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Energy Production from Sewage Sludge in a Proposed Wastewater Treatment Plant

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Abstract

The implemented technologies for sewage sludge processing are still very limited in Egypt. Unfortunately, dealing with the produced sludge is mainly given to the drying process through natural drying beds neglecting quality of the dried sludge. The undertaken work is devoted to provide a design proposal for a typical wastewater treatment plant suitable for the small communities on a very limited area of land compared to that required to construct the conventional treatment plant that serves the same population. The proposed sewage treatment plant is certainly beneficial in reducing the capital costs by 26%, in addition to about 20% reduction in the running costs. On the other hand, electricity generated from energy produced by anaerobic digestion of sewage sludge reduces the electrical power requirements from the main grid network to about 27% in the proposed wastewater treatment plant.

Keywords: Capital Costs; Electricity; Energy Production; Running Costs; Sewage Sludge Processing; Wastewater Treatment.

1. Introduction

Egypt faces great challenges due to the deficit in the balance of power and the gap between what is available and what is required for economic and social development. Therefore, it is necessary to seek non-conventional sources of energy and cost-appropriate, in the same context.

The sewage sludge production in Egypt is rapidly increasing due to the continuous growth of population, urban planning, expanding in construction of the infrastructure projects and the industrial developments. This sludge needs to be effectively treated and environmentally managed to reduce the negative impacts of its application or disposal [1, 2]. On the other hand, the Egyptian communities with high population density suffer from scarcity and limited land availability to accommodate new sewage treatment plants. Therefore, this problem creates a research challenge to optimize occupying the available land or more precisely reduce the land requirements for construction of new sewage treatment plants if available [3].

The implemented technologies for sewage sludge processing are still very limited in Egypt. Unfortunately, dealing with the produced sludge is mainly given to the drying process through natural drying beds neglecting quality of the dried sludge, in addition to disadvantages of the drying beds (i.e. large land requirements, stabilization of the sludge, and dealing with climate change conditions). Recently, there has been a great interest for the sewage sludge management because of the various and serious environmental impacts [1, 3-5].The innovative sludge treatment methods focus on energy recovery, reuse of valuable products from sludge after eliminating the toxins, and acceptable running costs [4, 6].

The formation of sewage sludge is characterized by six groups of components: (1) nontoxic organic carbon compounds (approximately 60% on a dry basis), for a large part from biological origin, (2) nitrogen and phosphorous containing components, (3) toxic organic and inorganic pollutants, i.e., (a) heavy metals, such as Zn, Pb, Cu, Cr, Ni,

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Cd, Hg (concentrations vary from more than 1000 ppm to less than 1 ppm) and (b) polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons, pesticides, nonyl-phenols, polybrominated fire retardants, etc., (4) pathogens, (5) inorganic compounds, such as silicates, calcium and magnesium containing compounds, and (6) water, differing from a small percentages to more than 95% [4].

Rulkens [4] divided energy recovery from the organic compounds in the sludge into nine groups: (1) anaerobic digestion of sewage sludge, (2) extraction of biofuels from sewage sludge, (3) direct production of electricity from sewage sludge, (4) incineration of sewage sludge with energy recovery, (5) co-incineration of sewage sludge in coal-fired power plants, (6) gasification and pyrolysis of sewage sludge, (7) utilization of sludge as an energy and raw material source in the production of Portland cement and construction materials, (8) supercritical wet oxidation of sewage sludge, and (9) hydrothermal treatment of sewage sludge. Several of these treatment options are already applied in practice; others are still in the research phase.

