A portrait of sewage sludge use for sustainable energy recovery potential in Turkey in the frame of EU environmental legislations

Ayşegül Abuşoğlu, Emrah Özahi, and Alperen Tozlu

***Abstract*—**This paper presents a comprehensive portrait of municipal sewage sludge use for renewable and sustainable energy recovery potential in Turkey. A brief information is given on the currently established and instructing municipal wastewater treatment plants in the country for a realistic estimation of total amount of sewage sludge generated and therefore energy recovery potential. Environmental Policy Chapter within the EU negotiations, as one of the most important issues regarding adaptation to the international legislation in Turkey's agenda, is discussed taking the sewage sludge elimination into consideration. Using an existing municipal wastewater treatment plant operating data, biogas production via anaerobic digestion process, cogenerating of electricity and hot water using biogas as fuel are described and also, three different hydrogen production methods are developed using a modest amount of power produced by the existing cogeneration system.

***Keywords*—**Wastewater treatment, sewage sludge, environment, hydrogen.

I. Introduction

MUNICIPAL wastewater sludge is a by-product of the biological or chemical treatment of sewage in wastewater treatment plants. Another issue which is as important as the quality of the treated wastewater is the economically feasible and environmentally friendly removal of treatment sludge. The requirement for the conditioning of the treatment sludge, reduction of its volume, its transport and storage gets tougher by the day due to increasing population, limited storage space availability and increasing pollution loads. The utilization of novel solutions or different application methodologies was therefore brought to agenda for the management and beneficial use of wastewater treatment sludge.

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Ayşegül Abuşoğlu is with the Mechanical Engineering Department, University of Gaziantep, Gaziantep, 27310 TURKEY (e-mail: ayabusoglu@gantep.edu.tr).

Emrah Özahi is with the Mechanical Engineering Department, University of Gaziantep, Gaziantep, 27310 TURKEY (e-mail: ozahi@ gantep.edu.tr).

Alperen Tozlu is with the Mechanical Engineering Department, University of Gaziantep, Gaziantep, 27310 TURKEY (e-mail: alperentozlu@gantep.edu.tr).

The sustainable sludge management in wastewater treatment systems is expected to focus basically on two issues; investigation of areas of direct use of enriched sludge via preconditioning and establishment of energy recovery systems fully utilizing all the waste sludge, whose the harmful active materials and infectious microorganisms were completely removed within reasonable cost margins. The utilization of waste sludge as raw material and/or secondary fuel in cement production industry, which has high energy requirements, was reported to be common [1]. Although the globally accepted main types of primary fuel used in the cement industry are coal, fuel oil and natural gas, many different types of waste could also be utilized in cement rotary kilns. Thermally dried sludge contains 40% of organic minerals and these minerals originally bond with the clinker during the clinker reaction taking place at around 1450°C facilitating complete adaption of the sludge ash with high silica and aluminum content within the clinker matrix, preventing the formation of another type of waste through this process. The biggest restriction for the use of waste sludge in cement production was reported as the requirement of very low phosphate and mercury containing sludge [2]. Svanström et al. reported the lab-scale experimental simulation of energy recovery from waste sludge through supercritical water oxidation as the most sustainable and economical method among the available methods for energy recovery [3]. However, an explicit implication of whether this method would potentially solve the waste sludge removal problem in the future could not be assessed since no large scale study was conducted using this proposed method.

A large proportion of the studies available in open-access literature on the removal of waste sludge, that is generally regarded as useful, focused on energy recover using it. Werle and Wilk carried out a detailed evaluation on the removal of the sludge that would be produced in Poland also taking the increase in population into consideration for the period of 2010-2018 using energy recovery methodologies such as pyrolysis, gasification, heat and power generation by incineration or by incineration mixed with a type of fossil fuel [4]. Cao and Pawlowski investigated the energy efficiency of two methodologies that they developed based on anaerobic sludge putrefaction followed by pyrolysis, which they considered as the most promising and sustainable in terms of bioenergy generation using waste sludge [5]. Horttanainen et al. conducted a technical and economic performance analysis of a heat and power producing waste sludge incineration plant that was developed based on the amount of waste sludge generated by a unit equivalent population and they compared their results with the performance of other sludge removal technologies [6]. Nges and Liu anaerobically putrefied waste sludge samples in a lab-scale experimental study and investigated the increase in the methane content of the obtained biogas [7]. They reported that thermophilic putrefaction was faster than mesophilic putrefaction although the methane production was higher during mesophilic one.

