Desalination and Water Treatment
www.deswater.com

33 (2011) 185–193
September

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doi: 10.5004/dwt.2011.2613

Evaluation of sewage sludge production and utilization in Greece in the frame of integrated energy recovery

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Received 7 January 2010; Accepted in revised form 12 January 2011

ABSTRACT

The objectives of this work were to provide an overview of municipal activated sludge units in Greece, to determine the sludge annual production rates and to examine potential for energy utilization of dewatered sludge. 37 wastewater treatment plants, serving a population equivalent of 1.6 million, located throughout Greece, were investigated during this study, in order to determine the sludge production rate after secondary and tertiary wastewater treatment processes. The average sludge production amount was estimated at 0.04 kg dry matter per capita per day, corresponding to an average wastewater production rate of 246 L per capita and day. Tertiary processes resulted to higher amounts of sludge production; nevertheless, such processes are often required aiming to the reclamation of secondary effluents with a high reuse and acceptability potential. Considering the disposal cost of produced sludge, energy utilization could be a promising alternative method for efficient sludge management. Utilization of the energy content of the sludge was examined by using three options, consisting in anaerobic digestion of dewatered sludge, incineration, and anaerobic digestion followed by residue incineration; it was found that excess energy production reached to high values in the case of combined anaerobic digestion and incineration, while single anaerobic digestion resulted to the lowest power production rates.

Keywords: Sewage sludge; Wastewater treatment; Energy utilization; Ddewatered sludge

1. Introduction

During the last decades, the incorporation of environmental principles in municipal wastewater treatment strategies was associated to a continuous effort for improving the quality of the effluent, by upgrading existing treatment plants and designing and implementation of new more effective treatment plants. This effort simultaneously proceeded with an enforcement of the industrial plants and households for reducing and eliminating the discharge of toxic pollutants into the sewer. In addition to the improvement of the effluent quality, an increasing awareness of the problems associated with the sewage sludge produced in the wastewater treatment plants was observed; these problems include:

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Presented at the 2nd International Conference on Environmental Management, Engineering, Planning and Economics (CEMEPE), Mykonos, Greece, June 21–26, 2009.

- The primary problem in sludge management is a continuous increase in the amounts produced; in 2000 there were over 50,000 wastewater treatment works (WWTPs) operating in the European Union yielding a total of about 7.9 million ton of dry solids [1]. The amount of sludge was increased as the Urban Waste Water Treatment Directive continued to be implemented [2], reaching about 8.3 million ton of dry solids by 2006.
- High costs are required for sludge treatment. In the municipal and industrial wastewater treatment plants, the separation of organic and inorganic particles by sedimentation and the treatment of biodegradable substances by a biological process, produce high quantity of primary and secondary sludge. Sewage sludge in a treatment plant may contain a high fraction of water with a small percentage of solid material and, even after drying out, water may remain greater than 60–70% by weight [3]. As a consequence, a high volume of material must be managed to the final disposal with considerable costs. In general, the costs of sewage sludge treatment often represent more than 50% of the total wastewater treatment costs [4].
- Sewage sludge may impose significant risks on the environment and human health. Today there are well recognised constraints on sludge use due mainly to heavy metals and pathogens that may be present, the occurrence of which reflects the nature of the catchment of the sewage treatment works (i.e. presence of industries, hospitals, abattoirs, combined drainage etc.). Furthermore, there are the potential problems of odour, litter (screenings) and bulk (high water content). While there have been considerable advances in control and treatment technologies in recent years that can reduce potential impacts, albeit with increased costs, sludge quality remains one of the principal constraints on sludge use, particularly as quality standards continue to be tightened [5].

The major applications for sludge are agriculture and landfill, with only a relatively small amount disposed by alternative methods. During the last decade, there has been a worldwide movement toward a common strategy for any kind of waste with the priorities of reusing waste materials and taking advantage of their material and energy content. As a result, European Directives in the recent past, stimulated reuse of sludge from municipal wastewater treatment plants on agricultural soils or in composting factories. Agricultural land has long been the natural outlet for sludge as it contains similar quantities of nitrogen, phosphorus and organic matter as farmyard manure or slurry, making it attractive to farmers as a supplement to other fertilisers, particularly in predominantly arable areas. However, the reduced availability of land, the increased public concerns over food chain safety, and the associated uncertainties and costs of reuse have required water utilities to explore alternative management options that can contribute to a more sustainable sludge strategy [6,7]. Parallel to this development, the government policies and regulations regarding the application of sludge in agriculture have changed considerably, although sludge application and sludge management policies in general are heavily dependent upon local, national, and regional conditions [8,9].