Anaerobic digestion is one of the most widely used procedures for wastewater sludge stabilization. The process transforms organic solids in sludge, in the absence of oxygen, to gaseous end products such as methane and carbon dioxide and to innocuous substances. A net reduction in the quantity of solids and destruction of pathogenic organisms are also accomplished in the anaerobic digestion process [4, 7-12]. Anaerobic digestion offers several advantages over the other methods of sludge stabilization, which produces methane gas and digested biosolids [8, 13]. The methane gas produced is a source of usable energy. In most cases, the energy produced exceeds the energy required to maintain the temperature for sludge digestion. Excess methane can be used for heating buildings, running engines for aeration blowers, or generating electricity. In addition, the digested biosolids include nutrients such as nitrogen and phosphorus, and organic matter that can improve the fertility and textures of soils.

Ghazy et al. [1] concluded that the application of anaerobic digestion process with energy recovery is shown to be a promising option for sewage sludge processing in Egypt. It prompts to the most reduced economic costs and environmental impacts because of energy recovery. The biogas production has a mitigating effect of environmental impacts because of fossil fuel substitution in addition to economic benefit due to the electrical generation [12]. In addition, Rashed et al. [3] recommended anaerobic digestion of sewage sludge after chemically enhanced primary treatment (CEPT) of sewage.

Nowak et al. discussed optimization of the energy balance of municipal wastewater treatment plants (WWTPs) in Austria. Nowak et al. [14] reported that the electricity production from biogas produced in two advanced WWTPs in Austria is sufficient for the consumption in these WWTPs. Moreover, IEA Bioenergy Members [15] reported that the electricity production from produced biogas in 45 WWTPs was 31 GWh/ year in 2012.

In Brazil, there are 5 biogas power plants installed on sewage sludge produced from WWTPs and connected to the electric grid to produce 42 GWh/ year in 2013. On the other hand, in Denmark, there are 65 biogas power plants installed on sewage sludge produced from WWTPs and connected to the electric grid to produce 220 GWh/ year in 2010. In Finland, the electricity production from sewage sludge processing was 135 GWh/ year in 2012 resulting from 15 biogas power plants. The corresponding value of the electricity production in France was 97 GWh/ year in 2012 produced from 60 biogas plants [15].

Chemically enhanced primary treatment (CEPT) is a wastewater treatment method that serves as a smart alternative to the conventional primary treatment. It can also be used as an efficient preliminary step of the biological secondary treatment processes. CEPT embraces coagulation and flocculation, and it accomplishes remarkable increases in the pollutants removal from the influent [3, 16-18]. Chemical precipitation is the technique of the CEPT process, the main idea of chemical precipitation that it converts soluble substances to insoluble particles, which can be flocculated and separated from the liquid. Removal efficiencies depend on coagulant (type-dosage), mixing times, and the care with which the processes are observed and controlled. With chemical precipitation, it is achievable to remove about 80-90% of total suspended solids (TSS), 50-80% of biochemical oxygen demand (BOD5), 30-70% of chemical oxygen demand (COD), 80-95% of the phosphorus as well as 20-25% of the nitrogen in the primary sedimentation. In comparison, well designed and operated primary settling tanks without addition of the coagulants may remove between 50-70% of TSS, 25-40% of BOD5 and 5-10% of phosphorus [17, 19-22].

The undertaken work is devoted to provide a design proposal for typical wastewater treatment plant suitable for the small communities on a very limited area of land compared to those required to construct the conventional treatment plant that serves the same population. In addition, this work aims to study the possibility of biogas production from sewage sludge after CEPT of sewage that can be used to produce part of the electricity consumed in the plant, which reduces the consumption of electric power from the main grid under a national strategy to rationalize energy consumption.

2. Methodology

2.1. The Provided Technology

The provided technology in the present study is using chemical pre-precipitation or CEPT of wastewater using alum [$Al_2(SO_4)_3.14H_2O$] as coagulant with an average dose of 80 mg/L with the average values of different parameters of sewage as shown in Table 1. to complete the coagulation, flocculation, and sedimentation processes in the swirl flow hydraulic clariflocculators investigated by Rashed et al. to carry 150-200% of the designed capacity of the conventional primary sedimentation tanks with the same dimensions [3, 23].The following Figure 1. displays the designed hydraulic clariflocculator to carry sewage discharge of 1250 m^3/d. On the other hand, CEPT produces large amounts of primary sludge with significant organic content, which can be anaerobic treated to produce biogas. Primary sludge thickeners and anaerobic sludge digesters should be constructed to complete the process of biogas production followed by electricity generators to produce part of the electricity consumption of the sewage treatment plant.