Direct incineration of dried wastewater sludge for heat and power production or its use along with any fossil fuel in a power production plant or in cement production as an auxiliary fuel are considered frequently by the researchers. Cartmell et al. developed a strategic and integrated evaluation method taking five different incineration processes into consideration within the context of waste management and energy recovery from biofuels in England [8]. Zabaniotou and Theofilou evaluated the impact of the process of using wet wastewater sludge as an alternative fuel in a cement production plant on environment and human health based on the emission values and concluded that the method was unequalled in the removal of waste sludge [9]. Nadal et al. conducted a cost-benefit analysis based on the use of wastewater sludge as an alternative fuel in an actual cement production plant and attempted to undisclosed the estimated economic impact on environment as a result of this incineration process [10].

In this paper, first, a short introduction is provided on the information on the readily established and operating municipal wastewater treatment plants in Turkey for presenting the waste sludge production potential of Turkey. The current utilization of the sludge produced in these plants and the restrictions imposed by the present environmental laws and regulations are then discussed. This is investigated in conjunction with the environmental policies that Turkey needs to realize in accordance with the process of adaptation to the European Union in terms of the use of waste sludge in energy recovery and its removal. Lastly, an existing municipal wastewater treatment plant is described in detail, in the frame of the biogas and electricity productions based on the actual operational data of the plant. The potential for hydrogen production using waste sludge in Turkey is investigated via three models that are developed for hydrogen generation using a high temperature electrolysis, a hydrogen sulphide electrolysis and a fermentative hydrogen production models.

II. Wastewater Treatment Plants In Turkey And Energy Recovery From Wastewater Sludge

The first wastewater treatment plant in Turkey was put into operation in 1982 with a capacity of 751 000 m^3/year. The total number of municipal wastewater treatment plants reached 326 by the end of 2014 with an approximate capacity of 5 300 Mm^3/year and the annual amount of water treated in these plants was reported approximately as 2 800 Mm^3/year [11]. As of 2014, a total of 326 wastewater treatment plants with the following breakdown of biological (199), advanced (53) and natural (35) treatment were in operation serving 438 municipalities. Of the total amount of wastewater that is processed in Turkey, 37.9% is processed via advanced treatment, 34.3% via biological treatment, 27.6% via physical treatment and 0.2% via natural treatment. The ratio of the Turkish population that was serviced by sewage network managed by a municipality was 73% in 2014 and this corresponded to 88% of the total municipality population. The ratio of the Turkish population that would be serviced by a municipality that has a wastewater treatment system is 52% and this corresponds to 62% of the total population that would be registered within a municipality. The average wastewater discharged into the receiving environment per person in the municipalities via the sewage network was determined as 182 litres per day in 2014 [11].

The analysis of the year 2014 data collected from the municipalities and the organized industrial zones indicated that municipal wastewater plants produced 526 000 ton/year wastewater sludge and the industrial sites produced 600 000 ton/year wastewater sludge totalling up to 1 126 000 ton/year of dry solid material as waste annually [12]. The environmental data in 2014 as reported by the Turkish Statistical Institute (TSI) indicated that the daily production of 60 g of waste sludge per person should be considered in calculations based on 25% dry matter content [11].

Conventional biological treatment units were present in the first wastewater treatment plant in Turkey. This system consisted of aerated sludge stabilization units and sludge drying beds. The dried sludge was used for land filling and agricultural purposed for a long time but this practice was abandoned due to the precautionary measures taken as a result of the increasing environmental pollution parameters and due to the increasing amounts of wastewater and sludge as a consequence of increasing population, which facilitated the establishment of advanced treatment systems in the past ten years.

III. The Legal Legislation On Wastewater And Treatment Sludge Management In Turkey Within The Framework Of European Union Environmental Adaptation Laws

One of the most important issues regarding adaptation to the international legislation in Turkey's agenda is the Environmental Policy Chapter opened to discussion on 21st December 2009 with ordinal number 27 within the context of the European Union negotiations [13]. The current legislation in Turkey was attuned with the Water Framework Directive in the European Union legislation no 2000/60/EC and the Municipal Wastewater Treatment Directive legislation no 91/271/EEC through the Municipal Wastewater Treatment Bylaws published in the Official Gazette no 26047 on 08.01.2006 [14]. The collaborative Capacity Building Project for Water Sector in Turkey (TR-06-IB-EN-01) between the Republic of Turkey, the Netherlands, the United Kingdom and Slovak Republic, which was financed within this framework of

The Pre-membership Program of the European Union, was thus completed [15].

