OPTIMIZATION OF ENERGY ECONOMY IN THE DESIGN AND OPERATION OF WASTEWATER TREATMENT PLANTS

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1. Introduction

The problem of water scarcity in Israel, where more than 90% of the conventional water potential is already in use, has led the country increasingly towards the use of wastewater for agricultural purposes. Irrigation is now considered to be the most feasible and economical way to dispose of municipal sewage in a sanitary manner.

The total amount of wastewater (WW) from domestic sources in Israel is about 400 million $m^3/year$, out of which 300 $m^3/year$ is collected by central sewage systems. Most of the collected wastewater are being treated by activated sludge plants, which undergoes various type of processes, such as: conventional, extended aeration and sequence batch reactor. In order to increase the utilization of the recycled water, by the farmers, the cost must be attractive relative to drinking water quality.

In a typical wastewater treatment plant (WWTP) large amounts of energy are consumed, representing about 50% of the variable operating and maintenance cost. Most of the plants are of extended aeration type with a specific energy consumption of 0.5 kWh/m^3. By the end of this decade, energy consumption for wastewater treatment in Israel will approximately result in 150 *GWh/year*.

Energy conservation plays an important role in the reduction of wastewater effluents cost, while meeting environmental standards.

This paper evaluates the reduction of energy cost in a typical extended aeration process flow configuration. Data and results are presented for a case study.

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2. Optimization of energy cost in activated sludge process

2.1 General

Activated sludge is a very complex biological process (1,2,3) which produces high quality effluents, suitable for direct reclamation and/or further polishing by ground recharge. Over 80% of the energy is consumed in the biological aerated reactor (ART). Air or oxygen is introduced to the reactor to provide the inflow wastewater the oxygen to sustain the necessary level of biological activity.

The demand of oxygen within a biological reactor can be met in various ways, but most aeration devices currently being used in activated sludge process may be classified as either diffused, dispersed, or surface aeration systems.

The process produces effluents with low level of carbonaceous organic (BOD) and low level of suspended solids. At the same time, however excess sludge is being produced. Although being a nuisance the sludge might produce bio-gas (CH_4 + CO_2) under anaerobic digestion. The bio-gas may be used for heating the digester, to produce steam, to produce electricity, or to run direct drive equipment. Fig. 1 demonstrates a typical flow configuration of activated sludge process.

The charge for electricity cost in Israel is based on Time of Use (TOU) tariff. The peak rates are fourth times the off peak, resulting in high incentive for energy consumption during off peak period.

For best results of operational cost reduction, energy conservation and process efficiency, selection of aeration devices, process flow configuration, bio-gas utilization and time of day consumption of energy, should be optimized.

In order to evaluate overall energy cost reduction, a case study will be used as described.

Flow	10,000	m^3/day
BOD in	500	mg/l
BOD out	20	mg/l
BOD removed	4,800	kg/day

The assumptions used are:

1 kg BOD removed requires 1 kg of O_2 transferred
10 hours of off peak per day
Electricity costs are: peak and shoulders - $0.11, off peak - $0.03
Aeration is uniform during the day
Process configuration is extended aeration
Investments spread on 20 years, 5% interest

2.2 Aeration

2.2.1 Technologies

Aeration is considered to be the main energy consumer in WWTP. Two main issues are to be considered in order to reduce WWTP energy consumption, as follows:

- Optimize aeration or in other words to optimize oxygen transfer to the process
- Use as much energy during off peak hours

First it is required to screen aeration technology. Few aeration methods are considered:

- Surface aeration
    - Brush aeration
    - Horizontal rotation
    - Vertical rotation
- Air diffusing
    - Coarse Bubbles
    - Micro Diffusers

Surface aeration is a process were ambient air is forced into the liquid in the aeration basin by the generation of violent turbulence in the liquid causing oxygen transfer into the liquid. All surface aeration systems vary by the shape and direction of rotation. Experience show that in most cases, horizontal surface aeration aerators are capable of transferring between 1.4 to 1.45 kgO_2 per 1 kWh, while brushes hold the ratio of 1.6 to 1.7 kg O_2 per 1 kWh. The numbers are subject to minor local changes because of shape modifications and environmental conditions, averaging, however, WWTP in Israel confirm the ratio.