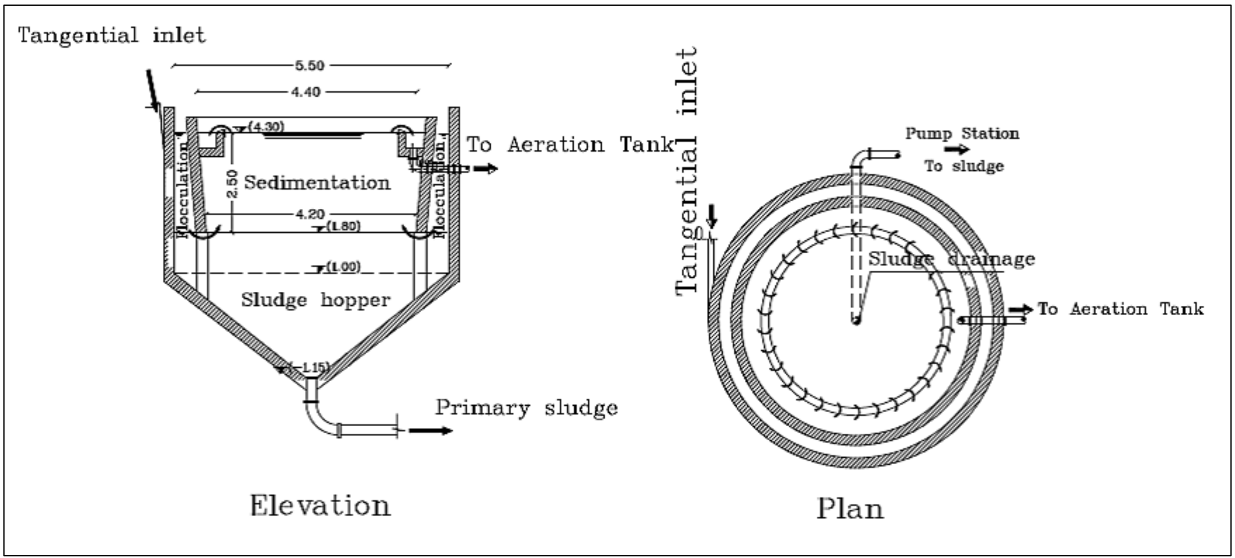

Figure 1. The designed hydraulic clariflocculator

2.2. The Proposed Wastewater Treatment Plant

The proposed wastewater treatment plant as shown in Figures 2 and 3. was designed to treat 2500 m^3/d of municipal wastewater appropriate for conditions of the Egyptian villages. Table 1. represents the wastewater characteristics of the proposed plant and it annotated with appropriated alum dose (i.e. 60-100 mg/L) according fluctuations of wastewater characteristics. Furthermore, it is noticed that wastewater is moderately biodegradable before and after CEPT process from BOD5/COD ratio shown in Table 1. according to Metcalf & Eddy [19].

The proposed plant is provided to enhance the primary treatment after inlet chamber, screens, and grit removal using chemical pre-precipitation technique via the previously mentioned hydraulic clariflocculators by applying 96 minutes as a retention time (30 minutes for flocculation process +66 minutes for sedimentation process) instead of 120 minutes (2 hours at least) for the conventional primary sedimentation process. In addition, the hydraulic clariflocculators were designed to remove at least 60% of BOD5, and 80% of TSS as results from the previous studies [3, 18, 22] instead of 30% of BOD5, and 60% of TSS in the conventional primary sedimentation [20]. Therefore, the consecutive activated sludge system (aeration tanks, final clarifiers, etc.) can be designed to receive only 40% of influent BOD5 in raw sewage. This leads to get relatively small units compared with the designed after the conventional primary treatment [3], as well as reduction in the land requirements to preserve the agricultural areas in Egypt.

