Energy Conversion and Management 101 (2015) 255–262

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Significance of anaerobic digestion as a source of clean energy in wastewater treatment plants

G. Silvestre, B. Fernández, A. Bonmatí *

IRTA, GIRO Joint Research Unit IRTA-UPC, Torre Marimon, E-08140 Caldes de Montbui, Barcelona, Spain

ARTICLE INFO

Article history:
Received 19 February 2015
Accepted 15 May 2015

Keywords:
Energy balance
Anaerobic digestion
Biogas recovery
Wastewater treatment plant
Flow analysis

ABSTRACT

Nowadays, energy consumption is one of the major concerns of wastewater treatment plants (WWTPs). Time ago, anaerobic digestion was usually implemented for sewage sludge stabilization but energy recovery optimization has recently gained importance. The energy balance of five WWTPs located in Catalonia revealed that depending on the configuration of the plant and its operation, between 39% and 76% of the total electric energy consumed in the WWTP could be supplied by the biogas produced. In the second part of this work, a carbon, nitrogen and sulphur flux analysis was carried out, together with an energy content evaluation for each stream in the WWTP. Results showed that 37% of the carbon found in the raw wastewater was removed during the active sludge process and 24% was transformed into biogas. The remaining carbon was found in the anaerobic dewatered sludge (22%) and in the treated water (19%). As a result, 34% of the initial energy was recovered in the form of biogas.

1. Introduction

Wastewater treatment plants (WWTPs) play an important role in environmental protection. In past decades, all efforts were focussed on obtaining high quality water and today mature technology based on biological removal of organic matter and nutrients is available. In particular, these technologies are highly effective but also not very efficient in terms of energy consumption. The activated sludge system is the most common biological treatment in WWTPs due to its good performance and its high effectiveness, but it also uses up high amounts of energy; representing over 40% of the total electric energy required to operate a sewage plant [1,2]. The amount of energy consumed in WWTPs depends on various factors such as the size of the plant, its design and operation, the composition of the wastewater (WW), urban WW/industrial WW ratio, the quality required for the discharge, as well as other local factors; but it is generally considered to add up 108,000–216,000 kJ/inhabitant equivalents per year [3].

The new challenge of WWTPs is to minimize energy consumption maintaining the quality of the discharged water [4]. Energy optimization could be obtained reducing the electric energy consumption of the different units of the WWTP, but also recovering energy from the WW [5]. The solids found in raw WW contain nearly 3.2 kJ g_{TS}^{-1} and the average energy requirements to treat raw WW is 0.35 kJ g_{TS}^{-1}, this means that the total energy available could exceed the electricity requirements for the treatment process [6]; suggesting that WWTPs could become net producers of renewable energy if an appropriate energy recovery technology is implemented applied in combination with a new conceptual design for the treatment of WW [7,8]. But nowadays this is still far from feasible.

In this context, anaerobic digestion (AD) is a well developed and robust technology commonly used to recover energy from organic streams. AD is a biological process able to transform organic compounds into biogas, a mixture of CH_4, and CO_2. The lower heating value of biogas depends on the percentage of methane which is usually found to be roughly around 23,400 kJ Nm^{-3} [9].

AD is not frequently used to treat WW due to the low organic matter concentration and the low temperature characteristics of raw WW, resulting in low treatment efficiencies and in the accumulation of suspended solids [8]. However, AD is often implemented in the sewage sludge (SS) treatment line aiming to SS stabilization and energy recovery in the form of biogas. Biogas can be used as fuel for a burner used to maintain the reactor's temperature, to fuel a combined heat and power (CHP) engine, or once upgraded, injected in the gas grid or as fuel for road transportation [9].

Anaerobic digestion optimization is a common practise to increase the energy self-sufficiency of WWTPs; in this regard SS pre-treatments aiming to improve the biodegradability of SS and consequently increase biogas production are a common practice,

---

* Corresponding author.
E-mail address: august.bomnati@irta.cat (A. Bonmatí).

http://dx.doi.org/10.1016/j.enconman.2015.05.033
0196-8904/

though a carefully energy balance is required [10,11]. Besides pre-treatments, co-digestion, in its turn, optimizes anaerobic digestion increasing the organic loading rate (OLR) with other organic wastes with high methanogenic potential showing an extensive increase in biogas production [12–14]. In all cases, the optimization of energy recovery through biogas production enhances WWTPs environmental performance and lowers its carbon foot print [15,16].

The primary energy produced from SS's biogas in Europe during 2014 was $4.97 \cdot 10^{13}$ kJ year^{-1} [17]. In Spain it has been estimated that the energy contained in SS produced is of around $5.94 \cdot 10^{12}$ kJ year^{-1} [18] though little ($1.41 \cdot 10^{12}$ kJ year^{-1}) is being nowadays recovered [17]. Catalonia (northeast of Spain) has 340 WWTPs with different size and flow chart configurations for organic matter and nutrient removal. AD is currently implemented in the 26 biggest WWTPs for the treatment of sewage sludge. Most of these plants use biogas to control the temperature of the reactor, the excess being burned in a flare. Only 11 of these plants generate electric energy using CHP engines fueled with biogas.

To perform an energy balance in a WWTP a necessary first step is to assess the energy content of the different streams, to analyze the energy recovery through biogas, and then estimate the maximum energy self-sufficiency attainable in the WWTP. Besides, it could be helpful to analyze different alternative configurations on the water and sludge lines so as to optimize said energy balance [19–21]. A calorimetric pump is the most common technique used to estimate low calorific value (LCV) of different kinds of samples [6] but, being it a device not always available, it is necessary to test simpler methods to estimate LCV. The aim of this study is to determine the role of anaerobic digestion on the energy self-sufficiency of the WWTPs target. The first part of the study assesses the electric and thermal energy balances in the WWTPs, analyzing the main factors involved in energy consumption, and also carries out an economic feasibility analysis on the possible inclusion of CHP engines. In the second part, an energy flow analysis and a substance flow analysis of the carbon (C), nitrogen (N) and sulphur (S) present in one of the WWTPs is performed. The use of elemental analysis is also tested to estimate the LCV of every stream in the WWTP.