Sewage sludge is expected to remain a permanent waste problem requiring an appropriate solution. It can be considered that sludge management and research into innovative treatment methods will focus on three aspects: recovery and reuse of valuable products and energy from sludge, a complete solution of the sludge problem, especially regarding the toxics, and acceptable costs. In this respect, it can be expected that the recovery of sustainable energy from sewage sludge will become more and more of interest [10].

The aim of this paper was the examination of potential sludge handling methods, for the recovery of the energy content of the sludge, as alternative to more conventional methods and the investigation of the potential application of such methods in Greek conditions where a large number of small scale wastewater treatment plants are in operation, with great variation in the annual amounts of produced sludge.

2. Production and treatment of sludge from wastewater treatment plants

A conventional wastewater treatment plant, consists in two subsequent treatment stages: a mechanical stage followed by a biological stage. Raw waste water comes through a preliminary treatment process, where residues mainly consist in coarse solid particles, grit, sand and grease and are typically disposed of in landfills. Fine undissolved particles sediment in the primary settling tanks (mechanical stage). Chemical dissolved pollutants are usually removed in a biological stage, which consists of the aeration tanks and the final (secondary) settling tanks.

Excess activated sludge from secondary settling tanks and primary sludge from primary settling tanks are mixed together and mixed raw sludge is created with a high water content (suspended solids concentration about 15 g/L). The mixed sludge has to be further treated prior to its utilization or disposal, aiming mainly to the elimination of pathogens and odours and the reduction of water content. On site sludge treatment methods include thickening, followed by anaerobic or aerobic digestion, and dewatering carried out by drying beds or mechanical dewatering devices, such as filter presses, belt presses and centrifuges. Thickened excess activated sludge contains approximately 7% of dry matter, while primary sludge and mixed raw sludge contain about 3% and 5% of dry matter, respectively. The solids content of the dewatered sludge may range from 18% to 35%, depending upon the type of sludge and the dewatering method adopted.

Dewatered sludge is still a material with such properties that may result to the environmental deterioration, due to the presence of pathogens, heavy metals and organic pollutants; thus, stabilization is required, i.e. a process for the reduction of the decomposition properties of sludge to such an extent that offensive odours are minimised, pathogens are eliminated and leaching of metals is reduced [11].

In order to promote the biological treatment of biodegradable wastes (including sludge), by harmonising the national measures concerning their management to prevent or, at least, reduce any impact thereof on the environment, a working document in preparation of a new Directive on this matter has been produced by the European Commission [12].

According to the general principles listed in the 2nd draft, an improved biowaste management should encourage:

- the prevention or reduction of biowaste production and its contamination by pollutants;
- the reuse of biowaste;
- the recycling of separately collected biowaste into the original material whenever environmentally justified;
- the composting or anaerobic digestion of separately collected biowaste with the utilization of compost or digestate for agricultural benefit or ecological improvement;
- the mechanical/biological treatment of biowaste;
- the use of biowaste as a source for generating energy.

Member states are requested to encourage home composting, and on-site composting or anaerobic digestion, whenever there are viable outlets for the resulting material.

As far as anaerobic digestion is concerned, it should have the purpose of reducing biowaste fermentability, maximising the production of biogas and ensuring that the digestate could be used for agricultural benefit or ecological improvement.

In addition, several alternative advanced sludge stabilization processes are recommended in the working document, including:

- thermal drying ensuring that the temperature of the sludge particles is higher than 80°C with a reduction of water content to less than 10%;
- thermophilic aerobic stabilization, as a batch, at 55°C for 20 h;
- thermophilic anaerobic digestion as a batch at 53°C for 20 h;
- pasteurization of liquid sludge at 70°C for 30 min, followed by mesophilic anaerobic digestion at 35°C for 12 days;
- chemical stabilization with lime at pH equal or above 12, maintaining the temperature at 55°C for 2 h;
- chemical stabilization with lime at pH equal or above 12 for 3 months.

3. Wastewater and sludge management conditions in Greece

211 wastewater treatment plants were constructed in Greece till 2008 serving a population of about 85% of the total population, as a result of the requirement for the harmonization of the national legislation to the Urban Waste Water Treatment Directive Council Directive 91/271/EEC. The largest plant is the Psyttalia plant in Athens, which is in operation since 1994, serving the Athens broader area that represents one third of the total country population, and resulting in a considerable improvement of the water quality of the Saronicos Gulf. Sludge production from this plant is about 800 ton/d. The second largest plant is located in Northern Greece, in Thessaloniki, with a treatment capacity of about 120,000 m^3/d and a daily production of 160 ton dewatered sludge.

An estimation of the amounts of sewage sludge produced in Greece, by the existing wastewater treatment plants is presented in Table 1, including the corresponding disposal routes for the period between 1996 to 2008 [13].