Table 1. Wastewater characteristics in the proposed wastewater treatment plant

Parameter	Raw sewage		Effluent (maximum values)	
	Range	Average	After CEPT	After biological treatment
TSS, mg/L	350-450	400	80	30
COD, mg/L	700-900	800	300	50
BOD_5, mg/L	400-600	500	200	40
TOC, mg/L	250-350	300	220	100
Biodegradability BOD_5/COD	0.44-0.86	0.63	0.67	0.8
T-P, mg/L	9-11	10	2.0	1.0
T-N, mg/L	20-24	22	15.0	10
$N\text{-}NH_3$, mg/L	12-16	14	5.0	4.0

Note:
***Alum ranges is between 60 to 100 mg/L according to fluctuations of wastewater characteristics in the present study. Alum was determined to become 80 mg/L with the average values of different parameters as shown in Table 1.**

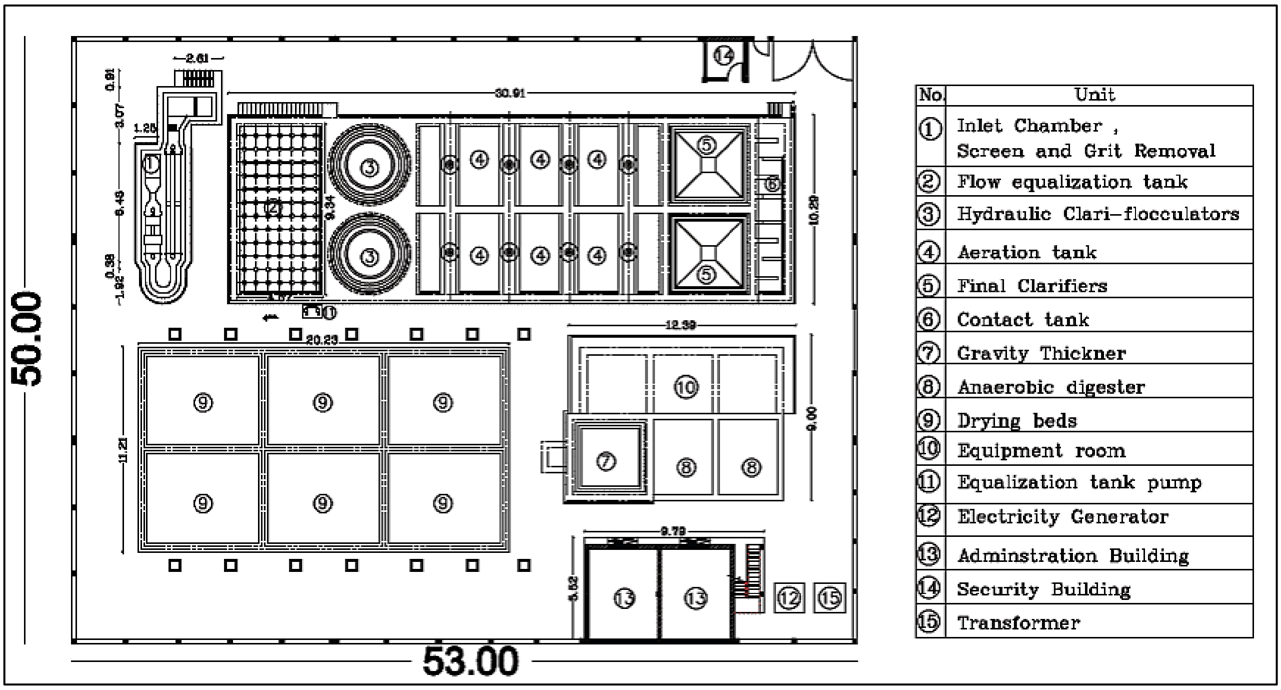

Figure 2. A general layout for the proposed wastewater treatment plant

