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Producing Bio-electricity and Bio-heat from Urban Sewage Sludge in Turkey Using a Two-Stage Process

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***Abstract*—This study investigates the bio-electricity and bio-heat production potential of an urban wastewater treatment plant using biogas-engine powered cogeneration system and fluidized bed sewage sludge incineration system operating data. The facilities of the Gaziantep Metropolitan Municipality Central Wastewater Treatment Plant were used as case studies. The operating data of the plants was analyzed to perform thermodynamically qualitative and quantitative assessments of the energy recovery potential. Wastewater treatment plant digests 68.26 kg of sludge with a dry matter content of 8.0% for each 1 m^3 of biogas. The annual production of the cogeneration plant is 8.760 GWh, which corresponds to an annual biogas consumption of 3,400,000 m^3. For each 1 kWh of electricity produced in the biogas-engine, 0.387 m^3 of biogas with a methane content of 60% is consumed. The average energy produced in the fluidized bed sludge incineration plant is 10,240,000 kcal/hour in the winter and 7,700,000 kcal/hour in the summer. On the other hand, the average energy consumed in the incineration plant 4,900,000 kcal/hour in the winter and 4,800,000 kcal/hour in the summer.**

Keywords—bio-electricity, bio-heat, biogas-engine powered cogeneration, fluidized bed sewage sludge incineration, sewage sludge

I. INTRODUCTION

Sewage sludge is a byproduct of domestic/urban wastewater treatment plants. This is especially true considering that it is an excellent resource for biogas production. However, since the stages of treatment including the treatment of wastewater and stabilization of sludge after discharge into a receiving body are resource-intensive, sewage sludge is regarded as a nuisance that must be disposed of by treatment plant managements. When the first author of this paper attempted to assess the energy recovery potential of urban wastewater for a national research project [1] conducted between 2010 and 2012, the peer reviewers of an international scientific journal began their review of the author's submission by commending their courage to make thermodynamic and thermoeconomic analyses of such an extensive system [2]. It is true that a wastewater treatment plant is a tough choice for a researcher with preposterous physical conditions and severe odor and hygiene issues. Regardless, they are an attractive and radical offshoot of the renewable energy concept because of their intensive energy consumption and possibilities for energy recovery.

Wastewater sludge is rich in organic matter and is therefore usually called biomass. One reason that the interest in energy recovery form sewage sludge has been increasing worldwide over the last twenty years is the necessity of disposing of sludge outside the treatment plant; as it will be rightly assumed, disposal consumes vast amounts of energy and brings a litany of environmental issues. Spreading sludge over agricultural soil or creating landfills with sludge cause seepage into subterranean waters and emission of waste gas, which pollute water resources and the air. It is also known that spreading sludge over agricultural soil disrupts the properties of the soil due to the contaminants in the sludge. As such, sewage sludge management needs to focus on two issues in the medium and long term: (i) developing conditioning methods that will enable the sludge to be used directly while reducing or eliminating harmful active materials at an acceptable cost; (ii) building energy recovery systems that will solve sludge issues once and for all (biogas production followed by incineration).

A survey of recent studies included in open scientific literature shows that most studies on the disposal of sewage sludge, a beneficial byproduct of wastewater treatment plants, focus on energy recovery from sludge [3-7]. The stabilization of wastewater sludge in anaerobic digestion tanks at varying temperature ranges, methane enrichment and purification of biogas produced, optimization of anaerobic digestion systems for increasing total biogas production, and the energy recovery potential of sludge drying, and incineration systems have been discussed in a reasonable number of studies.