As shown in Table 1, about 76% of the produced sludge is disposed in landfills; this percentage represents the highest value between the countries within EU, where approximately 27% of the sludge is disposed in landfills [1]. Currently, treatment and disposal of sewage sludge have become an important issue of the European waste framework first of all because of increasing limitation

Table 1
Treatment methods of sewage sludge produced by wastewater treatment plants in Greece, ton dry solids (DS)/y

Year		1996	1998	2000	2002	2004	2006	2008
DS ton/y		52,000	68,000	76,000	92,500	109,500	119,500	135,500
Disposal route (%)	Within the plant site	1.3	1.2	1.3	1.2	1.3	1.3	18.5
	Agriculture	0.2	1.3	1.3	1.3	1.3	2.5	3.5
	Composting	—	1.0	0.9	1.0	1.2	1.3	1.5
	Landfilling	98.1	96.2	96.1	96.1	95.8	94.5	76.1
	Forestry	0.4	0.4	0.4	0.4	0.4	0.4	0.4

to waste disposal in the landfills. The Council Directive 1999/31/EC on the landfill of waste excluded the disposal of liquid waste (e.g. sludge) to landfills giving a restriction to the general sewage sludge management. This Directive established measures, directions and guidance in order to prevent or reduce the adverse effect on the environment of landfilling of waste. In this regulation stringent operational and technical requirements concerning the waste and the landfilling were provided, mainly giving efforts for reducing the quantity of biodegradable waste going to landfills and discouraging the landfilling of both liquid and untreated wastes. Consequently, the disposal of sludge to landfills should be in the long run eliminated.

On the other hand, for an efficient land application, as described by the Directive 86/278/EEC, effective agronomical quality of sludge with high organic content is required and is achieved only after treatment and under specific safety requirements. Nevertheless direct land application remains the most important alternative for sewage sludge disposal, in particular for sludge produced by small or medium size wastewater treatment plants, with minor pollution by hazardous compounds and located close to the disposal site [12]. Land application of treated sewage sludge can lead to a complete reuse of its nutrients and organic carbon at a relatively low cost. Therefore, this practice should become a preferred management.

From the data presented in Table 1, it is apparent that although there is an adequate national legal framework towards the beneficial use of sludges, as a result of the harmonization to the EU guidelines, much work has still to be done in terms of large-scale sludge reuse schemes.

An efficient sludge management policy could be developed based on the analysis of available information regarding the amounts of produced sludge; furthermore, estimations for the preparation of a sludge plan should take into account potential variations due to the type of the associated wastewater treatment process applied, the local conditions etc. An analysis of the sludge quantitative and qualitative characteristics of sludge from a total number of 37 wastewater treatment plants has taken place during the work, and the corresponding results are presented in the following figures. Specifically, 37 municipal wastewater treatment plants with a population equivalent of about 1.6 million were investigated, located in various places in the country, and the corresponding wastewater influent flow, as a function of population equivalent is shown in Fig. 1.

The corresponding annual sludge quantities produced by the target plants as a function of the population equivalent and the applied process are shown in Figs. 2 and 3, on a dry and wet basis respectively, while the relation between the wastewater flow and the corresponding sludge production is illustrated in Fig. 4. As shown in Figs. 2 and 3, sludge production increases by the plant capacity: the higher the number of the population equivalent, the larger the produced sludge. In addition, process scheme seems to increase, as expected, the amount of produced sludge. As a result, about 3,300 ton/y of a dry sludge are produced from a population equivalent of 100,000 inhabitants, by tertiary treatment of wastewaters, while about half this amount, 1,600 ton/y are produced by secondary treatment of the influents.

Furthermore, as shown in Fig. 4, a linear relationship is established between the influent flow and the produced sludge on a dry basis, with advanced treatment systems usually located at the upper limits. The per capita wastewater and sludge production for the various wastewater treatment plants of the current study are shown in Figs. 5 and 6 respectively.

As shown in these figures, the daily wastewater production varied from 100 up to 450 L/d-p, which represents typical range of municipal influents; average value estimated to 250 L/d-p. On the other hand, sludge production ranged from 18 to 150 g DS/d-p, with an average value of about 40 g DS/d-p. This value is close to the typical value of 50 g DS/d-p. Estimation of the total sludge production from the wastewater treatment plants under operation is required for the preparation of a sludge management