Chemical pre-precipitation produces large amounts of primary sludge with great organic content, which can be treated anaerobically to produce biogas; a gravity sludge thickener and anaerobic sludge digesters should be constructed to complete the system of biogas production as shown in Figure 2. Thereafter, the methane resulting from biogas can be delivered to the electricity generator to produce a part of the electrical power required to operate the sewage treatment plant.

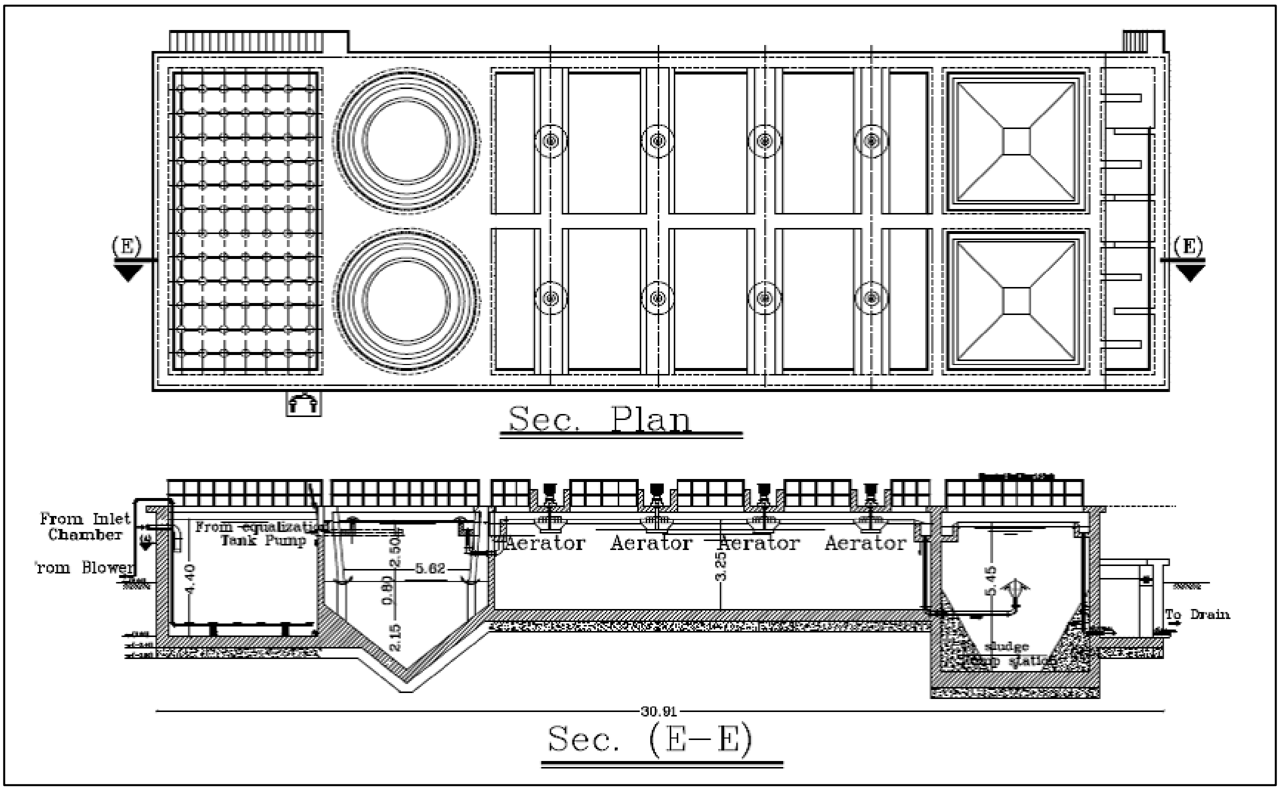

Figure 3. Section elevation in the compact unit in the proposed wastewater treatment plant

3. Results and Discussions

3.1. The Operational Conditions of the Proposed Plant

Table 2. shows a summary of the estimated operational conditions of the proposed wastewater treatment plant. Moreover, the results were compared with the typical design criteria for the conventional activated sludge process [19].