The framework legislation in the Turkish Law regarding waste management is considered as the Legislation for The General Principles of Waste Management published in the Official Gazette no 26927 on 5 June 2008 [16]. The Turkish legislation is in full compliance with the former Framework Waste Directive no 2006/12/EC of the EU and with the ruling no 2000/532/EC stating the waste list. Furthermore, the Legislation for Waste Management internalized several predications of the Waste Framework Directive no 2008/98/EC. The predications of Legislation no 2006/12/EC were envisaged to be fully transferred into practice by the end of 2015 and the predications of Legislation no 2008/98/EC were envisaged to be internalized in the Turkish law by the end of 2015 and to be put into practice. Five major targets of the EU policy regarding waste management are [16]:

- Investigation of environmentally friendly and less waste-incentive technologies and processes and prevention of waste via the production of environmentally friendly products.
- Incitement of re-processing of waste through specifically its reuse as raw materials and its recycling.
- Improvement of waste removal through the Europe-wide binding environmental standards (specifically as legislations).
- Tightening of the predications regarding the transport of hazardous substances.
- Reformation of the polluted land.

The reuse of waste as raw materials if possible or its recycling to be put into use as a requirement of the European Union environmental legislation also outline the general application framework of the Turkish waste sludge management policies. Broadly speaking, the applications towards the beneficial reuse of waste sludge would be listed as its distribution over agricultural or wood land for reformation, its incineration alone or as an auxiliary fuel, improvement of the mine lands and its spreading over regular storage areas as covering material. The Legislation Regarding the Use of Domestic and Municipal Wastewater Sludge on Land published in the Official Gazette no 27661 dated 3 August 2010 strictly prohibits the use of raw wastewater sludge for land reformation or its removal by spreading it on the surface of the land [17]. The use of stabilized treatment sludge on land was limited with restrictions and prohibitions in the indicated additions to the same legislation. Treatment sludge is categorized within the group of “residues” in the Legislation for the Incineration of Waste published in the Official Gazette no 27721 dates 6 October 2010 [18]. Limit values for emissions are listed in all legislations and these were separately given for the incineration of sludge alone or its incineration together with other wastes. The EU member states were forced to shut down or organize their current solid waste storage lands as indicated by the standards by July 2009 according to the European Union regular Storage Directive (99/31/EC). This legislation necessitates the reduction of the waste to be stored in regulate storage land down to 75% by mass of the total biological waste produced in 2005 by 2015, to 50% in 2018 and down to 35% in 2025. This enforcement indicates the significant restrictions that Turkey will bring in near future towards the reduction in the storage of treatment sludge, which is currently intensively used.

In conclusion, Turkey has completed its legislative adaptation regarding the wastewater sector within the framework of the acquis including the EU Municipal Wastewater Treatment Directive. All necessities regarding wastewater treatment and waste sludge removal were thus fulfilled in the Turkish legislation and the duties and the responsibilities of all institutions and organizations operating in municipal wastewater management were clearly stated. Although the current regulations were incorporated into the Turkish law, uncertainties still exist in application. Generally speaking, an urgent increase in the proficiency and the capacity of the field personnel on national, provincial and municipal basis is evaluated as necessary to facilitate the applicability of the legislation.

IV. GASKI Gaziantep Wastewater Treatment Sludge Management

The project contract of GASKI Wastewater Treatment Plant (WWTP) was signed by the consortium of Gaziantep Municipality Water and Wastewater Works, Gunal Construction Incorporated Company and Degremont Company (France), in Gaziantep city, in 1990. GASKI WWTP was financed by European Social Development Bank with the credit of 56 million US Dollars. Wastewater treatment in the plant was started in 1999. The plant has been serving to 1,000,000 equal inhabitants in the Gaziantep city and the total daily capacity of treated wastewater of the plant is 200,000 m^3. Treated wastewater is discharged to a local river for use in irrigation of 80 million m^2 agricultural land located in the region. Main design data of the GASKI WWTP is presented in Table 1.