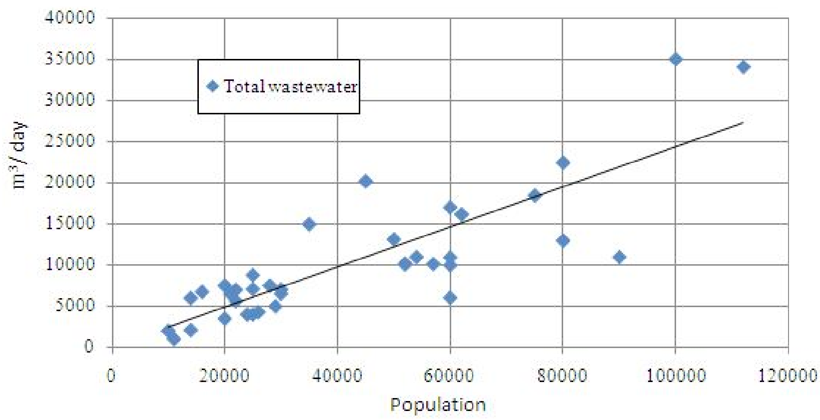

Fig. 1. Wastewater influent flows in the studied municipal wastewater treatment plants.

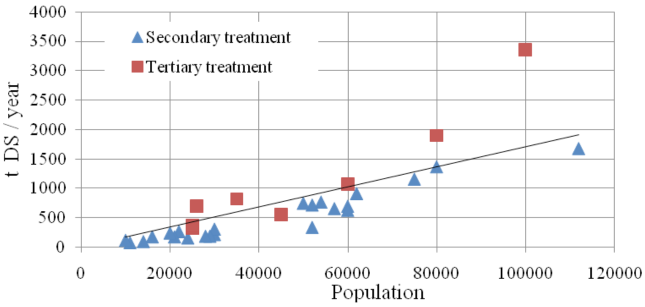

Fig. 2. Sludge production (on a dry solids basis) as a function of process type and equivalent population from 37 municipal wastewater treatment plants in Greece.

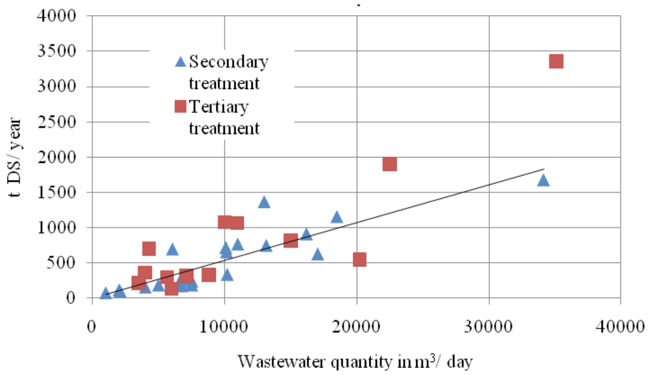

Fig. 4. Sludge production (on a dry basis) as a function of process type and wastewater flow.

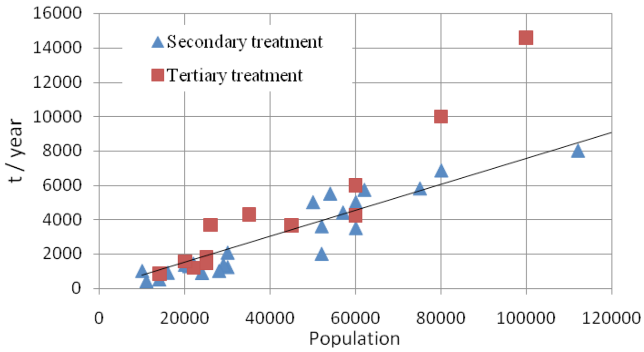

Fig. 3. Sludge production (on a wet basis) as a function of process type and equivalent population from 37 municipal wastewater treatment plants in Greece.

plan. Projection of available sludge production data was performed aiming to the calculation of sludge produced from the existing plants during the next 25 years, and the corresponding results are presented in Fig. 7.

The total sludge production from the 211 treatment plant under operation in Greece was estimated to about 160,000 ton DS/y in 2030, considering that the average value of 40 g DS/d-p will remain constant (intermediate scenario). In addition, two more cases were examined as shown in Fig. 10: a best case scenario was applied (optimistic scenario), taking into account that all facilities would be upgraded to tertiary treatment level providing the highest sludge production rate, corresponding to about 50 g DS/d-p; and a worst case scenario (pessimistic scenario) where all facilities would have a low sludge production rate, corresponding to the average value of secondary treatment units, i.e. to 30 g DS/d-p.