Table 2. The estimated operational conditions for the proposed WWTP

Parameter	The proposed WWTP	Design criteria [19]	Notes
Average influent flow rate (m^3/d)	2500	-	-
Volume of hydraulic clariflocculator tank (m^3)	66.5 × 2 units	-	-
Retention time of hydraulic clariflocculator (hr)	1.6	1.5-2.5	CEPT reduces retention time and increases the overflow rate
Surface overflow rate (m^3/m^2/d)	55	30-50	
Volume of aeration tank (m^3)	208 × 2 units	-	-
Volume of final sedimentation tank (m^3)	98 × 2 units	-	-
Aeration period (θ) (hr)	5	4-8	-
Mean cell residence time (θ_c) (day)	10	3-15	-
Mixed liquor suspended solids (MLSS) (mg/L)	3500	1000-3000	-
Food/Mass of microorganisms (F/M) (Kg BOD_5/Kg MLSS)	0.3	0.2-0.4	-
Waste sludge flow rate (Q_w) (m^3/d)	12	-	-
Mass of solids produced (Kg/d)	1156	-	-

Volume of anaerobic digester (m^3)	100 × 5 units	-	-
Biogas production (m^3/d)	440	-	-
Methane production (m^3/d)	286	-	-
Electric power production rate from biogas* (KWh/d)	400	-	20% consumed for boilers

Notes:
*** Electricity production rate can be estimated as 800 KWh/total solids (t/d), or 1.3-1.5 KWh/m3 of biogas as reported in [24].**

In Table 2, it is noticed that the operational conditions in the proposed WWTP are still in the appropriate values. Moreover, the excess sludge production can be treated using anaerobic digesters to produce about 440 m^3/d of biogas, which can be used to generate about 400 KWh/d of electric power.

3.2. The Economic Feasibility Study

The cost of the proposed WWTP has been estimated based on the current prices of the year 2016 and the costs of recently constructed plants. The intention of this estimation is to introduce a comparative cost analysis between the proposed wastewater treatment plant and another conventional wastewater treatment plant with the same design discharge of 2500 m^3/d [25, 26].

3.2.1. The Costs of the Proposed Wastewater Treatment Plant 2500 m^3/d

3.2.1.1. The Fixed Capital Costs

The fixed capital costs of the proposed WWTP (2500 m^3/d) have been estimated based on the current prices of the year 2016, and referring to USAID [25] as shown in the following Table 3.

Table 3. The fixed capital costs of the proposed WWTP [25, 26]

Item	Cost (EGP)
Civil works (excluding the sludge processing system)	4,500,000
Mechanical and Electrical works (excluding the sludge processing system)	1,500,000
Anaerobic digesters and accessories	1,000,000
Electricity generators	360,000
Total fixed capital costs	7,360,000
Total fixed capital costs per 1 m^3 of wastewater	$7{,}360{,}000/2500 = 2944$

3.2.1.2. The Operating Costs

The costs of chemicals required for the proposed WWTP are shown in Table 4. based on the current prices of the year 2016. Moreover, the costs of power required for the proposed WWTP were estimated depending on the KWh expenses 0.23 EGP based on the current prices of the year 2016. In addition, the methane produced from the anaerobic digestion can be used for the generation of 400 KWh/day, there is 80 KWh/day have to be deducted from this production used for the operation of the hot boilers for the anaerobic digestion process [8]. Therefore, the excess electricity power becomes 320 KWh/ day. The electricity consumption of the proposed WWTP is 1200 KWh/m^3/d [26]. Hence, the daily-consumed power from the main grid network is 880 KWh/day. Therefore, the reduction of the electricity requirement from the main grid network is about 27%. The costs are shown in Table 4. Furthermore, maintenance of the plant reaches to about 1.0 % of total fixed capital costs as shown in Table 4 [24, 26].

