10]
α	Heat energy of biogas, kJ/ m^3 biogas	23,270	Metcalf and Eddy, 1991
π	Efficiency of electrical generation of CHP	0.35	Astal et al., 2012
β	Efficiency of thermal generation of CHP	0.55	Astal et al., 2012

2.3.2 Energy calculation for scenario 2, with sludge dewatering and dumping

In scenario 2, energy consumption for sludge treatment processes such as pumping, stirring, and dewatering and transportation was calculated as provided in Table 2 [10, 11, 12, and 13].

Table 2. *Calculations of energy requirements in scenario 2*

Parameters	Equations	Unit	Values	Source
Energy demand for a process "i"	$E_{pumping} = \Sigma$ Q.θ; $E_{stirring} = \Sigma$ V.ω	kJ/day	-	See equations (3) and (4)
Energy demand for recycling	E re =3600*(e-re *Σm-w)/ρ; e-re is electricity for recycling, W/m^3; m-w is recycled water mass, tons/day	kJ/day	- 15 565.14	Calculated based on ATV-DVWK 368; Calculated based on [10]
Energy demand for transportation	E_{trans} =3600* (e_{diesel} * m_{cen})/ρ; e_{diesel} is energy of diesel engine, kWh/tons; m_{cen} is dewatered sludge mass, tons/day	kJ/day	0.4 188.03	Calculated based on [10]; Calculated based on [10]
Energy demand	E = ($E_{pumping}$+$E_{stirring}$+E_{re} + E_{trans})/3600	kWh/day	-	Calculated

3. Results and Discussions

3.1 Mass balance calculation

Figures 1a and 1b show the results of mass balance calculation for the sludge treatment processes in scenario 1 and scenario 2, respectively. The results shown the mass flows analysis of two systems based on the STAN software.

Biogas yield from anaerobic digestion (scenario 1) was about 3,710m^3/day; in addition, 25.2tons of solids and 90.6tons of liquid per day was produced (as seen in Figure 1a). In scenario 2, it was required to supplement about 0.15tons of polymers and 37.64m^3 of air per day in order to treat 630.65tons of sludge per day; resulting in 75.2tons of dewatered sludge per day and releasing 555.43tons of liquid per day. In anaerobic digestion, less amount of both solid and liquid phases were produced than in dewatering and dumping. Since anaerobic digestion produced biogas, it therefore gave chance for energy recovery.

3.2 Energy analysis

The energy consumption and energy generation (in forms of heat and electricity) in two scenarios are shown in Table 3.

