# APPLICATION OF ANAEROBIC DIGESTION FOR SEWAGE SLUDGE STABILIZATION IN EGYPT: ECONOMIC ASPECTS AND AREA OF APPLICATION

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## Abstract

Sewage sludge production in Egypt is continuously increasing. Therefore, the pressing needs are to find/develop more efficient, economic and sustainable technologies for sludge treatment. For many years, the main attention was devoted only to sludge drying processes, mainly through natural drying beds, without any interest to sludge quality. Recently, there is an increasing interest in the application of anaerobic sludge stabilization and power generation. The main objectives of this paper are to evaluate and compare the application of aerobic and anaerobic digestion processes for sewage sludge stabilization with respect to various parameters including energy balance, environmental impacts, sludge capacities and economic aspects. Moreover, the area of application for aerobic/anaerobic digestion processes according to the Egyptian conditions is evaluated. The study showed that, while continuous operation of the aerobic digestion process requires approximately 1176 kWh/ton of dry digested solids, the energy recovery from the anaerobic digestion process is estimated to be 667 kWh/ton electrical energy and 678 kWh/ton thermal heat. The economic analysis showed that, the anaerobic digestion process becomes more cost effective for wastewater treatment plant of capacity greater than 40,000 inhabitants (8000 $m^3$/day) under Egyptian conditions. Furthermore, the life cycle assessment analysis demonstrates that the anaerobic digestion process is the most environmentally friendly for all tested environmental impact categories.

## Keywords

Anaerobic digestion, aerobic digestion, environmental impacts, economic aspects, area of application, life cycle assessment, Egypt.

## Introduction

For a long period, Egypt has been concentrating its efforts on provision of sanitation services mainly on water supply, sewerage networks and wastewater treatment, while little priority has been given to sludge management in practice. The implemented methods and technologies for sludge treatment were very limited. Recently, there has been a strong interest in sewage sludge management due to the environmental risks, which have resulted from the expansion of wastewater treatment plants (WWTPs) without equal attention to dealing with the sludge produced, especially in the main cities. Therefore, the pressing needs are to develop appropriate low cost methods to treat the sewage sludge to be safe and suitable for reuse in agriculture. Furthermore, the current legislations should be adapted to the actual conditions with improvement of the institutional capacity to guarantee their enforcement.

Only about 15 % of rural area population (more than 56 % of Egypt's population) and 57 % of urban areas have access to wastewater collection and treatment facilities (data from 2007). Egypt has currently 303 WWTPS that handle of $11.85 \times 10^6$ $m^3$/day of sewage producing $2.4 \times 10^3$ tons/day of dry sludge with a sludge production rate of 0.225 kg/$m^3$ of treated wastewater (Ghazy *et al*., 2009). Due to the continuous rapidly growing population and industrial development as well as the Egyptian government planning to invest more than 20 billion US$ in the next 10 years, sewage sludge generation is expected to increase significantly in the future (Soliman, 2005). The recent application of anaerobic digestion technology for sludge stabilization and power generation at Al Gabel Asfer WWTP, which is the biggest wastewater treatment plant in Egypt (its current capacity of $1.8 \times 10^6$ $m^3$/day and will be increased to $3.0 \times 10^6$ $m^3$/day in 2020), has achieved good results with regards to the produced sludge quality and also a lot of experience in operation and maintenance has been gained. There is a growing interest in using such technologies on large scale in the future (Ghazy *et al.,* 2009). The focus of present study will be on the conventional aerobic and anaerobic digestion application, which are considering the most widely, and common stabilization processes used in USA and many other countries.

The main issue for the selection of a given process or technology lies in deciding which one is the most appropriate and applicable for each project. The economic considerations are the most important parameters that influence final selection, especially in developing countries (Nobuyuki et al., 2007). Due to the limited available data on sludge treatment costs in Egypt, published EPA costs data and variety of other documents which have been issued by the U.S. EPA and other references are used to estimate the missing data of aerobic and anaerobic digestion processes costs (EPA, 1985, Gerrard, 2001., Murray et al., 2008, Arlt et al., 2002, Zessner et al., 2010). Before using any cost data, it is important to take the local construction market (location factors) and the time value of money (inflation) into account. It is important to know the valid time of any cost data and to adjust the costs according to inflation and location (Murphy et al., 2004). Cost indices are used to update the costs of any technology to the present time of estimation (Peter and Bengt, 1994).

It is important to consider the quantity of treated sewage sludge as well as many other ecological, technical and economical factors before choosing the stabilization process. The anaerobic digestion process has generally been used for WWTPs having wastewater flow less than 4,000 $m^3$/day (1 MGD) to more than 757,000 $m^3$/day (200 MGD). Furthermore, it becomes more cost effective for plants with average flows greater than 8,000 $m^3$/d (2 MGD) and the production of electricity from digested gas recovery becomes more cost effective for plants with daily flows greater than 38,000 $m^3$/d (10 MGD) (WEF, 1992). However, it can be a preferable choice for WWTPs capacities less than 10,000 inhabitants in Germany referring to many technical discussions (ATV-DVWK, 2003). This area of application is likely to differ in Egypt due to the different operating conditions and energy prices, which are less than about one fifth of international prices. The evaluation of application area for such technologies according to the Egyptian conditions is very necessary as well as very helpful for decision makers.