Air diffusing is a rather new approach to the issue of oxygen transfer in WWTP process. In this technology air is first compressed in compressors and then transferred in pipes to a distribution system at bottom of the aeration basin. Air is then introduced to the liquid transferring oxygen on it's way to the surface of the basin, Two main technologies are used: Coarse bubbles is a process were air is diffused through rather large holes in a distribution pipe resulting large bubbles transfer into the liquid. Coarse bubbles systems hold very low oxygen transfer rate as low as 1 kgO_2 per 1 kWh. Micro diffuser technology uses the same compressed air approach, but transferring micro air bubbled resulting due to large surface area a rate of 2 to 3 kg O_2 per 1 kWh.

2.2.2 Time of energy use

The following evaluation methodology will be used:

1st. Use most efficient aeration technology (micro diffusers), when ever possible
2nd. Compress air during off peak hours and use during peak
3rd. Evaluate new energy cost
4th. Calculate and add investment and O&M costs

A. Use most efficient aeration

	Coarse bubbles	Micro diffusers	Surface aeration
			Not applicable
Specific rate kgO2/kWh	1	2	
kWh per day	4,800	2,400	

B. Air compression during off peak

In order to calculate the overall energy cost, it is first required to calculate the compression energy. This is done as follows:

During off peak compressed air production two values are considered:

1. Aeration required for the normal operation of the plant thus: calculate on going micro diffusers air supply during 10 hours of off peak.

$$\frac{2{,}400\left(\frac{kWh}{day}\right)}{24\left(\frac{hours}{day}\right)}\ x\ 10\left(off\ peak\ \frac{hours}{day}\right)\approx 1{,}000\left(\frac{kWh}{day}\right)$$

2. Calculation of the amount of air required for compression in order to maintain aeration during peak hours. 14 hours air supply requirements are calculated as follows:

First calculate the oxygen required for 14 hours per day as

4,800 kgO_2/day *x* (14/24) = 2,800 kgO_2/day

For micro diffusers the common efficiency ratio of $kgAir/kgO_2$ is taken as 6.7, thus giving total air amount of -18,800 *kgAir*. This amount of air needs to be compressed during 10 off peak hours. The electricity required for the above amount is calculated by the following formula (4):

$$P(kW)=\left\{\frac{L\cdot R\cdot T}{M_{Air}\cdot n\cdot \eta}\right\}\left\{\left(\frac{P_{in}}{P_{out}}\right)^{n}-1\right\}$$

Were:

	Definition	Value use for case study
L	*kg Air/sec*	0.522
R	*Gas constant (k joul / k mole K)*	8.314
T	*Inlet air Temp K*	290
M_{Air}	*Average molecular Weight of air*	29.7
n	*Adiabatic factor*	0.283
h	*Compressor efficiency*	0.9
P_{in}	*Air pressure in (atm)*	1
P_{out}	*Air pressure out (atm)*	10
P	***kW required (calculated)***	**153**

Total energy shifted from peak to off peak is then 153 *x* 10 = 1,530 *kWh per day*.

C. Aeration energy costs are calculated as follows:

24 hour aeration:	1,000*x* $0.03	=	$30
	1,400*x* $0.11	=	$154
	Total		**$180**

10 hour compression	1,000*x*$0.03	=	$30
	1,530*x* $0.03	=	$46
	Total		**$76**

Daily difference is $104 (per one year ~$40,000)

D. Add investment and O&M costs.

Item	**Investment cost $**	**Yearly cost $**
Compressing system	100,000	6,400
Compressed air tank	250,000	16,000
O&M		10,000
Total		**32,400**

Total yearly energy cost saving is about $8,000.

Perusing the same calculation methodology with a coefficient of 1 kgO_2 per 1 kWh gives a yearly reduction of electricity cost of ~$79,000 with yearly investment and O&M cost of about $50,000, thus, providing about $29,000 of energy cost saving per year.

The cost effectiveness of energy utilization during off-peak hours depends on the off-peak to peak rates ratio and on the efficiency of oxygen transfer to the ART. Fig. 2 presents the cost breakdown for the modification of air compression during off-peak hours. It seems that a combination of low values of off peak to peak rates ratio with low efficiency of oxygen transfer system, results in a positive net present value, while increasing the efficiency of air transfer with an increasing of the off peak to peak rates ratio, reduces the profitable of the suggested modification.