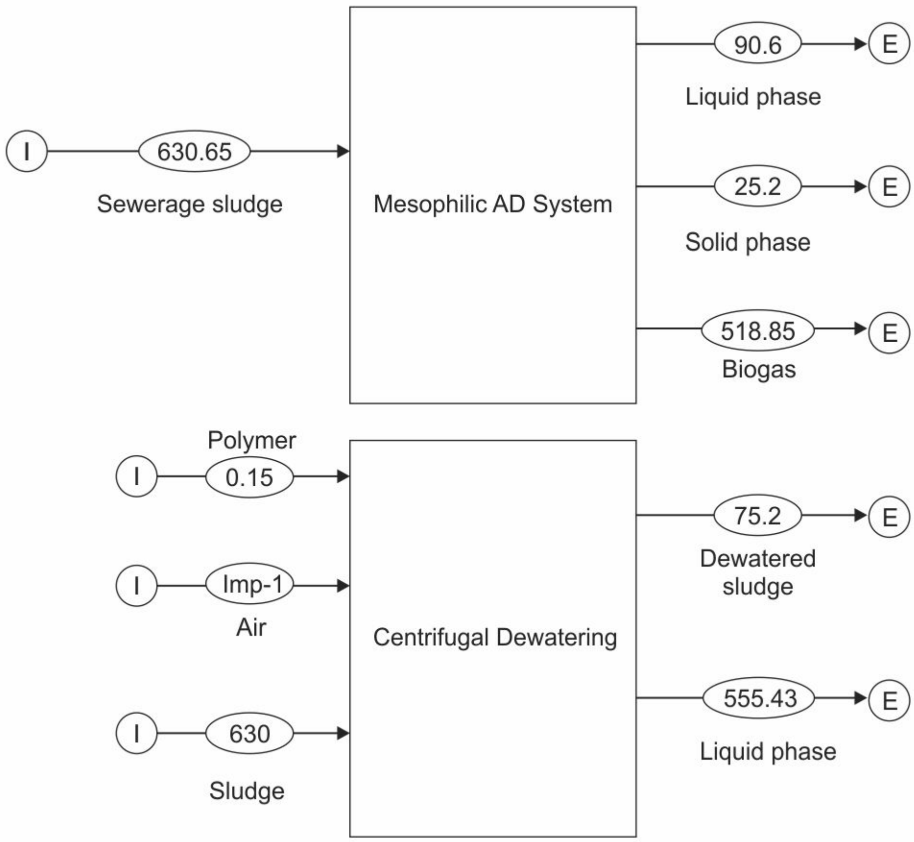

Figure 1. *Mass balance calculations (unit: tons/day; I: input; E: output)*
a) Scenario 1, with anaerobic digestion; b) Scenario 2, with sludge dewatering and dumping

Table 3. *Energy analysis for 2 scenarios*

No.	Parameters	Anaerobic digestion	Dewatering + dumping
1	Sludge loading (tons/day)	630.65	630.65
2	Surplus energy from AD system (kWh/day) - I	17,267	-
2.1	Energy demand (kWh/day)	4,318	1,309
2.2.1	Electricity generation from CHP (kWh/day)	8,394	-
2.2.2	Heat generation from CHP (kWh/day)	13,191	-
2.2	Total energy generation from CHP (kWh/day)	21,585	-
3	Energy demand for WWTP (kWh/day) - II	39,750	39,750
4	Energy demand for heat drying (kWh/day) - III	1,031	-
5	Energy demand for water circulation (kWh/day) - IV	1.667	-
6	Energy demand for sludge transportation (kWh/day) - V	235	
7	Energy balance in treatment complex (kWh/day) (EB = $\Sigma E_{surplus} - \Sigma E_{consumption}$) = I – (II + III + IV + V)	-23,752	-41,051
8	Energy recovery ratio (%) (RR = ($\Sigma E_{surplus} : \Sigma E_{consumption}$) = I / (II + III + IV + V)	42.1	0

With a biogas production as 3,710m^3/day (Table 1) from treatment of 630.65tons of sewerage sludge per day, energy generation from CHP in scenario 1 was 21,585kWh/day, including 8,394kWh power and 13,919kWh heat. At the same time, about 4,308kWh/day of power consumption was required for anaerobic digestion system. The surplus energy obtained was therefore 17,267kWh/day. The energy consumption for heat drying of digested sludge was 1,031kWh/day, for water recycling was 1.667kWh/day and for sludge transportation was 235 kWh/day. Since the total energy required for WWTP (capacity of 75,000m^3/day) was 39,750kWh/day, thus, the energy balance in treatment complex was -23,752 kWh/day. That mean about 42.1% energy demand could be self-supplied. In case of further utilization of dried sludge as fuel, an additional energy would be further gained.

In the scenario 2, centrifugal dewatering of sludge required energy consumption of 1,309kWh/day, while a total energy requirements for the wastewater treatment plant was up to 41,051kWh/day (Table 3) with non-recovery ratio of energy. The results hence demonstrate the clear benefits of anaerobic digestion, dewatering, heat drying and incineration compared to dewatering and dumping.

4. Conclusions and recommendations

The analysis of two scenarios of sewage sludge treatment in the case study of Long Bien district, Hanoi city has shown the benefits in energy efficiency of a solution with mesophylic anaerobic digestion, thanks to yield of generated biogas as energy source. With application of heat exchanger for feeding sludge heating and CHP unit, the recovered energy from 15-day retention anaerobic digester in this scenario could self-supply about 42.10% of total energy required for the whole wastewater and sludge treatment plant needs. The digested sludge after anaerobic reactor could be further utilized for soil application or energy generation as fuel. Ash (from incineration) could be used for production of construction materials. The liquid phase could be further treated at the wastewater treatment plant for final discharge, or reused as a liquid fertilizer in suitable farms.

Self-sufficient energy at wastewater treatment plant could be potentially achieved thanks to enhancing energy recovery options: 1) co-treatment of sewage sludge with other organic waste fractions, such as septic tank sludge, food waste, market waste, selected industrial wastes...; 2) pre-treatment of sludge before anaerobic digestion; and 3) energy recovery from sludge incineration. These options are being further studied in the Laboratory by the authors.

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