Table 1. Main design data of the GASKI WWTP

Total plant area	200,000 m^2	**Equivalent population**	1,000,000
Wastewater		**Pollution load**	
Daily flow	200,000 m^3/day	Maximum BOI_5 load	60 ton/day
Hourly flow	8333 m^3/h	Average BOI_5 concentration	300 mg/liter
Average instan. flow	2.3 m^3/h	PH	5.5<PH<8.5
Dry weather instan. flow	3.7 m^3/h	Temperature	<30°C
Humid weather instan. flow	4.6 m^3/h	Biogas production	20,000 m^3/day
Treated wastewater			
Average BOI_5 concentration		<25 mg/l	
Suspended solid		<35 mg/l	

Sludge stabilization process consists of some subsystems. First step of the sludge process is flotation and thickening process (see Figure 1). Sludge thickening system is a process used to increase the dry matter content of sludge by removing a portion of the liquid fraction. To illustrate, if waste activated sludge, which is typically pumped from secondary settling tanks with a content of about 0.8% solids, can be thickened to a content of 4% solids, then a fivefold decrease in the sludge volume is achieved. Thickening is generally accomplished by physical means, including, co-settling, gravity settling, flotation, centrifugation, gravity belt, and rotary drum [19]. The volume reduction obtained by sludge concentration is beneficial to subsequent treatment processes, such as digestion, dewatering drying and incineration from the following standpoints: a) capacity of thanks and equipment required, b) quantity of chemicals required for sludge conditioning, and c) amount of heat required by digesters and amount of auxiliary fuel required for heat drying or incineration, or both [19].

A. Anaerobic Sludge Digestion

Anaerobic sludge putrefaction is a microbiological digestion process that takes place in the absence of air and can be summarized as the production of methane gas (CH_4) via decomposition of organic materials in a non-oxygenated environment via microorganisms. Anaerobic sludge putrefaction is composed of four consecutive sub-processes that were realized by different population s of micro-organisms: Hydrolysis (conversion of insoluble biopolymers into soluble organic compounds), acidogenesis (conversion of soluble organic compounds into volatile fatty acids (VFA) and carbon dioxide (CO_2), acetate formation (conversion of volatile fatty acids into acetate and hydrogen (H_2)) and methane production (conversion of acetate, carbon dioxide and hydrogen into methane) [20].

The sludge putrefaction process occurs at two different temperature ranges; mesophilic (20-40°C) and thermophilic (50-60°C). While mesophilic putrefaction requires relatively smaller reactor volumes, thermophilic putrefaction is preferred in processes in which the removal of infectious pathogens was preferred from the waste since the process takes place at higher temperatures. Theoretically, anaerobic putrefaction can also take place at very low temperatures, such as at or around 0°C, however, the production of biogas and, in conjunction, methane increases with increasing temperature and research indicated that the optimal methane production was achieved in the temperature range of 35-37°C in which the mesophilic bacteria were the most effective. The optimum temperature range for the effective operation of thermophilic bacteria was reported as above 55°C [21]. The processing capacity of the microorganisms during anaerobic sludge putrefaction depends on a regular high loading of the reactors. The system performance could be increased in low loading systems by increasing the relative residence time of the sludge in the reactor. Sludge residence time is one of the most important parameters in anaerobic sludge putrefaction process in principle. Very short periods would not allow methane formation and would allow the formation of acid compounds as a reactor output. A sludge residence time of 15-30 days at 25°C was reported to be required to allow for the methane formation, hydrolysis and acidification of the fats [19]. Lower temperatures reduce the rate of methane production and therefore longer residence times would be required. Chemical oxygen demand (COD) would determine the amount of organic materials in wastewaters as an indicator of the pollution parameter, which would assist the prediction of the biogas production potential [22]. COD in the organic materials, which would biologically degrade throughout anaerobic sludge putrefaction, would be maintained as methane, carbon dioxide, ammonia and hydrogen sulphide at the end of the process as a result of the restructuring of the bacterial population. Another parameter that would be used in the quantitative evaluation of the organic pollution in wastewaters was reported as the biological oxygen demand (BOD). This parameter indicated the amount of dissolved oxygen used by the aerobic micro-organisms in the waste during the biochemical oxidation of the organic materials [22].

Biogas is a volumetric gaseous mixture of 55-75% methane (CH_4), 25-45% carbon dioxide (CO_2), 0.1-1.5% hydrogen sulphide (H_2S) and 0.01-0.05% ammonia (NH_3). Biogas is saturated with water vapour and it may contain dust particles, hydrogen (H_2), nitrogen (N_2) and carbon monoxide (CO) in trace amounts depending on the content of the waste sludge and due to the nature of the anaerobic putrefaction process. In the plant, controlled digestion is performed in mesophilic (30-40ºC) temperature conditions.