2.2.3 Optimal operation methods (5, 6, 7, 8)

Operation of ordinary designed and controlled WWTP usually does not consider the variation of variables such as: influent variation during day, week, month, season and the variation of environmental aspects (temperature, etc.). Because operation and control does not follow changes the WWTP are normally operating at a certain working point, which is never the optimal one.

In the last years some new methods have been implicated regarding the optimizing process operation of WWTP. An innovative optimal operation of WWTP is achieves by the dynamic simulation of the biological and mechanical process involved in WW treatment. This is done by identifying most of the relevant variables involved in the process, and the mathematical equations related to them. Few WWT simulation models have been developed, and are used as a basis for commercial computer programs. Computer programs such as

SIMBA, WEST and others take more and more place in the design and operation of

WWTP control systems.

The reduction of energy related operation costs can be achieved by the use of the following methodology:

- Model the WWTP
- Establish data base containing:
    - Influent characteristics variation over time
    - Environmental changes
    - Effluent requirements
- Simulate the process
- Calibrate the simulation
- Modify aeration in relation to changes

This approach can be used off line and on line, were in on line simulation the model receives process change directly from sensors on the site and directly controls the aeration system. This approach have been used in various places around the worlds, providing aeration energy reduction cost of 10-20%.

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2.3 Sludge digestion (SDG)

In anaerobic process highly polluted WW are treated. The load is converted to biogas that has energetic value. Bio-gas can be utilized in a variety of way amongst are electricity, steam, heat and other energetic products. In order to maximize energy saving, two issues are considered: The maximizing bio-gas quantities and optimizing bio-gas utilization.

2.3.1 Maximizing biogas quantities

Suspended solids content in WW are known to contribute a large part to the total BOD loading, while on the other hand have a high capacity of bio-gas production value. The most common ways to reduce aeration energy costs providing while at the same time providing bio-gas are hereby described:

Primary settling (PST)

Properly designed primary settling reduces as mach as 35% of the influent BOD. This first causes a direct reduction of 35% of the aeration requirements. Using anaerobic digestion the reduced BOD load can be converted into bio-gas at a conservative conversion ratio of 0.4 m^3 bio-gas to 1 kg of BOD removed. The main constituents of WWTP bio-gas are methane (60%-70%) and CO_2 (30%-40%), thus the caloric value of one m3 of bio-gas is 5000-6000 kcal. To be conservative we use 5,000 for our case study.

Secondary settling (SST)

The sludge settled in secondary settlers is already partly digested due to the aeration process, however, it still has a substantial value of bio-gas potential which is about 0.1 m>^{3} bio-gas to 1 kg of BOD digested.

To show these numbers related to the case study we pursue as follows:

BOD removed during primary settling is 4,800 *kg BOD x* 0.35 = 1,680 *kg BOD*. Using the conversion ratio specified above this is converted into about 670 m3 of bio-gas with a caloric value of 3,360,000 *kcal per day*.

Digestion of secondary sludge produces in our case:

(4,800-1,680)*kg BOD x* 0.1 *m3 biogas/kg BOD* = 312 *m3 biogas*

With the primary sludge digestion this yields 4,920,000 *kcal/day,* the equivalent of 4,750 *kWh/day*.

An efficient way to utilize this energy amount is to produce electricity while recovering sufficient heat for the anaerobic process requirements. The amount of electricity produced in a gas engine generator (32% efficiency) is about 1,500 *kWh/day*. In our case a gas generator of 150 kWh for a 10 hours a day operation seems adequate. The investments cost for the system is about $250,000.

The electricity produced is best used during peak hours. Because in a typical WWTP there are other energy consumes such as pumps, electrical motors, The electricity produced can be used during peak time. In Israel it is also possible to sell electricity back to the net. Because gas production is some what regulated during the day, it seems a good idea to buffer bio-gas by the use of a gasholder. For about 1,000 m^3 bio-gas produced in the case study specified above, appropriate gas holder seems to be 500 m^3, in which 12 hours of bio-gas production can be buffered.