The choice of optimal sewage sludge treatment process should be based on the comparison of total costs (US$/ton), which are necessary to achieve the desired quality as well as the sustainability of process (more resources efficiency, conserving resources and less pollutant emissions). Sustainable sludge handling may be defined as a socially acceptable, cost-effective method that meets the requirements of efficient resources recycling while ensuring that harmful substances are not transferred to humans or environment (Lundin et al., 2004). The Life Cycle Assessment (LCA) is one of the most widely known and internationally accepted methodologies to compare the environmental impacts of processes and systems and to evaluate their sustainability in the entire life cycle (Amarantos et al., 2007, Lundin et al., 2000). In the life cycle assessment, all resources consumption and pollutant emissions associated with the life cycle of a system or process are considered, such as extraction and processing of raw materials, manufacturing of chemicals, operation, transportation, recycling and final disposal (Lundin et al., 2004). An advantage of LCA is that, it is a well-established standardized method, which also includes an impact assessment phase whereby the environmental potential impacts are aggregated and quantified. Moreover, several authors adopted this methodology to evaluate the environmental burdens of sewage sludge treatment processes (Houillon and Jolliet, 2005, Hospido et al., 2005, Hong et al., 2009, Young and Rousseaux, 2002, Tjalfe. and Hansen, 2003). In this work, LCA approach was used to evaluate the environmental burdens associated with the application of aerobic and anaerobic digestion processes according to Egyptian conditions. This was done by identifying and quantifying the energy and materials used and the wastes released to the environment as well as assessing the impacts of those energy and material uses and releases to the environment.

## Goal and scope of the study

The main objectives of this study are to evaluate/compare the application of conventional aerobic/anaerobic digestion processes in sludge stabilization with respect to various parameters including energy balance, environmental impacts, and economic aspects. The area of application of aerobic/anaerobic digestion processes according to the Egyptian conditions is evaluated. Moreover, evaluation of resource consumptions, pollutant emissions and their consequent environmental impacts during their operation period. The results shall show which system is better and give useful information to decision-makers.

## Methodology

### *Anaerobic/aerobic economic assessment*

During a field study for the main Egyptian WWTPs in 2008, a data survey from many sources such as Egyptian Holding Company for Water and Wastewater (HCWW), National Organization for Potable Water & Sanitary Drainage (NOPWSD) and WWTPs in Cairo and Alexandria governorates was conducted. The current unit costs of energy, labour hour and land in Egyptian market were evaluated. Data on operation and maintenance (O&M) requirements and costs were collected from the main six wastewater treatment plants in Cairo (*AL Gabel Asfer1, Helwan, AL Berka, Shobera, Zenin and Abu Rawash)*. The conventional activated sludge systems without nitrification or denitrification process is the wastewater treatment system which is used in all WWTPs except Abu

Rawash WWTP which is still using only primary treatment. The sewage sludge treatment processes in the listed WWTPs are:

- *Helwan and Shobera WWTPs*: thickening facilities (mainly gravity thickeners) followed by natural dewatering units (sand drying beds).
- *AL Gabel Asfer1 WWTP*: thickening facilities followed by anaerobic digestion and power generation process and mechanical dewatering (Belt filter press BFP) units.
- *AL Berka WWTP*: thickening facilities followed by natural dewatering and windrow composting processes.
- *Zenin and Abu Rawash WWTPs*: The mixed sludge produced from the activated sludge system in Zenin and primary treatment in Abu Rawash is pumped to natural sludge storage lagoons at desert.

*Investment costs*

The available data base of sewage sludge management costs in Egypt is very limited and does not allow detailed analysis. The data are often contradictory and show very broad ranges. The Investment costs are estimated using the collected data from various reports as well as EPA data for actual bid documents of sludge treatment processes that have been constructed across the United States (EPA, 1985). To adapt the time value for the estimated investment costs (inflation), the Marshall and Swift Equipment Cost Index (MSECI) is used to adjust the mechanical equipments costs or combined costs in which equipments are the major costs component (Chemical Engineering, 2009). The remainder costs are adjusted using the Engineering News Record Construction Cost Index (ENRCCI) (ENR, 2009). Moreover, the results of EPA costs based model are adapted to Egyptian conditions (location factor) as follow:

The capital costs of sludge treatment technologies can be divided into construction costs as well as mechanical and electrical equipment costs. Based on USA investment costs proportions, the construction costs are assumed to be 70 % of investment costs (machinery and electrical installation 30 %). Whereas, the personnel costs represent 55 % of construction costs and the material costs represent 45 % [6]. These assumptions were used to estimate the corresponding investment costs in Egypt:

- The mechanical and electrical installations are assumed to be higher than the international prices by 15 %. This is because most of the mechanical and electrical equipments are imported from abroad with its global prices in addition to custom duties on import.
- In general, the material costs are assumed less than its international prices by 15% due to the government support for energy and other services.
- The personnel costs (salaries) are 70% less than global market salaries based on own investigations.

*Annual O&M costs*

The annual O&M requirements of aerobic and anaerobic digestion processes are estimated based on the design dimensions, annual electrical energy consumption (kWh/ton) and annual man-hour labor requirement (hr/ton) calculations consequently, the annual O&M costs are estimated based on the actual current unit costs of electricity (US$/kWh) and man-hour (US$/Hr) in Egyptian market.