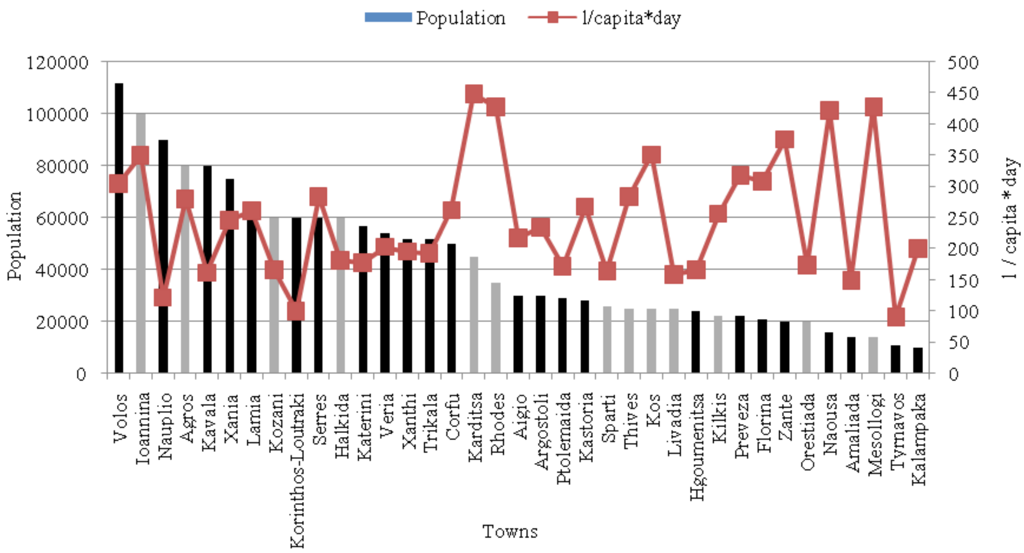

Fig. 5. Per capita daily flow of wastewaters in the studied municipal wastewater treatment plants.

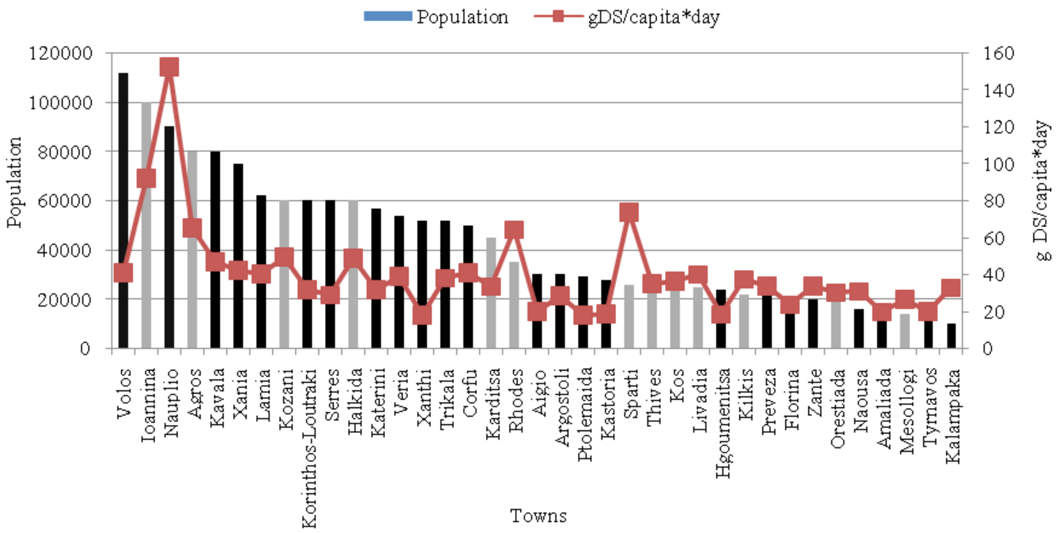

Fig. 6. Per capita daily production of sludge (on a dry basis), for the studied municipal waste treatment plants.

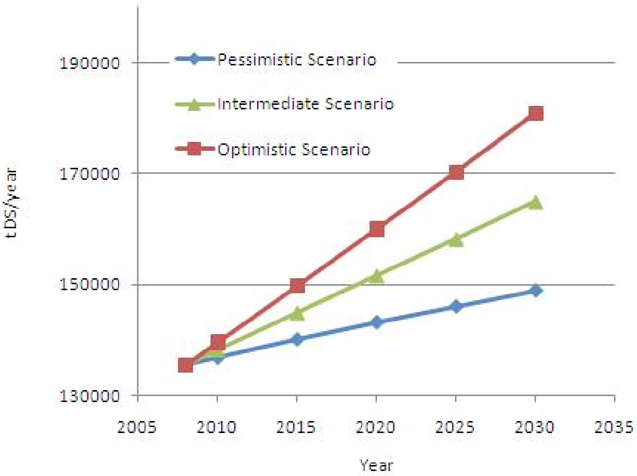

Fig. 7. Estimation of total sludge production from existing treatment facilities till 2030.