2. Materials and methods

2.1. Wastewater treatment plants

Five WWTPs ($WWTP_1$–$WWTP_5$), located in Catalonia (Spain), treating a mixture of domestic WW (60–70%) and industrial WW (30–40%), were analyzed. All WWTPs have a similar flowchart comprising a physical pre-treatment, a primary treatment, a secondary treatment and a sewage sludge line. The main characteristics and operational parameters of the WWTPs are summarized in Table 1. The pre-treatment consisted of several bar screens and fine screens with different spacing, and a dissolved air flotation (DAF) unit to remove floatables as greases, and sand. A primary settler removes then the suspended solids, and the activated sludge system does the same with the organic matter dissolved. The activated sludge systems of $WWTP_1$, $WWTP_3$ and $WWTP_4$ were designed to operate with low organic loads, between 0.09 and 0.15 $kg_{BOD}\,m^{-3}\,d^{-1}$ and Food to Microorganism ratio (F/M) between 0.09 and 0.13 $g\,g^{-1}\,d^{-1}$, while the remaining two WWTP ($WWTP_2$ and $WWTP_5$) operated in high load mode, close to 0.5 $kg_{BOD}\,m^{-3}\,d^{-1}$, and F/M ratio around 0.3 $g\,g^{-1}\,d^{-1}$. Despite these differences, the BOD and COD removal were similar in the 5 WWTPs, above 90% and between 80% and 87%, respectively. $WWTP_1$ and $WWTP_4$ were designed and operated to remove nutrient (nitrogen and phosphorus) with efficiencies higher than 80%. Accordingly they have high sludge retention time (SRT), 18 days and 15 days, respectively. Contrary, $WWTP_{2,3,5}$ were not designed to remove nutrients, with low SRT, 8, 6 and 4 days respectively. Nevertheless, small amounts of nutrients are also removed by these plants.

The sewage sludge line consisted of a thickener unit, a mesophilic anaerobic digestion unit, and a dewatering unit. In all five plants the primary sludge was thickened by sedimentation while the secondary sludge was thickened by aerated flotation, in $WWTP_2$, $WWTP_3$ and $WWTP_4$, and by centrifugation with the addition of an organic polymer in $WWTP_1$ and $WWTP_5$. The anaerobic digestion process, in all cases, consisted of a continuous stirred tank reactor (CSTR) with a digestion volume between 7000 and 8800 m^3. The average hydraulic retention time (HRT) applied on the different WWTPs varied between 18 and 32 days. Dewatering was performed with a centrifuge in all WWTPs except for $WWTP_3$, where a filtration unit was employed (Table 1).

WW and sewage sludge flow rates, physicochemical characteristics (COD, BOD, TSS, TN and TP) of the different streams of the WWTP, operational parameters of the aerobic and anaerobic processes, biogas production, and the electric and thermal energy production (considering the use of a CHP engine) and consumption of the plant were jointly used for the energy and economic balance calculations. The aforementioned data were provided by the plant operators, and correspond to the monthly average of an entire year in operation of the WWTPs.

2.2. Energy and economic balance calculations

2.2.1. Electric and thermal energy production from biogas

The biogas conversion into electricity and thermal energy was calculated considering a CHP and the monthly biogas production rates in Eqs. (1) and (2), respectively.

$$EE_P = Y_{CH_4} \cdot P_{calCH_4} \cdot \eta_E \cdot t_{we} \cdot t_{wd}^{-1} \cdot 0.9 \tag{1}$$

$$TE_P = Y_{CH_4} \cdot P_{calCH_4} \cdot \eta_T \cdot t_{we} \cdot t_{wd}^{-1} \tag{2}$$

where EE_P (kJ d^{-1}) is the net electric energy production, TE_P (kJ d^{-1}) is the net thermal energy production, Y_{CH_4} is the methane production ($m^3\,d^{-1}$), P_{calCH_4} is the heating value of methane (34,020 kJ m^{-3}), η_E is the electric efficiency of the CHP engine (35%), η_T is the thermal efficiency of the CHP engine (55%), t_{we} are the working hours per month of the CHP engine (666.7 h month^{-1}, with a total of 8000 h year^{-1}), t_{wd} are the hours that the digester is producing biogas (considering 24 h per day, and 30 days per month), and 0.9 is a factor taken into account for the CHP engine's self consumption (10% of the total electric energy generated).

2.2.2. Electric and thermal energy consumption

All data relative to the electric energy consumption (EE_C) were provided by plant operators and corresponded to the monthly average of electric consumption during an entire year in operation.

Thermal energy requirements (EE_T) for each WWTP correspond to the requirements for heating the raw sludge (q_T – kJ d^{-1}) and maintaining the anaerobic reactor's temperature (q_L – kJ d^{-1}). Heat requirements were calculated on a monthly basis considering the average temperature of the city where the WWTP is located. Thermal energy requirements were calculated according to Eqs. (3) and (4), considering that the reactor shape was cylindrical with a diameter 3-fold higher than its height, with a conical floor, and made of concrete with a wall thickness of 300 mm.

$$q_T = F_S \cdot \rho \cdot (T_D - T_S) \cdot C_p \tag{3}$$

$$q_L = A_W \cdot (T_D - T_A) \cdot U_W + A_F \cdot (T_D - T_F) \cdot U_F + A_R \cdot (T_D - T_A) \cdot U_R \tag{4}$$