This paper will deal with two interdependent systems in terms of sludge energy recovery potential: (1) the digestion of sludge in an anaerobic (oxygen-free) environment and the use of the resulting biogas for producing bio-electricity and bio-heat in a gas-powered cogeneration system; (2) exploring the energy recovery potential of the complete disposal of sewage sludge in a fluidized bed incinerator. The actual systems that the paper examines are two separate public facilities that are part of the urban wastewater treatment plant currently in operation in Gaziantep. The purpose of the study is to make a comprehensive analysis of the potential for sustainable power production based on water treated and sludge produced in the existing wastewater treatment plants in Turkey. Although there are extensive reviews and analyses of Turkey's renewable energy potential, the specific position and importance of sewage sludge in this equation is poorly studied due to both the complex structure of existing facilities that pose challenges to detailed data analysis, and to the amount of

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time lost as municipalities in Turkey have only recently stopped focusing on the treatment of water, and discovered that sewage sludge is a continuous and renewable source of energy. This is the leading motive for the present study. The authors hope that the paper will be a starting point for local administrations and particularly researchers of energy from waste for making use of Turkey's sewage sludge potential, which is admitted having an irreplaceable position in Turkey's energy policy.

II. THE STATE OF SEWAGE SLUDGE IN TURKEY

According to 2017 Turkish Statistics Institute data, out of the 4.5 billion m^3 of wastewater discharged from sewage systems, 3.85 billion m^3 was treated in municipal treatment systems. Advanced treatment was performed on 44.5 of the treated water, followed by 31.6% biological treatment, 23.6% physical treatment, and 0.4% natural treatment. Although wastewater treatment plants have precise data for wastewater, there is no systematic regarding sewage sludge, so production data is limited. With over 40 wastewater treatment plants and a population exceeding 15 million, Istanbul is the largest producer of sewage sludge. It is estimated that the amount of sludge produced in WWTPs in Istanbul will exceed 160,000 tons by 2020 [8]. Nevertheless, there is significant sludge production in other cities as well. Plants in Ankara, Eskişehir, Bursa, Adana, Gaziantep and Antalya produce over 200 tons of wet sewage sludge every day. Although the approximate sewage sludge production capacities of wastewater treatment plants are known, there is yet no extensive inventory of the amounts and properties of sludge produced. Therefore, priority objectives should be establishing regional sewage sludge inventories, preparing archives of volumetric and quality properties, and determining suitable alternatives for disposal and energy recovery. The most extensive method used for sludge disposal in Turkey remains sanitary landfilling. This is followed by comparatively advanced methods such as incineration in energy-intensive cement factories, and traditional methods like spreading on agricultural soil or using as landfill.

This study provides the procedure for energy recovery from sewage sludge in a dual-stage process. This is based on the process of sludge from production to incineration at the Gaziantep Metropolitan Municipality Central Wastewater Treatment Plant (see Fig. 1), and the energy recovery potential provided by this process. The thermodynamic, thermoeconomic and environmental assessments of the first stage, namely anaerobic digestion and biogas engine-powered cogeneration systems, were previously published in scientific journals.

III. THERMODYNAMIC ANALYSIS OF BIOGAS AND BIO-ELECTRICITY PRODUCTIONS IN WASTEWATER TREATMENT PLANT

The total exergy of active sludge at entry into sludge digestion reactors is calculated at 8.1 MW. The solid matter content of active sludge is calculated to be 5.0% at reactor entry. During anaerobic digestion, solid matter content increases to 8.0%, which brings the total exergy of digested sludge upon exiting secondary digestion reactors to 11.3 MW.