4. Potential for utilization of the energy content of municipal sewage sludge

Wastewater comprises a mixture of organic and inorganic compounds, and associated water. The organic component of the sludge displays a heat value of approximately 25 MJ/kg-dried solids. Considering the inert fraction in the sludge this value is reduced to 16–20 MJ/kg-ds for raw sludge, or 10–14 MJ/kg-ds for digested sludge [14]. These values can be considered the upper limits of energy recoverable from the sludge. As a result, feasible alternative technologies for sludge management should include the utilization of the high energy content of the sludge. The energy utilization of sludge may include various alternatives such as anaerobic digestion and subsequent utilization of the produced biogas or thermal treatment, mainly incineration.

Since sludge is initially a suspension, the large quantity of associated water makes it a low-density energy source. The moisture in the sludge is bound with the solids phase by a certain binding strength [15]. This binding strength limits mechanical dewatering. The wastewater sludge from the clarifiers has a solids fraction of 1–5%. Sludge incineration is influenced mainly by the lower heating value (LHV) of sludge. The LHV value of the clarifiers' suspension is around 0.16–0.8 MJ/kg-sludge. This suspension is usually subjected to anaerobic digestion treatment. Chemical conditioning followed by mechanical dewatering are frequently applied to further remove the free water from wastewater sludge. Following mechanical dewatering, the moisture content in the dewatered cake is ranged from 70–85% w/w. The LHV of mixed raw sludge is approx. 15 MJ/kg of dry matter, while the LHV of anaerobic digested sludge is approx. 12 MJ/kg of dry matter [7,8]. However, common dewatered sludge contains usually 20–30% of dry matter and the LHV is very low; thus, the dewaterability process represents a key component in any process based on the utilization of the energy content of the sludge [16].

The utilization of sewage sludge was examined in this work, for the three scenarios (intermediate, optimistic and pessimistic sludge production rate), according to the following alternative techniques [16]:

- Case 1 – anaerobic digestion of mixed raw sludge with subsequent cogeneration from the obtained biogas.
- Case 2 – incineration of mixed raw sludge utilizing energy contained in the flue gas via cogeneration.
- Case 3 – incineration of anaerobic digested sludge, utilizing energy contained in both the biogas and the flue gas via cogeneration.

Regarding the energy utilization of biogas, a great number of legislative measures and financial directives are today available to support biogas investments in Greece and a series of information campaigns aiming to public awareness and stakeholders' involvement in the biogas market have been established. Biogas in Greece is promoted in the electricity market to reduce both dependence on imports and exposure to international energy markets, as well as to reduce GHG emissions in the atmosphere. The primary production of biogas in 2006 and 2007 in Greece, originating from various sources and the corresponding data are summarized in Table 2 [17].

The energy balance was performed in each alternative case in order to estimate the feasibility of each option, considering the same amount of dewatered sludge as a basis for calculations. Anaerobic digestion in the first and the third method resulted in the production of biogas which was then burnt in the cogeneration units, resulting to energy release in the form of electric power and heat used for maintaining a constant temperature at the digesters, sludge heating, or other uses (e.g. heating of buildings). The sludge residue produced by the digesters is treated by different methods, in each case: in Case 1, the residue is landfilled, while in Case 3, sludge is further utilized by thermal treatment (incineration) and flue gases are used for steam production. Steam is then utilized for power production in a steam turbine. Dewatered sludge is directly incinerated in Case 2 and power produced through a steam turbine is utilized for electric power and heat production.

Table 2
Biogas annual production rates in Greece from various sources, during 2006 and 2007, in kton [10]

Year	Landfill gas	Sewage sludge digestion	Total
2006	21.2	8.6	29.8
2007	38.0	9.8	47.8

The highest amount of excess energy was obtained by incineration of mixed raw sludge (Case 2). The case with the lowest energy efficiency proved to be the single anaerobic digestion of sludge (Case 1) since the energy content of digested sludge is not further used. Biogas production on one hand and auxiliary fuel consumption on the other result to ranking Case 3 between Cases 1 and 2. The calculated results considering a daily production of sludge of 111 tons of dry matter were:

- Case 1 – anaerobic digestion of mixed raw sludge with subsequent cogeneration of obtained biogas — 1.378 MWh/ton dry matter.
- Case 2 – incineration of mixed raw sludge utilizing energy contained in flue gas — 1.706 MWh/ton dry matter.
- Case 3 – incineration of anaerobic digested sludge utilizing energy contained in biogas and flue gas —1.477 MWh/ton dry matter.

The potential for the energy utilization of sewage sludge in Greece, considering the three scenarios of sludge production till 2030, as given in Fig. 7, and taking into account the above values of power production, were calculated, and the corresponding results are shown in Fig. 8 for the anaerobic digestion case, in Fig. 9 for the incineration of the sludge, and in Fig. 10 for the anaerobic digestion followed by the incineration of the residue.