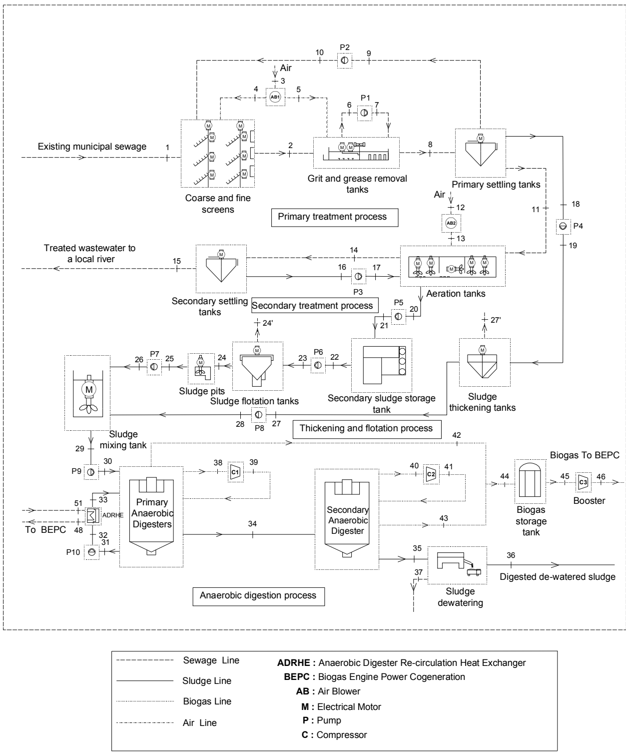

Figure 1. Schematic of GASKI Gaziantep Wastewater Treatment Plant

Optimum heating temperature in reactors is around 35ºC. The activated sludge loading rate to the reactors is 800-1200 tons per day with the density of 35-55 g/l and the total volume of reactors is 32,000 m3. At the end of the anaerobic sludge digestion process, 10,000-18,000 m3 biogas is generated daily which means approximately 60% of the organic fraction is converted to gaseous end products after a 15-day period. The higher and lower heating values of biogas containing 55-75% methane ranges between 22-30 MJ/Nm^3 and 19-26 MJ/Nm^3, respectively [23]. The composition of biogas produced through anaerobic digestion reactors in the plant is given in Table 2.

Table 2. The produced biogas composition in GASKI WWTP

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)	0.25-0.30
LHV (kJ/kg)	17,892
HHV (kJ/kg)	21,250

B. Biogas Engine Driven Cogeneration

The biogas engine in the GASKI WWTP cogeneration facility is a DEUTZ TCG 2020 V12K gas engine which is a four stroke, spark ignition engine with 12 cylinders in a V configuration. It uses biogas which is produced by anaerobic digestion reactors. The annual electrical energy production is 8.760 GWh, and the annual biogas consumption is nearly 3,400,000 m^3 at designed operating conditions, which means 61% of the biogas produced through anaerobic digesters is consumed by on-site cogeneration system of the plant.

C. Hydrogen Production Models

Three hydrogen production models are developed for the GASKI WWTP. In the model-1 (see Figure 2), a high temperature electrolysis process is considered to produce hydrogen. In this model, the work demand for the electrolysis system is provided by the biogas engine powered cogeneration system of GASKI WWTP. The biogas used as fuel in this cogeneration system is produced by a totally renewable process which takes place in the anaerobic digestion reactors of the WWTP. The biogas consumed for 1000 kWh electricity generation in the existing cogeneration system is nearly 61% (0.129 kg/s) of the total biogas produced in the anaerobic digesters, which is 0.212 kg/s. A small amount of the remaining part (0.083 kg/s) of the biogas can be used to obtain high temperature steam production in the boiler, which is 0.025 kg/s. Before the boiling and electrolysis processes, the water must be purified through a clean water treatment system. The mass flow rate of the water entering the electrolysis process is taken as 0.09 kg/s. The temperature and pressure of the steam produced in the boiler are 800°C and 5 bar, respectively.