*Anaerobic/aerobic digestion and area of application*

A cost effective analysis is carried out to assign which digestion process is more cost efficient according to the Egyptian conditions based on the WWTPs capacities, total equivalent annual costs (EAC) and the following assumptions:

- Amortization period of capital costs is 20 years with annual discount rate of 10%.
- The unit cost of labor manpower is **6** US$/hr, electricity is 0.02 US$/kWh and diesel fuel is 0.25 US$/litter.
- Operation temperature in aerobic digestion 20 °C and 35 °C in anaerobic process.
- The electrical energy production from biogas was assumed at 32 % and 57 % for the thermal. The heating value of digested gas is 24 $MJ/m^3$.
- The heat loss during anaerobic digestion process is assumed 1260 w/100 $m^3$.
- The excess electrical generation is supplied to the main grid and the produced thermal energy is used only for digestion process operation.
- The daily sludge production is 60 g TDS/capita.

This analysis may differ from one country to another based on many factors such as the availability of operation experience, energy and manpower costs as well as the ambient climate conditions.

*Life cycle impact assessment (LCIA) methodology*

The environmental impact assessments of anaerobic and aerobic digestion processes were compared using the life cycle assessment (LCA) methodology largely in accordance with the ISO 14040/14044 standards (ISO 14044, 2006, ISO 14040, 2006). The life cycle inventories of each digestion process included parameters describing energy use, raw materials, emissions to air, emissions to water and waste generation. The flows were normalized to a functional unit (FU) defined as the handling of 1 metric ton of dry thickened solids.

In the Life cycle impact assessment phase, the values of environmental interventions assessed in the inventory analysis phase are interpreted on the basis of their potential contribution to environmental impact. LCIA is typically divided into five phases: selection of impact categories, classification, charactersation, normalisation and weighting. In the ***classification step***, the emissions and resources are divided into different groups or impact categories according to their potential impact on environment. In this study, a set of seven categories as well as the cumulative energy demand were selected. Table 1 depicts the selected impact categories and assessment methods. The third step is the ***characterization step***, where all relevant emissions are characterized and quantified by scientifically derived factors (characterization factors) depending on their contribution to the potential damage they cause to the environment allowing aggregation into a single score in each impact category.

The ***normalization step*** is an optional step for LCA that can be applied for a better understanding of the relative importance and magnitude of the characterization results (ISO 14040, 2006). The usual approach is to normalize the environmental impacts from characterization step by relating these impacts to the total impact of a given community (Lundin et al., 2004). Due to the limited data on annual emissions in Egypt, the normalization and weighting steps were left out of this study.

**Table 1: Environmental impact categories and method of assessment**

| Impact category | Units | LCIA method |
|---|---|---|
| Abiotic depletion (ADP) | kg Sb eq | CML 2001* |
| Acidification (AP) | kg $SO_2$ eq | " |
| Eutrophication (EP) | kg $PO_4$ eq | " |
| Fresh water aquatic ecotoxicity (FWETP) | kg p-DCB | " |
| Global warming (GWP) | kg $CO_2$ eq | " |
| Human toxicity (HTP) | kg p-DCB | " |
| photochemical oxidation (POFP) | kg ethylen | " |
| Terrestrial ecotoxicity (TETP) | kg p-DCB | " |
| Cumulative energy demand (KEA) | kWh | |

*Source: (Guinée et al., 2002, Frischknecht et al., 2007).

*Systems boundaries*

The system boundary of applied anaerobic digestion process is indicated in figure 1, which includes the impacts associated with the digestion process itself and the energy recovery in combined heat power (CHP) units. Furthermore, the avoided impacts associated with the avoided energy (heat/electricity) required for process operation as well as avoided excess energy recovery from produced biogas. The environmental impacts associated with chemical substances that may be used during the process are not taken into account.

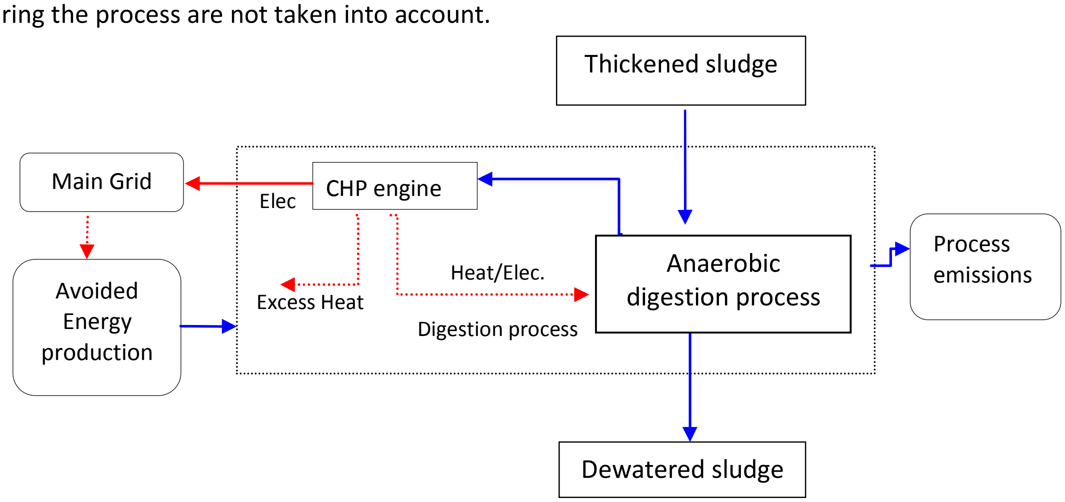


**Figure 1: System boundary of anaerobic digestion process**

The system boundary of applied aerobic digestion process is including the impacts associated with the aerobic digestion process and the treatment of digester supernatant liquid as shown in figure 2.