The costs related to the installation of 500 m3, double membrane gasholder are about $50,000. The yearly costs for the financial terms specified in our case study are given below:

Item	Investment cost $	Yearly cost $
Gas generator	250,000	20,000
Gas holder	50,000	4,000
O&M of both		20,000
Total		**44,000**

Daily income produced due to electricity production is 1,500 *kWh x* 0.11 *$/kWh* = 165 *kWh per day*, which amounts approximately to $50,000 *per year*.

3. Conclusion

It is very easy to observe that for new WWTP optimized design and operation should be adopted in order to reduce energy cost to a minimum.

Modification of existing WWTP can reduce the the current energy cost remarkably. Optimization of oxygen transfer, primary sedimentation, utilization of bio-gas from the primary and secondary waste sludge, while considering in both cases the TOU tariff, can reduce energy cost to a minimum. The implementation of methods and steps toward reduction of energy cost, depends on flow configuration of the process and aeration technology.

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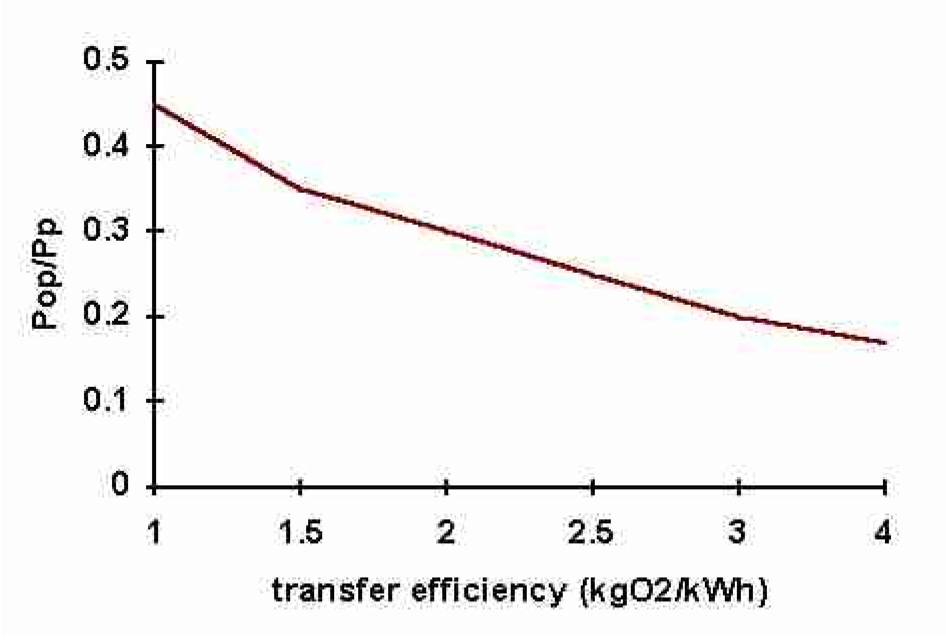
Fig. 2 - Cost breakdown for air compression in ART



Summary

Modern wastewater treatment plants (WWTP) are based on a combination of biological and mechanical processes, designed to provide an ever-increasing demand for high quality effluent water. The later is achieved by consuming large amounts of energy. In a typical WWTP, large amounts of energy are consumed, representing up to 50% of the facility's total operating costs. Energy-related operating costs will continue to increase as new regulations for higher effluent quality are applied. Modern WWTP energy consumption is between 0.4-0.6 kWhr per m^3 of inflow wastewater (WW). More than approximately 1 kg of excess sludge is produced for every kg of BOD removed.

In order to reduce operation cost, the energy use in the treatment plant must be evaluated and optimized. An integrated design and operation of WWTP enclosed:

- Selection of optimal aeration technology.
- Implementation and optimization of anaerobic process
- On line advanced modeling of the WWTP process.

The above can reduce energy cost up to 50% of the initial value i.e., values of 0.2 -0.3 kWhr per m^3 or cost reduction of $0.016 per m^3 of wastewater.

In Israel energy consumption in conventional WWTP is about 150 GWhr per year. Preliminary studies conducted in Israel show that this amount can be reduced up to 75 GWhr per year, which is equivalent to saving of $5 10^6 per year.