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Thermo-economic analysis of a novel cogeneration system for sewage sludge treatment

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A B S T R A C T

Wastewater treatment plants are high energy-consuming systems, and their electric energy consumption contributes to 25–30% of the total operating costs. A significant part of thermal energy is needed for management of the sludge produced during the process. Sludge drying by Combined Heat and Power (CHP) systems is attractive to obtain substantial economic and energy savings, especially if all the waste heat can be used. Since biogas production, where available, is insufficient for sludge drying, the direct use of the exhaust gases of a CHP system fuelled with syngas derived from sludge gasification and waste vegetable oil, is proposed. The profitability of this system is comparable with that of the systems currently employed in advanced wastewater treatment plants. The economic convenience derives from the reduction of sludge to be disposed and the overall energy saving in the plant. The simple payback of the proposed system, equal to 6.8 years, is only one year higher than that found for of an analogue conventional system, while the Net Present Value is 30% higher than that calculated for a conventional system. In terms of environmental impact, the layout presented is more efficient as biomass-derived fuels are used instead of fossil fuels.

1. Introduction

In WasteWater Treatment Plants (WWTP) electric energy consumption represents the highest operating cost, roughly 25–30%, followed by sludge treatment and disposal, that cover up to 20% of the total operating costs. The use of cogeneration systems for sludge thermal treatment can have positive impacts on the reduction of both these costs. Energy demand of WWTP depends on several aspects, such as size, treatment cycle, and effluent quality requirements [1]. The highest percentage of electric energy consumption is used for aeration in the biological section, 55%, followed by sludge treatment and disposal, 35% [2]. Sludge is one of the solid by-products of wastewater treatment. Its production has dramatically increased in recent years due to demographic increase, percentage of population served by urban wastewater treatment plants, and introduction of more restrictive legislation concerning the quality of water effluents [3]. According to the final report *“Environmental, economic and social impacts of the use of sewage sludge on land”* published by the European Commission in 2008, sewage sludge production in the EU27 is estimated at 10 Mtonnes per year (dry solids).

The majority of sewage sludge from WWTP in Europe is currently used in agriculture, by direct land spreading, in order to take advantage of its nutrient and organic content. Other disposal methods are represented by landfilling, incineration and composting. In recent years, other innovative thermal treatments, such as pyrolysis and gasification, are emerging for sewage sludge processing [4]. Dewatering is needed for all the listed options of final reuse and disposal, since solids content in the sludge produced from WWTP is very low, from 0.6 to 5%, depending on the treatment systems [5]. Mechanical dewatering treatments allow partial removal of the free water content, that constitutes the largest fraction; the maximum dry solid content that can be reached by mechanical treatment is 40%. In order to further reduce water and biodegradable content, thermal drying is necessary, as it improves sludge handling and workability, increases its heating value, and reduces pathogen content and volume, positively affecting post processing and disposal costs [6,7]. Currently, thermal drying is commonly used in most EU-15 countries, while in the others, sludge is just mechanically dewatered up to 25–30% of dry matter [3].

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Sludge drying becomes economically convenient when excess or waste heat can be used [8]. Waste heat in WWTP in Europe generally derives from the use of biogas from anaerobic digestion. This process is commonly self sufficient from the energetic point of view [9]. If available, excess heat can be used for thermal drying, however it is usually insufficient since the process is energy intensive [7].

In the present work, the authors analyse the advantages of using an innovative Combined Heat and Power (CHP) system for thermal drying of sludge. The exhaust gas produced by the CHP system is directly used for thermal drying of the sludge. The CHP system is fuelled with both the syngas derived from gasification of dried sludge and Waste Vegetable Oil (WVO).

WVO potential amount in Europe is estimated between 700 and 1000 ktonnes per year [10], a large part of which is generally discharged into the environment [11]. WVO not only constitutes an important feedstock for energy production, but its recovery as fuel can also improve sustainability in waste management. Direct use of WVO as fuel in diesel engines can cause operational problems, such as an effort increase at start, poor atomization of fuel, carbon deposition, filter plugging [12,13], mainly due to its high viscosity. To reduce WVO viscosity, several methods can be used: preheating [14], mixing with other fuels or conversion to biodiesel [12]. Currently, the use of WVO for biodiesel production is the most diffused option, but its direct use in an integrated system like the one analysed in this work, can have a lower environmental impact and be more energy efficient and economically convenient. Direct use of WVO allows sensitive energy and economic saving with respect to biodiesel production, which requires several physical and chemical processes, such as transesterification, that present a higher energy demand and environment impact. Transesterification is commonly carried out in the presence of alkali catalyst, usually toxic and flammable liquid methanol, and caustic compounds, such as sodium or potassium hydroxide [12]. Considerable environmental impact is due to the electricity needed for preesterification and transesterification [15]. This last requires an excess of methanol, whose recovery presents high energy demanding treatments [16]. Moreover, the use of methanol significantly affects the abiotic resources depletion as fossil fuels are used for its production [16]. Therefore, the potential of WVO utilization in CHP systems to reduce GreenHouse Gas (GHG) emissions is demonstrated to be higher than in case of biodiesel production [17]. From an economic point of view, this process is sustained by a combination of final feed-in and regulations.