The scope doesn't include the emissions (e.g. nitrogen oxides) associated with the nitrification/denitrification processes that may be occur during the aerobic digestion process.

To model systems or processes and evaluate their environmental impacts, the ***Umberto*** software (Umberto 5.5) developed by ***ifu Hamburg***, Germany was used (Ifu, 2005). Umberto is a commercial software tool to model, calculate and visualize material and energy flow systems. It is used to analyze the process streams along a product life cycle. Results can be assessed using economic and environmental performance indicators. Cost data for materials and processes can be entered to support managerial decision-making.

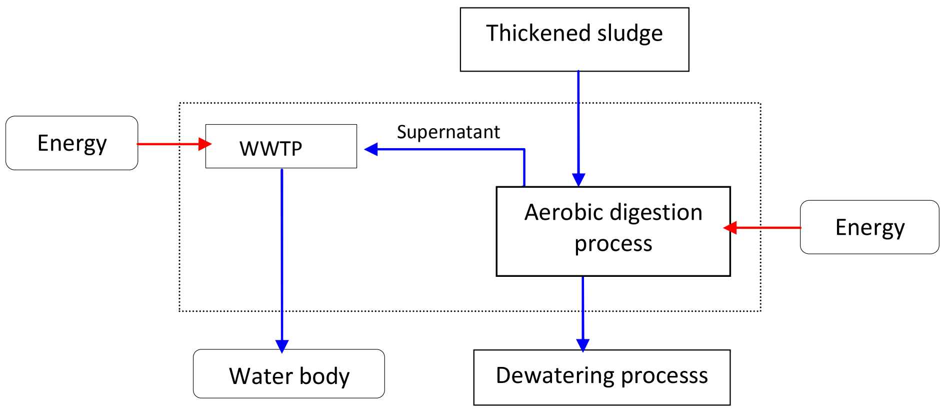


**Figure 2: System boundary of aerobic digestion process**

## Results and discussion

*Current annual O&M requirements of Egyptian WWTPs*

Tables 2 shows the actual current monthly O&M requirements and costs (including sludge management) for the main six WWTPs in Cairo. The current unit cost of electricity (US$/kWh), manpower (US$/Hr) as well as sewage treatment cost (US$/$m^3$) in Egyptian market are estimated as illustrated in table 4.

**Table 2: O&M requirements and costs in Cairo WWTPs in 2009**

| WWTP | Treatment Capacity ($10^3$ $m^3$/day) | Annual O&M requirements | | | Annual O&M costs | | | | total O&M costs ($10^3$ US$/yr) |
|---|---|---|---|---|---|---|---|---|---|
| | | Elec. Energy ($10^3$ kWh/yr) | Diesel fuel ($10^3$ Lit/yr) | Man power ($10^3$ hrs/yr) | Man power ($10^3$ US$/yr) | Elec. Energy ($10^3$ US$/yr) | Overall materials ($10^3$ US$/yr) | Other ($10^3$ US$/yr) | |
| Helwan | 440 | 21827 | 365 | 642 | 189 | 591.6 | 42 | 17 | 840 |
| Zenien | 300 | 30715 | 73 | 748 | 659 | 807.4 | 44 | 19 | 1,529 |
| Shobera | 580 | 23725 | 31 | 819 | 498 | 842.1 | 91 | 50 | 1,481 |
| Abu Rawash | 400 | 19236 | 31 | 707 | 41 | 57.1 | 55 | 7 | 160 |
| Al Berka | 520 | 36500 | 91 | 806 | 594 | 761.5 | 150 | 10 | 1,516 |
| AlGabel Asfr1 | 1200 | 125071 | 1570 | 1688 | 3432 | 1094.7 | 2324 | 1,503 | 8,354 |

Source: NOPWASD and HCWW, Egypt 2008.
The annual O&M cost of sludge treatment processes are included.
Without considering annual amortized capital cost recovery.

The average required electrical energy for wastewater treatment process is 0.19 kWh/m$^3$ and the required manpower is 4.6 hrs/10$^3$m$^3$. According to the Egyptian market prices in 2009, the average unit price of hourly manpower in municipal sector is about 0.77 US$/hr. This may seem too low according to the US market (34 US$/hr). On the other hand, the number of manpour requirements (hr/yr) in Egypt is about 7.5 times higher than that required number in USA. Therefore, the unit cost of O&M man-hour according to Egyptian conditions can be assumed to be 6.0 US$/hr. The unit price of electrical and diesel energy at the Egyptian market are less than one fifth of international market prices due to the government support to energy sector. However, there is a general trend in Egypt to lift the subsidies on all goods and services to keep pace with the international market prices. The current energy unit costs in Egyptian market are considered whereby the unit cost of electricity is assumed to 0.02 US$/kWh and the diesel fuel 0.25 US$/Lit.