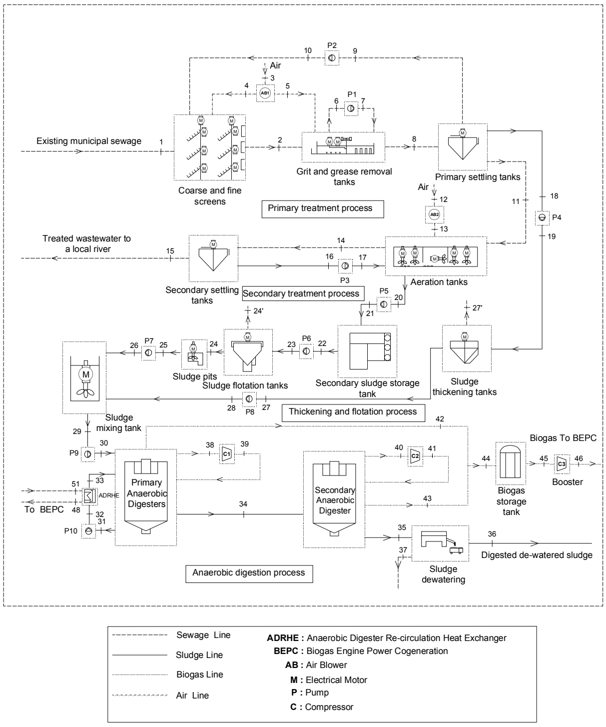

Fig. 1. GASKI Wastewater Treatment Plant Process Flowchart

Digested sludge left at the end of biogas production is conveyed to the dewatering unit from the reactors, where the sludge is dewatered until solid matter content becomes 22.0%. Following mechanical dewatering, which is the final process applied to digested sludge, its mass flow rate drops as low as 2.48 kg/s. This partially-dried sludge with a low mass flow rate is called "sludge cake", which has a total exergy of 7.3 MW at the treatment plant exit. The energy consumed for dewatering is 81.0 kWh per ton of solid matter in digested sludge. The sewage cake discharged from the plant is taken to a fluidized bed incinerator commissioned by the Gaziantep Water and Wastewater Treatment Company (GASKI) in late 2013, where it is dried and then incinerated. The average amount of sludge dewatered in the plant is 199.0 tons/day in the winter, and may go up to 240 tons/day in the summer. The average solid matter content of dewatered sludge is 27%.

Sewage sludge is processed in anaerobic digestion reactors in order to enable biogas production. The amount of biogas produced varies by sludge properties and the operating conditions of anaerobic reactors. The wastewater treatment plant in question digests 68.26 kg of sludge with a solid matter content of 8.0% for each 1 m^3 of biogas. The composition of the biogas produced in the facility under mesophilic (30-35℃) conditions is given in Table 1.

The lower heating value of the biogas produced in the facility is 21.47 MJ/Nm^3 (17892 kJ/kg). Based on the composition of biogas in Table 1, its specific chemical exergy is calculated to be 31168 kJ/kg. Since the mass flow rate of biogas produced in the facility is 0.212 kg/s, the total exergy of the gas produced at the outlet of anaerobic reactors is 6.65 MW.

The GASKİ biogas engine-powered cogeneration system consists of a four-stroke, plug-fired, V-12 Deutz TCG 2020 engine and connected equipment (see Fig. 2). The system is fueled by biogas produced at the same facility by digesting sewage sludge. The annual production of the cogeneration plant is 8.760 GWh, which corresponds to an annual biogas consumption of 3,400,000 m^3. The cogeneration system consumes 61% of the biogas produced in anaerobic digesters in a year. For each 1 kWh of electricity produced in the gas engine, 0.387 m^3 of biogas with a methane content of 60% is consumed. The total exergy of fuel and air entering the gas engine is calculated at 4.054 MW.

Table 1. Composition of biogas produced at the GASKI WWTP[a]

Content	Volumetric values (%)
CH_4	60
CO_2	35
N_2	1.5
H_2	0.3
O_2	0.5
H_2S (2500-3000 ppm)	2.5-3.0
LHV[b] (kJ/kg)	17892
HHV[c] (kJ/kg)	21250

[a] Values taken from the 2017 Annual Report issued by GASKI WWTP.
[b] LHV: Lower Heating Value.
[c] HHV: Higher Heating Value.