The costs of labor and employment salaries for the plant are shown in Table 6. based on the current plan for the year 2016.Additionally, fixed charges for civil construction are about 2.5% depending on that the life period of concrete is about 40 years. Besides, fixed charges for mechanical and electrical equipments are about 6.6% depending on that the life period is about 15 years. The mentioned costs are shown in Table 4.

Table 4. The operating costs of the proposed WWTP [8, 25, 26]

Item		Cost (EGP/year)
Chlorine, 6.0 mg/L = 5.50 tones/ year (1800 EGP / ton)		9900
Alum, 80 mg/L = 73.0 tones/ year (2000 EGP / ton)		146000
Power consumption		$880 \times 0.23 \times 365 = 73876$
Maintenance		$0.01 \times 7{,}360{,}000 = 73600$
Labour and employment salaries	1 First technician (2200 EGP / month)	26,400
	1 Technician (1800 EGP / month)	21,600
	1 worker (1200 EGP / month)	14,400
Fixed charges (depreciation)	Depreciation of civil construction	$0.025 \times 4{,}500{,}000 = 112{,}500$
	Depreciation of mechanical and electrical works	$0.066 \times (1{,}500{,}000 + 1000{,}000 + 360{,}000) = 188{,}760$
Total annual operating costs for WWTP (2500 m^3/d)		667036
The treatment cost of 1 m^3 of wastewater		$\frac{667036}{2500} \times 365 = 0.74 \frac{EGP}{m^3}$

3.2.2. The Comparative Cost Analysis

The comparative cost analysis was conducted for the proposed WWTP versus a recently constructed conventional wastewater treatment plant with the same design discharge of 2500 m^3/d based on the fixed capital costs and the operating costs. The operating costs include costs of chemicals, power, labor requirements, maintenance, and depreciation of the fixed capital costs (i.e. civil works, and electro-mechanical works) as presented in Table 5. Costs of the conventional WWTP were obtained from GHWSC [26].

Table 5. Results of the comparative cost analysis for the proposed WWTP versus the conventional WWTP

Item		The proposed WWTP (2500 m^3/d)	The conventional WWTP (2500 m^3/d)
The Fixed capital costs (EGP/m^3/d)	Civil works, Mechanical, and Electrical works (EGP/m^3/d)	2944	4000
The operating costs (EGP/m^3)	Chemical costs (EGP/m^3)	0.173	0.010
	Power costs (EGP/m^3)	0.082	0.283
	Maintenance (EGP/m^3)	0.082	0.110
	Labour requirements (EGP/m^3)	0.069	0.069
	Depreciation (EGP/m^3)	0.334	0.458
Total treatment cost of 1 m^3 of wastewater (EGP)		0.74	0.93
Notes		Calculated from section 3.2.1	Obtained from GHWSC [26]

The above analysis shows that the treatment cost of 1 m^3 of sewage by the proposed WWTP reduced to about 80 % of that produced by the conventional WWTP. Figure 4. indicates the comparison between the two schemes from the operating cost point of view. Moreover, the reduction in the capital costs is about 26%. The obtained results revealed that using of CEPT technology with anaerobic digestion of sewage sludge is definitely advantageous in reducing the capital costs by 26% and the treatment costs by 20%. It is expected to obtain more cost reductions with relatively high-capacity wastewater treatment plants [1, 5].