**Table 3: Main O&M requirements unit costs for Cairo WWTPs in 2009**

| WWTP | O&M unit requirements | | O&M unit costs | | Overall annual O&M cost (Cent/m$^3$) |
|---|---|---|---|---|---|
| | Elec. Energy (kWh/m$^3$) | Man power (hrs/10$^3$ m$^3$) | Elec. Energy (US$/kWh) | Man power (US$/hr) | |
| Helwan | 0.14 | 4.00 | 0.03 | 0.29 | 0.523 |
| Zenien | 0.28 | 6.83 | 0.03 | 0.88 | 1.396 |
| Shobera | 0.11 | 3.87 | 0.04 | 0.61 | 0.699 |
| Abu Rawash | 0.13 | 4.84 | 0.01 | 0.06 | 0.110 |
| Al Berka | 0.19 | 4.25 | 0.02 | 0.74 | 0.798 |
| AlGabel Asfer 1 | 0.29 | 3.85 | 0.01 | 2.03 | 1.907 |
| ***Average*** | ***0.19*** | ***4.61*** | ***0.02*** | ***0.77*** | ***0.91*** |

The exchange rate used in 2009 was the US$ = 5.76 LE (Egyptian pound)

*Egyptian WWTPs investment costs estimation*

The investment costs of aerobic and anaerobic digestion processes resulting from EPA based cost models are adapted to the Egyptian conditions as depicted in figure 3. Based on the previous assumptions, out of total investment costs in Egypt about 47 % (115 % of their global values) are due to mechanical and electrical installation costs and 53 % (55 % of its global value) due to construction costs. The results of capital costs adaptation based on Egyptian conditions indicate that the capital costs of sludge treatment processes in Egypt are representing about 73 % of its global value.

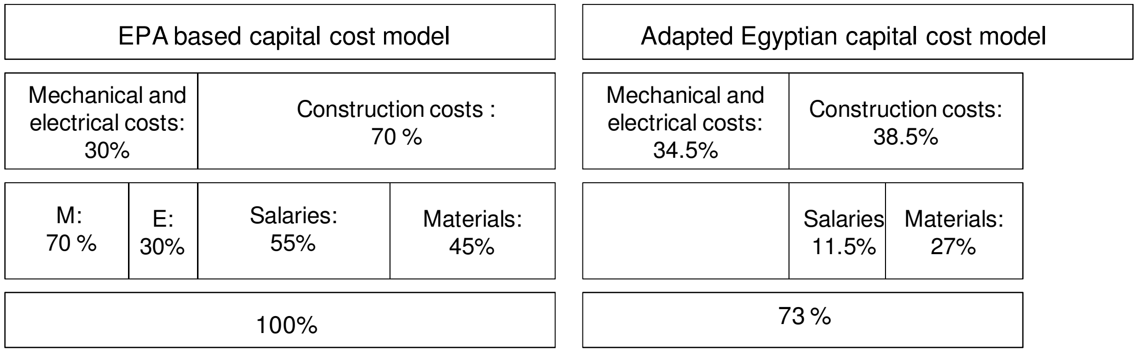


**Figure 3: Subdivision of capital costs based on EPA cost model and Egyptian adapted model**

*Anaerobic/aerobic digestion capital cost:*

The capital costs of anaerobic digestion (high-rate at mesophilic temperature) and conventional aerobic digestion process (mechanical aeration system) adapted to Egypt market prices in 2009 are estimated based on assumptions of 20 days solid retention time (SRT) for aerobic digestion and 15 days for anaerobic digestion at average influent temperature of 20 °C. Moreover, the organic loading rate (OLR) in anaerobic digestion is 1.7 kg VS/day $m^3$ of digestion volume and the influent sludge concentration is 4 %. The capital cost of anaerobic digestion to handle daily total solid capacities from 1 to 30 tons/day are estimated to $122x10^3$ to $933x10^3$US$/ton dry solids digested per day with average value of 169 $x10^3$US$/ton. Where, it is estimated at 160 $x10^3$ to 472 $x10^3$ US$/ton for aerobic digestion with average value of 222 $x10^3$US$/ton as shown in figure 4.