As shown, anaerobic digestion resulted to the lowest values of energy release, reaching up to 250×10^3 MWh, even considering the highest annual sludge production rate. Higher power production was calculated for the combined alternative, where anaerobic digestion of sludge is coupled to residue incineration, while the high-

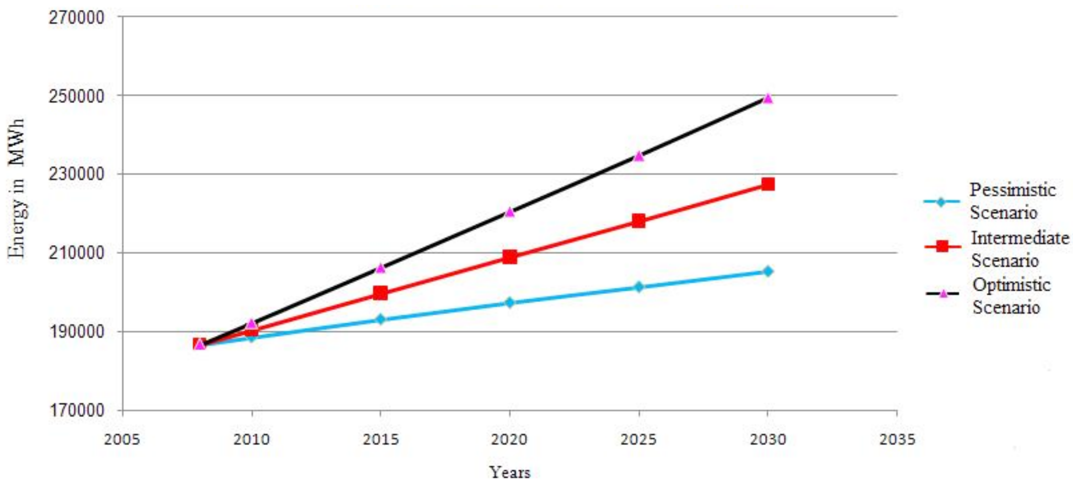

Fig. 8. Potential of excess energy production during anaerobic digestion of sludge, in Greece, under three different regimes of municipal sludge annual production.

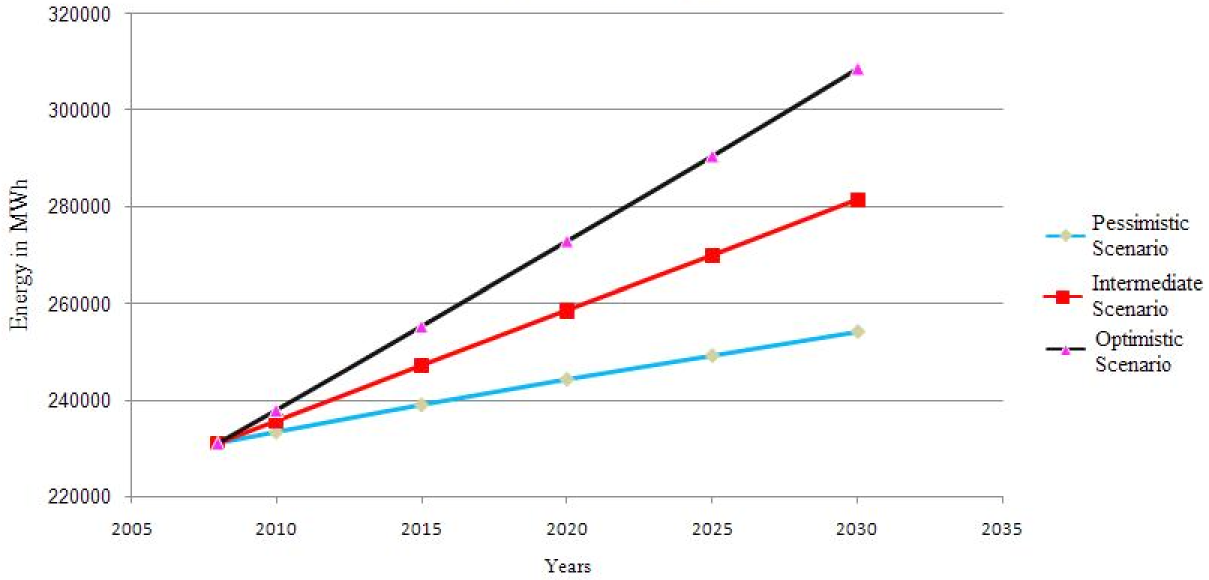

Fig. 9. Potential of excess energy production during incineration of sludge, in Greece, under three different regimes of municipal sludge annual production.