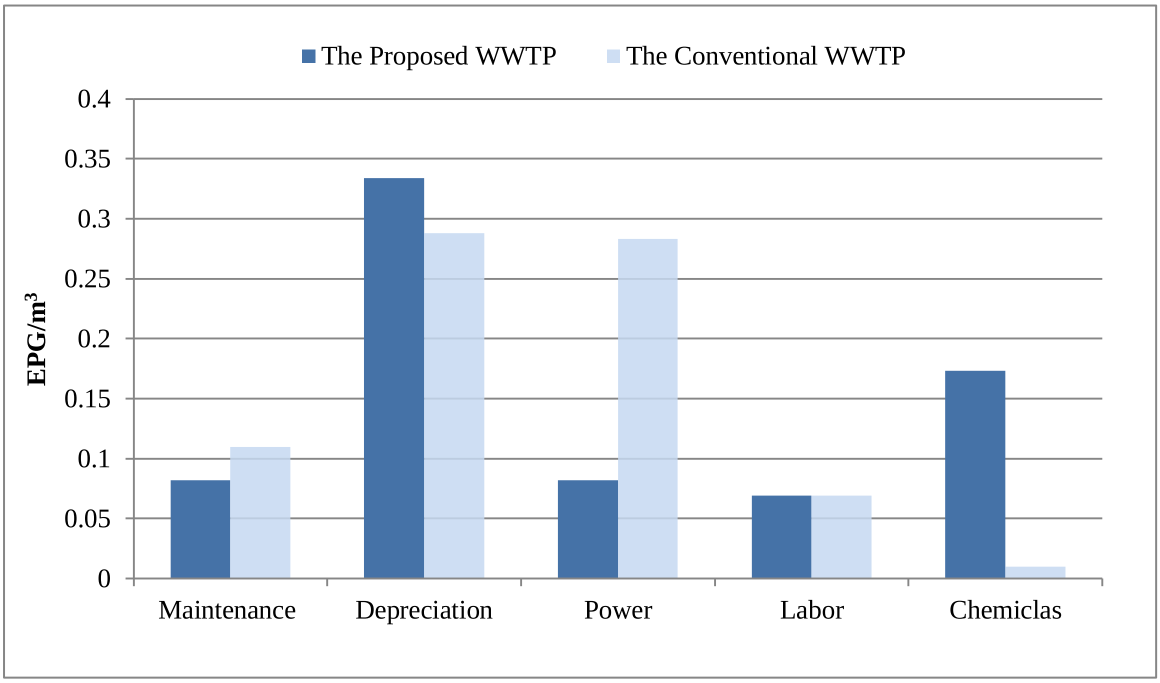

Figure 4. Comparison between the operating costs of the proposed WWTP versus the conventional WWTP

It is worth noting that despite the noticeable reduction in the operating costs in the proposed WWTP by using of chemicals to improve the primary treatment, which lead to the reduction of electricity consumption, but it can get more reduction in the operating costs if the calculated electricity price is free instead of its price as it subsidized in Egypt.

4. Conclusion

Chemically enhanced primary treatment (CEPT) of wastewater with anaerobic digestion of sewage sludge is a promising technique for construction of new sewage treatment plants in Egypt. This technique reduces capital and operating costs when compared with the conventional sewage treatment plants in Egypt.

Electricity production after anaerobic digestion of sewage sludge reduces the electrical power requirements from the main grid network to about 27% in the proposed wastewater treatment plant. Furthermore, more reductions can be acquired with relatively high-capacity wastewater treatment plants that reach up to 60%. On the other hand, the application of CEPT with anaerobic digestion of sewage sludge in Egypt can be more economic if the electricity price is not subsidized by the Egyptian Government.

Using CEPT technology with anaerobic digestion of sewage sludge is certainly beneficial in reducing the capital costs by 26% that leads to acquire the same cost reduction in the maintenance and depreciation costs, in addition to about 20% reduction in the running costs in comparison with the same capacity of conventional sewage treatment plant. It is expected to get more cost reductions with relatively high-capacity wastewater treatment plants.

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