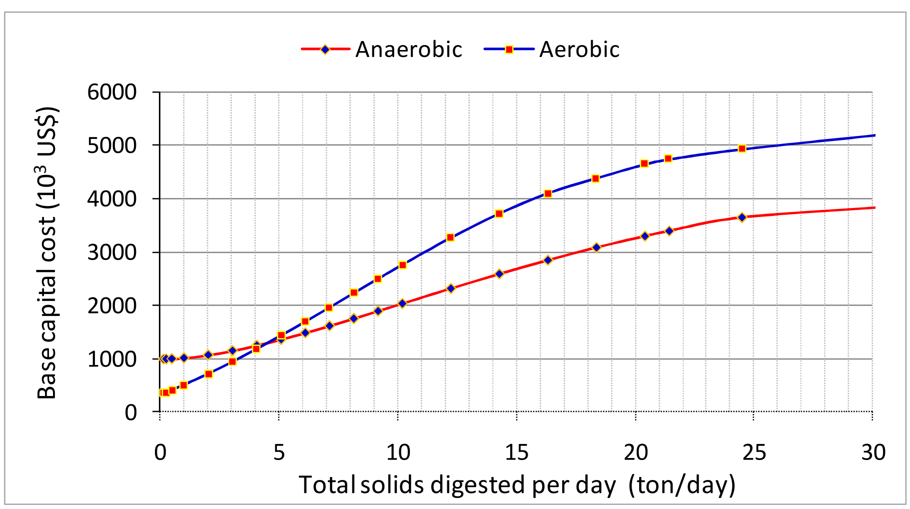


**Figure: 4 Total capital cost of Anaerobic/Aerobic digestions according to Egyptian market**

*Anaerobic/aerobic digestion O&M requirements*

The annual O&M man-hour requirements for aerobic digestion process to handle dry solid capacities from 1-30 tons per day are estimated to be 6.4 to 0.6 hr/ton. While, it is estimated to 6.15 to 0.7 hr/ton for anaerobic digestion process. The average required electrical energy for a continuous operation of aerobic digestion is estimated to 1176 kWhr/ton of digested dry solids. While, it is estimated at 675 kWhr/ton without considering the effect of energy generation from biogas production. Figure 5 indicates the annual O&M labor and electrical energy requirements for continuously operating Aerobic/Anaerobic digestion processes expressed in total digested dry solids per day.

*Anaerobic digestion energy recovery*

Considering the effect of energy recovery from produced biogas in the anaerobic digestion process, the average electrical and heat energy generation is estimated at 746 and 1330 kWh/ton respectively. From this energy, about 10 % of electrical energy and 45 % of thermal energy are used in the process operation. Consequently, the excess electrical energy recovery is estimated at 667 kWh/ton and the excess thermal heat (heat loss) at 735 kWh/ton. The excess electrical energy can be supplied to the main grid and the excess thermal energy is diffused to the atmosphere due to the warm climate in Egypt and the current limited purposes of thermal energy application.The operating conditions, and energy balances during the Anaerobic/Aerobic digestion process under Egyptian condition are depicted in figure 6.

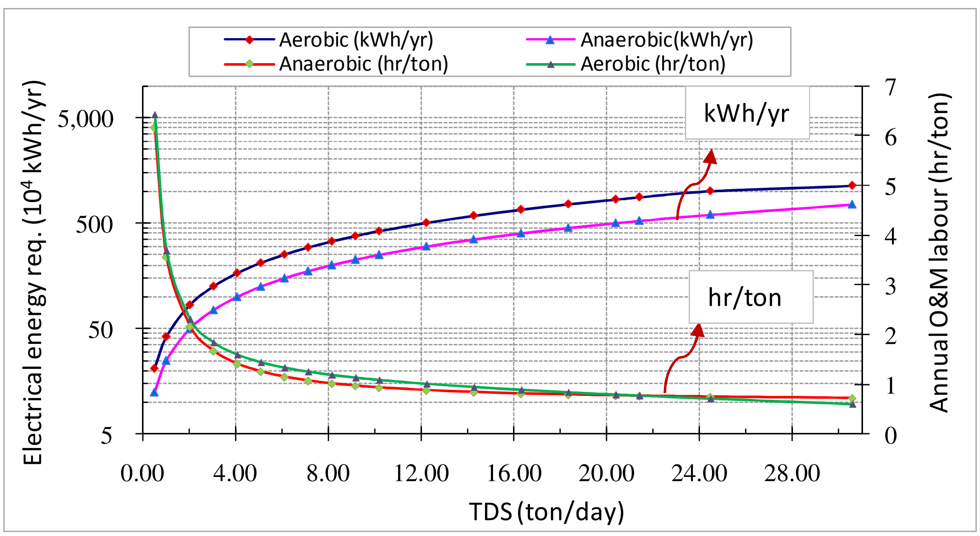


**Figure 5:** **Annual O&M labour and energy requirements for Aerobic/Anaerobic digestion**

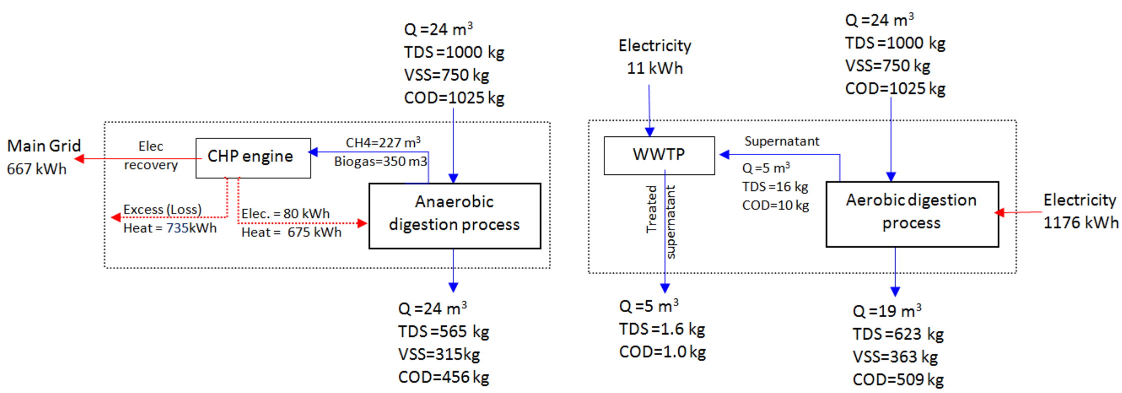


**Figure 6:** **Mass and energy balances of Anaerobic/Aerobic digestion processes**

*Anaerobic/aerobic digestion and area of application*

Based on the total equivalent annual costs (annual investment costs over project period and annual O&M costs) for aerobic and anaerobic digestion processes, the results of the cost effective analysis according to Egyptian and American operation conditions showed that:

- According to Egyptian conditions, the using anaerobic digestion process will be less expensive for WWTPs with capacities greater than 37,000 inhabitants considering the effect of energy recovery from produced biogas as illustrated in Figure 7.
- Referring only to the effect of capital costs without considering the annual operating and maintenance costs as well as the energy recovery from produced biogas, the aerobic digestion process is to be more expensive for WWTPs with served population less than 75,000 inhabitants, where it becomes less expensive after that.
- According to US market prices in 2009 (unit cost of labor manpower is 34 US$/hr, electricity of 0.1 US$/kWhr, diesel fuel 0.75 US$/litter and annual discount rate of 5%) at the same previous operation conditions, the application of anaerobic digestion process for WWTPs with a population not less than 14,000 inhabitants was the best choice. Furthermore, the anaerobic digestion application can recover the total annual equivalent costs of the process during the project life period due to the benefit from energy generation.
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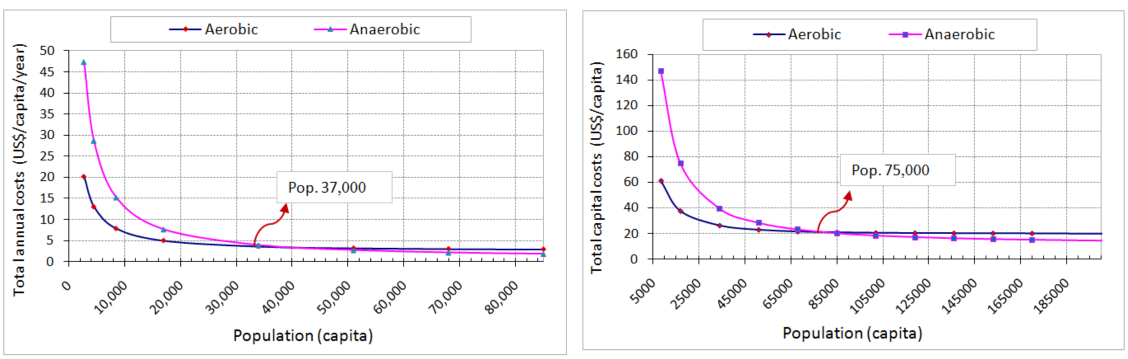


**Figure 7: Area of anaerobic/aerobic digestion application in Egypt**

Due to current low price of energy in Egyptian market, the application area of anaerobic digestion technology is smaller than that in USA. It should be noted that, the price of energy in Egyptian market is continuously increasing due to the general trend of government to lift the subsidies at energy sector (to be in line with the global market prices). Consequently, the area of anaerobic digestion application in Egypt can be raised to 20,000 inhabitants considering the global price of energy. In spite of this perspective and as a result of current limited experience of anaerobic digestion operation and lack of control and monitoring for the WWTPs operation in Egypt, especially in small plants, it is recommended to use the anaerobic digestion for WWTPs capacities of more than 40,000 inhabitants (8,000 $m^3$/day in rural area and 10,000 $m^3$/day in urban) with preparing qualified staff for operation.

*Environmental impacts of Anaerobic/aerobic digestion process*

Figure 8 shows the contribution of each digestion process to the tested environmental impact categories irrespective of the environmental enhance due to avoided emissions resulting from the energy recovery. The potential environmental impacts of aerobic digestion process were significantly higher in all categories under study. For example, the global warming potential for the aerobic digestion application was 1010 kg $CO_2$ eq/ton of dry digested solids. While it was only 64 kg $CO_2$ eq/ton due to the anaerobic digestion without considering the effect of excess energy recovery. This is mainly due to the increase in energy consumption for aerobic digestion process. The total cumulative energy demand (KEA) accounts to 3565 kWh/ton of dry digested solids in aerobic digestion process, while the anaerobic digestion process produces a cumulative electrical energy of 1694 kWh/ton. The cumulative energy (primary energy) is the energy embodied in natural resources (e.g. coal, crude oil, natural gas, uranium) which has not undergone any anthropogenic conversion or transformation. Thereby, it has a mutual influence on efficiency of using natural resources in the overall system or process (Amarantos et al., 2007).