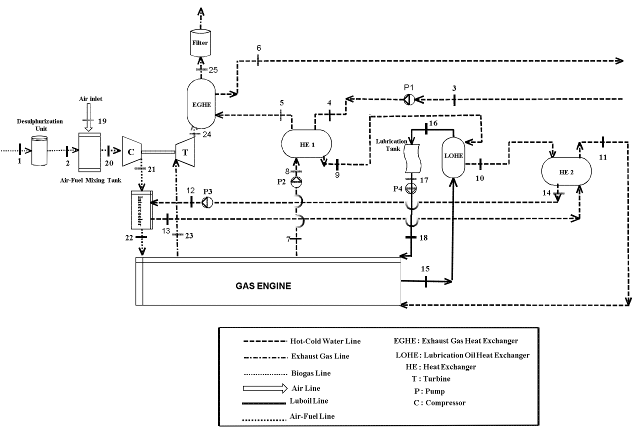

Fig. 2. GASKİ Biogas Engine-Powered Cogeneration Process

IV. FLUIDIZED BED SEWAGE SLUDGE INCINERATION SYSTEM FROM AN ENERGY ANALYSIS PERSPECTIVE

Although the higher heating value of biomass leaving the dewatering unit in the incineration system is 2,833 kcal/kg, the summer average is 2,175 kcal/kg. The variation occurs because of the operating conditions of anaerobic digesters in the winter, which causes the undigested organic matter content of the sludge to be high. The thermal dryer in the facility works by transferring the heat conveyed by approximately 22 tons of heat transfer oil circulating in the fluidized bed incinerator to sludge with a dry matter content of 27% spread across the dryer surface. The average inlet temperature of the oil is 220ºC, and the average outlet temperature is 205ºC.

The dryer unit consists of four modules that are 3.0 m high and 1.2 m in diameter, so the mass flow rate of the oil passing through each module is calculated to be 62.64 kg/hour at 60% pump efficiency. The average temperature of the water circulated in the thermal dryer is 40ºC. Assuming a summer and winter flow rate of 180 tons/day and a solid matter content of 27%, the energy needed for evaporating water in the dryer for increasing dry matter content to 40% is 1,400,742 kcal/hour. The interior of the dryer is lined with double-walled and perforated steel. The conductivity coefficient of carbon steel used is 33 W/m^2K, while that of stainless steel is 17 W/m^2K. The energy required for heat transfer through two separate surfaces of carbon and stainless steel is calculated at 17,645 kcal/hour and 9,090 kcal/hour for winter and summer, respectively, by considering surface resistance. The total energy to be consumed in the thermal drier for both winter and summer is 1,427,486 kcal/hour. Under the current operating conditions, the hourly energy transferred to the drier from the circulating heat transfer oil is calculated at 2,315,174 kcal/hour for both winter and summer. Under these circumstances, the waste heat discharged from the heat transfer oil at the end of the thermal dryer process will be 887,600 kcal/hour. The waste heat from the transfer oil is dissipated by cooling towers.

At the outlet of the thermal dryer, 122 tons/day of biomass with a dry matter content of 40% is fed into the fluidized bed incinerator using pumps. The higher heating value of the fed biomass is 2,833 kcal/kg. Additionally, coal pellets with a higher heating value of 2,750 kcal/kg are fed into the incinerator. Part of the heat generated by the incineration process is passed through the economizer unit that is serially connected to the incinerator outlet. The mixture of air and exhaust enters the economizer at 550ºC, where it collides with atmospheric air at an average temperature of 5ºC based on the reverse flow principle and enters the combustion chamber at a temperature of 450ºC. This serves to prevent cooling of the combustion chamber and sand bed. After the economizer, the mixture of air and exhaust enters a cyclone and membrane dust filter serially connected to the economizer outlet for screening particles and ash. The temperature of the air and exhaust mixture at the wet funnel inlet is about 120ºC. The average energy generated in the incineration plant is 10.240.000 kcal/hour in the winter and 7.700.000 kcal/hour in the summer. On the other hand, the average energy consumed in the incineration plant is 4.900.000 kcal/hour in the winter and 4.800.000 kcal/hour in the summer. Based on these figures, there is a large amount of waste heat that is not accounted for. There is a graduate thesis ongoing at the facility to explore methods for low-temperature electricity production and waste heat recovery in order to make use of the waste heat generated.

V. CONCLUSIONS

This study investigated the production of biogas in an anaerobic digester operating in a municipal wastewater treatment plant, electricity generation using a cogeneration unit, and the drying, incineration and disposal of sewage sludge. The energy recovery potential of sewage sludge in Turkey was considered from the energy and exergy analysis perspective. Although wastewater treatment plants require vast amounts of energy, they can generate the required energy on-site using the recovery methods explained above. It is a certainty that sewage sludge is a pressing matter for municipalities today and will continue to do so in the future. The authors hope that the energy recovery and sludge disposal methods explored in this paper will set an example for municipalities in the disposal of sewage sludge.

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