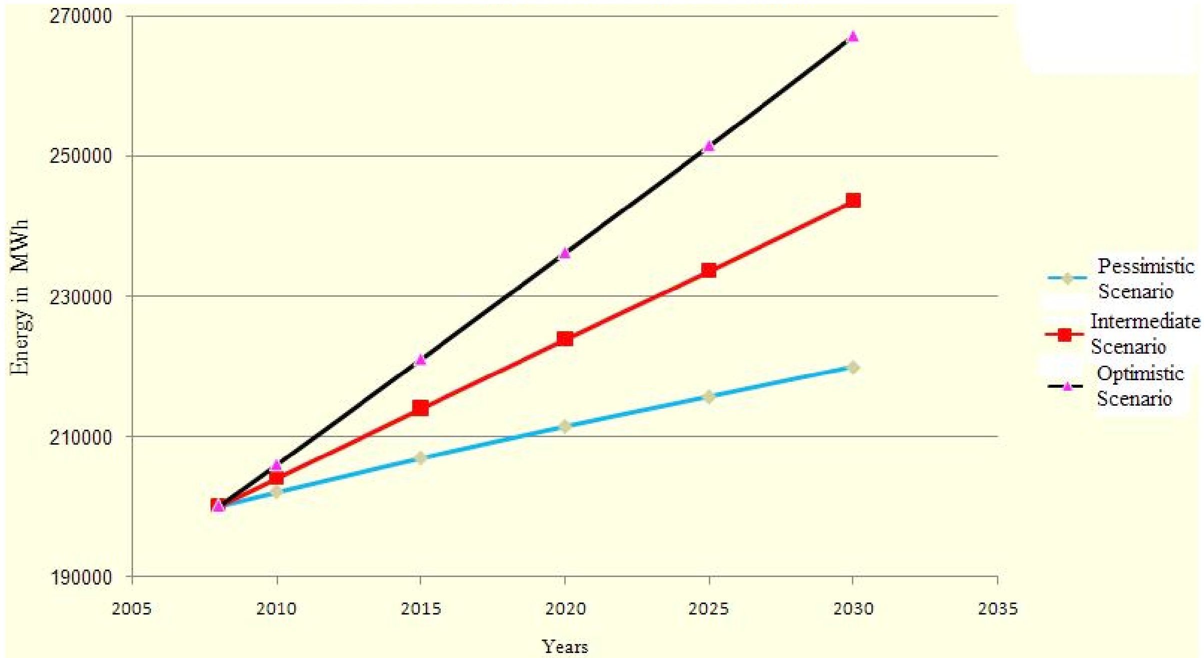

Fig. 10. Potential of excess energy production during anaerobic digestion followed by residue incineration, in Greece, under three different regimes of municipal sludge annual production.

est values of energy utilization were calculated for the direct incineration of dewatered sludge; excess energy in this case exceeded 300×10^3 MWh, and was always higher than the single anaerobic digestion, even for the worst scenario of the lowest sludge production rate.

According to these results, energy utilization of sludge seems a promising technique for enhancing the energy balance in the country. However, several parameters have to be considered such as costs of collecting and transferring the sludge, ash disposal costs, flue gas treatment devices etc, that may affect the cost of the final solution. Nevertheless, energy utilization of sludge represent a challenge and a better option to the current conditions, where sludge is considered as a waste and it is disposed in landfills or stored on-site, while there is a lack of efficient management methods, with negligible environmental effects.

5. Conclusions

The preparation of an appropriate municipal sludge plan should include two main components: estimation of the annual sludge production rate and the corresponding variations, and examination of the alternatives technologies available for an integrated recovery/utilization of both materials and energy content of sludge.

37 sewage treatment plants, serving a population equivalent of about 1.6 million, located throughout Greece, were investigated during this study, in order to determine the sludge production rates and the effect of the treatment level, secondary and tertiary, on sludge. The average sludge production rate was estimated to 40 g dry solids per capita per day, with an average wastewater production rate of 246 L per capita and day. In addition, wastewater treatment plants employing tertiary processes, resulted to higher wasted sludge amounts than secondary systems; nevertheless, such processes are required in order to produce an effluent with a high reuse potential.

Energy utilization of the produced sludge was examined considering three alternative options: anaerobic digestion of sludge, biogas cogeneration and landfilling of the residue; incineration of the sludge and power production through a steam turbine; and anaerobic digestion followed by incineration of the residue. The total sludge production from the existing 211 sewage treatment plants in Greece was estimated and potential future sludge and wastewater production was calculated up to the year 2030 for 3 different scenarios. It was found that direct incineration of dewatered sludge was the best option offering a high excess energy balance, while single anaerobic digestion resulted to low energy production rates. However, utilization of the energy content of sewage sludge should represent a promising alternative to the current methods, where landfilling is prevailing, with significant environmental impacts.

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