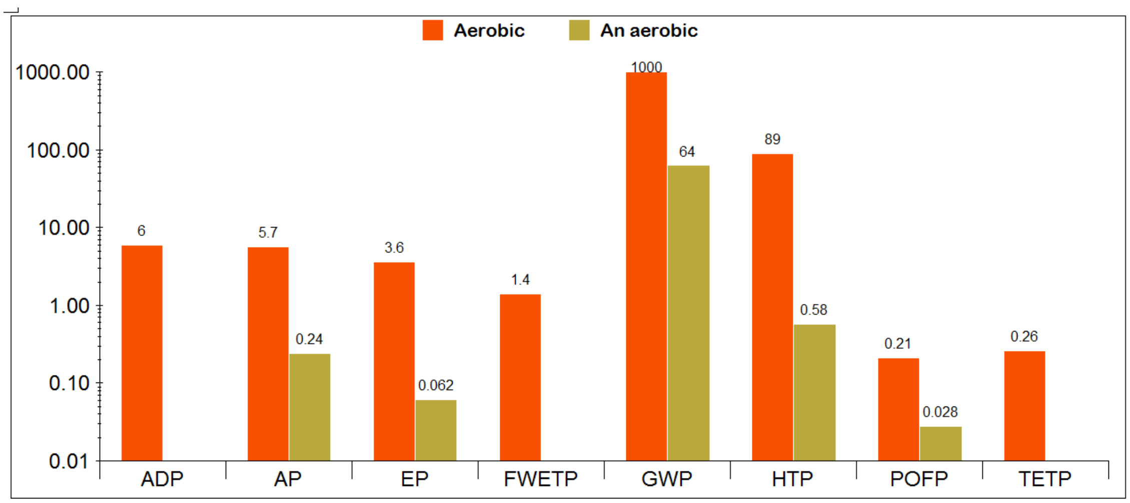


**Figure 8: Environmental impact categories of anaerobic/aerobic digestion process in Egypt**

Considering the effect of avoided emissions resulting from the avoided electric energy generation, the anaerobic digestion process showed a positive enhancement in all environmental impact categories as indicated in table 4. This benefit is particularly significant in acidification, climate change, and depletion of abiotic resources categories, due to energy saving credit. While the application of aerobic digestion process was increasing the potential contribution of global warming, acidification and abiotic resources depletion to 1010 kg $CO_2$ eq, 5.72 kg $SO_2$ eq and 5.97 kg Sb eq/ton dry digested solids, the anaerobic digestion process was reducing the potential impacts of these categories to -480 kg $CO_2$ eq, -2.72 kg $SO_2$ eq and -2.83 kg Sb eq /ton respectively.

**Table 4: Environmental impact categories considering avoided emissions due to energy recovery**

| Item | Aerobic digestion | Anaerobic digestion | Unit |
|---|---|---|---|
| Abiotic depletion (ADP) | 5.97 | -2.83* | kg Sb eq |
| Acidification (AP) | 5.72 | -2.72 | kg $SO_2$ eq |
| Eutrophication (EP) | 3.62 | -0.12 | kg $PO_4$ eq |
| FW aq. ecotoxicity (FWETP) | 1.39 | -0.66 | kg p-DCB |
| Global warming (GWP) | 1010 | -480 | kg $CO_2$ eq |
| Human toxicity (HTP) | 89 | -42 | kg p-DCB |
| Photochemical oxidation (POFP) | 0.21 | -0.10 | kg ethylen |
| Terrestrial ecotoxicity (TETP) | 0.26 | -0.12 | kg p-DCB |
| Cumulative energy demand (KEA) | 3565 | -1694 | kWh |

* The negative sign means a positive enhancement to environmental categories

## Conclusion

The main conclusions that can be drawn from this study are:

- Although the average income (GDP) in Egypt is up to 87 % lower than in USA, the capital costs of sewage sludge treatment processes are only less than about 27 % that in USA. The average unit price of hourly manpower in the municipal sector in Egypt is less than about 10 % of that in USA, while the number of required manhour is about 7.5 times higher as in USA.
- The current unit cost of electrical energy in Egyptian market is less than one fifth of that on the US market due to governmental support of energy sector. However, there is general trend in Egypt to replace the subsidies on all goods and services to keep pace with the international market prices.
- The main difference in the total costs of sewage sludge treatment processes in Egypt compared with the international market can be explained by the significant difference in the annual O&M costs resulting from the low hourly manpower and energy prices. This difference can be rapidly changed in future as a result of government tendency to follow the policies of globalization and free market mechanisms.
- The average required electrical energy for a continuous operation of aerobic digestion process is estimated at 1176 kWh/ton of digested dry solids. The final electrical energy production from anaerobic digestion process is estimated at 667 kWh/ton and the thermal heat at 735 kWh/ton. The excess electrical energy can be supplied to the main grid, while the excess thermal energy is diffused to atmosphere due to a warm climate and limited thermal energy application areas in Egypt.
- The economic assessment showed that the application of anaerobic digestion technology in Egypt is more cost effective for WWTPs with capacities greater than 40,000 inhabitants, while it can be the best choice for USA at a population generally greater than 14,000 inhabitants. This is mainly due to the current low energy prices on Egyptian market.
- The application of aerobic digestion for sewage sludge stabilization in Egypt showed higher negative impacts for all environmental categories in this study. On the other hand, the application of anaerobic digestion showed a positive enhancement in all categories considering the effect of avoided emissions resulting from the avoided of electric energy generation.

As a general conclusion, the application of anaerobic digestion process with energy recovery is shown to be a promising option for sewage sludge stabilization in Egypt. It leads to the lowest economic costs and environmental impacts due to energy recovery. The biogas production has a mitigation effect on environmental impacts due to fossil fuel substitution as well as economic benefit due to the electrical generation.

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