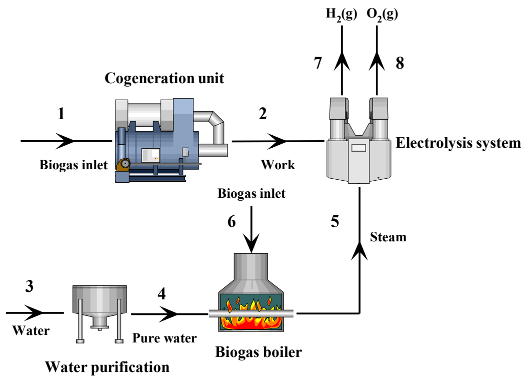

Figure 2. Hydrogen production model-1

In the model-2 (see Figure 3), a hydrogen sulfide (H_2S) electrolysis process is developed for the hydrogen production. Biogas produced by anaerobic digestion of sludge is mostly methane (up to 60%), the remaining part is mostly acid gases, primarily carbon dioxide, with hydrogen sulfide causing the most problems. When biogas is directly burned as a fuel, engines tend to wear out quickly. To prevent this, H_2S in the biogas is eliminated in a desulfurization unit ($DeSO_x$) before the combustion process. Although its presence in the biogas may cause lots of system and environmental problems, the energy demand for the electrolysis process of H_2S is lower about 3.25 times than that of the water. In the model-2, biogas produced by the anaerobic digestion of sludge in the WWTP is first passed through a hydrogen sulfide separator and H_2S content of it is collected. Biogas with H_2S free enters the cogeneration unit with the same mass flow rate as in the case of model-1 and 1000 kWh electricity is produced. The mass flow rate of H_2S entering the electrolysis process is 0.0021 kg/s, which can be found theoretically by taking the H_2S content of the biogas produced. In this model, due to the small amount of H_2S collected, the work demand of the electrolysis process is in small quantities (5.83 kWh for GASKI WWTP case).

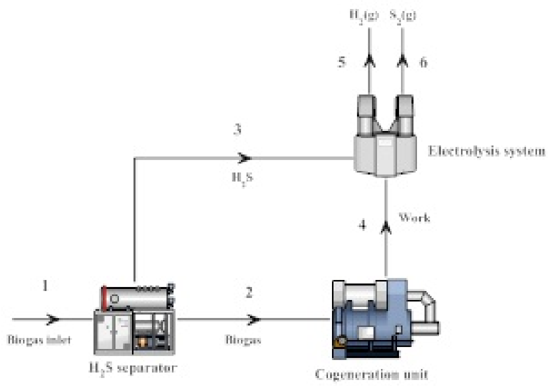

Figure 3. Hydrogen production model-2

In the model-3 (see Figure 4), a fermentative hydrogen production (bio-hydrogen) model is considered. In this process digested sewage sludge can be used directly for the hydrogen production in the fermentative conditions. In contrast to anaerobic methane digestion in which the intermediate product hydrogen is converted to methane, the final product of the dark fermentation process is hydrogen. An important distinction with anaerobic methane digestion is that in hydrogen fermentations only hydrogen producing microorganisms are active. Another essential difference is that complex organic compounds in the feedstock are converted to simple molecules not during the digestion process, but rather in a separate process preceding the fermentation [24]. This pre-treatment process is performed by means of physical or chemical methods and resulting organic compounds are converted into hydrogen, acetic acid and carbon dioxide. In the model-3, pre-treatment process is applied to the activated sludge to increase hydrogen production. The mass flow rate of the sludge before the digestion and fermentation processes in the WWTP is 12.06 kg/s. Since hydrogen produced through dark fermentation is only 60% by volume, it must be purified by using a gas separator.

Figure 4. Hydrogen production model-3

V. CONCLUSION

The origin and nature of organic wastes, such as sewage sludge, always causes a hygienic risk in storage, collection, processing, handling, and utilization. Beside this, sludge can be seen as alternative renewable energy source because of its energy production potential. Anaerobic digestion of sewage sludge is an established technology for environmental protection through the wastewater treatment, and it takes place with the absence of oxygen. The end product is biogas, a useful renewable energy source. This biogas can be used as a fuel for power production in WWTPs. Hydrogen is considered as a clean and high quality energy carrier, since its combustion only produces water as a byproduct. Electricity produced from the WWTP's cogeneration facilities can be used as energy input for the installed water electrolysis unit, which then produces hydrogen. This hydrogen production method in which biogas is used as a renewable energy source is a completely eco-friendly and green process.

Total annual biogas production potential of all the existing WWTPs of Turkey is slightly above 200 million m^3. If this estimate of biogas production potential was totally used for power production, the annual electricity production from sewage sludge, based on biogas in Turkey, would be over 530 GWh. This can meet nearly 1% of the total annual energy demand of the country. Considering the digested sludge output as a secondary valuable fuel source for incineration facilities for further power production, this percentage would increase by 2%, which indicates that WWTPs are obviously remarkable renewable energy sources.

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