In this work, the syngas proposed for fuelling a dual-biofuel CHP system, is obtained from sewage sludge gasification. Gasification is a thermal decomposition process in a net reducing atmosphere with conversion of carbonaceous content of biomass into combustible gas and ash [4]. Under steady operation the process is energetically self-sustained if sludge solid content is higher than 90% in mass [18].

Convective thermal drying is an energy-intensive process from the thermal energy point of view, while its electric energy demand is very low. Therefore, electric energy produced by a CHP system can be used to supply the other plant facilities. Energy demand of WWTP is rather constant on daily and seasonal basis. Moreover, WWTP require electric and thermal energy supply simultaneously, so that CHP can be used very efficiently and economically. With respect to conventional scenarios, in which sludge drying is carried out by using natural gas or thermal energy produced by sludge incineration, the use of syngas derived from sludge gasification in a CHP system is the most beneficial in terms of GHG savings [19].

In this study, the authors present a thermo-economic analysis of a new system in order to assess its full-scale application in actual plants. The paper is organised as follows. In Section 2, a description of the system layout is presented, by focusing on the three main processes of the plant, thermal drying, gasification and cogeneration. For each one of them a brief analysis is reported. In Section 3, the simulation sub-models used to assess the feasibility of the system are described in terms of:

- Mass and energy balances to investigate the anaerobic digestion;
- Thermal drying model implemented in the software ASPEN Plus;
- Thermochemical equilibrium model of gasification, developed by the authors to estimate syngas production;
- CFD model developed to evaluate the variation of the combustion efficiency of the considered engine, as the syngas is supplied in conjunction with WVO, in order to evaluate the performance of the CHP system;
- Economic analysis of the overall process, performed to assess the profitability of the proposed system.

In Section 4, the results obtained from the sub-models are presented. In order to investigate the advantages of the proposed system, this is compared to an analogue conventional system. A sensitivity analysis is carried out to estimate the influence of several parameters on the profitability of the plant. Finally, the main results are summarized in the conclusions.

2. System layout

The feasibility analysis of the proposed system is carried out by evaluating its energy consumption and recovery, and overall costs of the process, in comparison to traditional systems. Such a comparison is based on the assumption that both systems have to satisfy the same thermal demand of the drying process, depending on which the other variables are determined. The proposed system is sketched in Fig. 1. Wet sludge, with a dry solid content of 20–30%, enters the dryer and is dewatered to 90% of dry solids. The dryer exhausts are cleaned by a scrubber: the purified air is discharged into the atmosphere, while the wastewater is processed in the WWTP. After drying, the sludge is gasified: the syngas produced by gasification is used as fuel in a cogenerative internal combustion engine, together with WVO. The electricity produced by the dual fuel CHP engine is used for WWTP facilities, while the heat recovered from the CHP cooling system and the exhausts, is used for sludge drying. Low grade waste heat from the CHP is used to increase WVO temperature, in order to reduce its viscosity, and to pre-heat the fresh air that is mixed to the exhausts. The mixing process is needed to satisfy the thermal requirement of the dryer, in terms of flow rate and temperature. The three main sections of the system, sketched in Fig. 1, namely dryer, gasifier and CHP, are described in detail in the following sections.

2.1. Thermal drying

Thermal drying systems for waste treatment sludge can be classified on the basis of the main heat transfer mechanism, conductive and convective [7], with the possibility to combine the two mechanisms. In conductive systems the hot medium, usually thermal oil or saturated steam, is not in contact with the wet sludge. The separating heated surface constitutes the medium that transfers heat to the sludge [20]. In convective dryers, hot air or steam flows through the dryer causing water evaporation [6]. The heat transfer depends on the exposed area to the hot medium and on the temperature difference between the desiccant flow and the wet sludge surface. Among convective dryers, belt dryers present a design that allows easy manipulation and high flexibility [6], due to

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