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EXERGY EFFICIENCY AS A MEASURE OF THE ENVIRONMENTAL IMPACT OF WASTEWATER TREATMENT PLANTS

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Abstract. This work evaluates the environmental impact of Wastewater Treatment Plants (WTP) based on data generated by the exergy analysis, calculating and applying environmental impact indexes for two WTP located in the Metropolitan Area of São Paulo. It is proposed the exergy efficiency as an environmental impact index which quantifies the aspects of energy efficiency and environmental impact of the energy conversion processes. The environmental exergy efficiency is defined as the ratio of the exergy of the useful effect of the process to the total exergy consumed by human and natural resources, including all the exergy inputs. That relation is an indication of the theoretical potential of future improvements of the process. Besides the environmental exergy efficiency, it is also used the total pollution rate, based on the definition done by Makarytchev (1997), as the ratio of the destroyed exergy associated to the process wastes to the exergy of the useful effect of the process.

Keywords: exergy efficiency; environmental impact; wastewater treatment plants

1. Introduction

There is an increasing demand for more sustainable wastewater treatment systems. However, the criteria needed to characterize such a system are not fully developed. One important tool in the analysis of the sustainability of a wastewater treatment system is the exergy analysis. Hellström (1997) showed how an exergy analysis could be used to estimate the consumption of physical resources at a wastewater treatment plant.

Some authors have suggested that the quantification of the environmental impact of energy conversion processes can be better driven by the use of the exergy concept (Rosen; Dincer (1997); Gong (1999); Wall; Gong (2001)). Others went beyond and calculated that impact based on the exergy (Botero (2000); Creyts; Carey (1997); Gong; Wall (2001); Makarytchev (1997); Rosen; Dincer (1999); Valero; Arauzo (1991)). According to Szargut (1988), exergy is defined as the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes, involving interaction only with those components of nature.

2. Exergy Indexes for Evaluation of the Environmental Performance and Impact

Exergy can be defined as a sustainable development registration that emphasizes the connection between generated services/products and used resources. This fact makes exergy a better measure of the damage and a good ecological index since a high exergy efficiency means less exergy wastes to the environment or less environmental damage (Gong (1999); Gong; Wall (2001)).

Based on this premise, in this work the "exergy efficiency" is proposed as an environmental performance index which includes the aspects of energy efficiency and environmental impact of the energy conversion processes.

The evaluation of the environmental impact of energy conversion processes using the environmental exergy efficiency, $\eta_{env,exerg}$, can be complemented with the calculation of the total pollution rate $R_{pol,t}$ (Makarytchev (1997)).

2.1. Environmental Exergy Efficiency ($\eta_{env,exerg}$)

The environmental impact of the energy conversion processes can be reduced by the increase of the exergy efficiency of these processes. An increase in the exergy efficiency would have as consequence, a decrease in the consumption of resources and thus a reduction of the wastes and the emissions to the environment. This implies an improvement in the environmental performance of these processes.

The environmental exergy efficiency is defined as the ratio of the final product exergy (or useful effect of a process) to the total exergy of natural and human resources consumed, including all the exergy inputs. That ratio is also an indication of the theoretical potential of future improvements for a process. The environmental exergy efficiency is calculated in agreement with Eq. 1

$$\eta_{env,exerg} = \frac{B_{Product}}{B_{Nat,Res} + B_{Prep} + B_{Deact} + B_{Disp}} \quad \mathbf{(1)}$$

where:
$B_{Product}$ = exergy of the useful effect of a process.
$B_{Nat.Res}$ = exergy of the natural resources consumed by the processes.
$B_{Prep.}$ = exergy required for extraction and preparation of the natural resources.
$B_{Disp.}$ = exergy related to waste disposal of the process.
$B_{Deact.}$ = exergy of additional natural resources destroyed during waste deactivation.

Fig. 1 illustrates the interaction of these process with the environment, in terms of exergy transformations, showing the quantities used for the definition of the exergy efficiency.

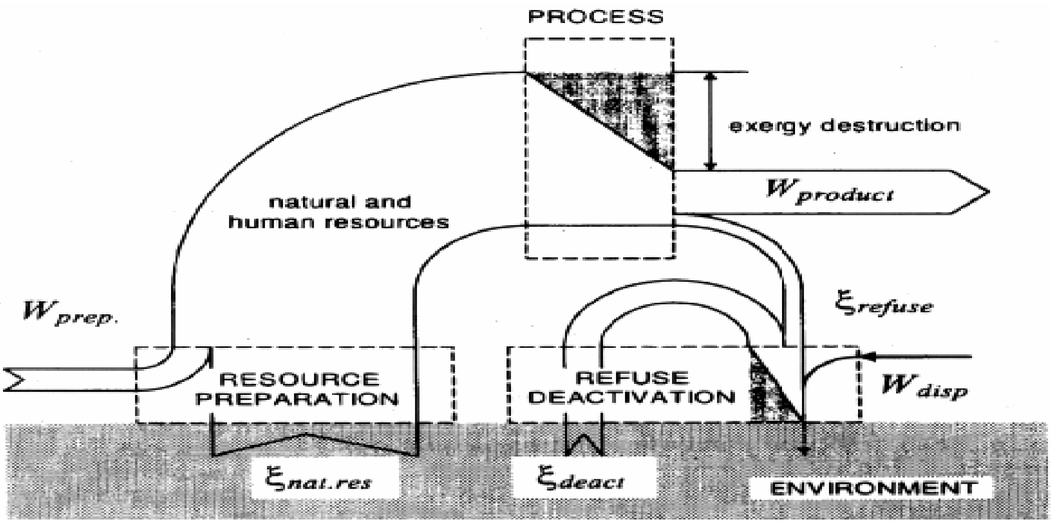

Figure 1. Environmental impact of the energy conversion processes (Makarytchev (1997))

The differences, found in the literature, between the usual definitions of the exergy efficiency and the environmental exergetic efficiency, proposed in this work, are based on the choice of different control volumes for each one of them. This fact determines the inclusion or exclusion of some terms of the total exergy consumed by human and natural resources. It is important to notice that the values of the indexes are influenced by the definition of the boundaries of the considered system.

2.2. Total Pollution Rate ($R_{pol,t}$)

The environmental performance information obtained with the determination of $\eta_{env,exerg}$ can be complemented with the calculation of the total pollution rate ($R_{pol,t}$). This index was initially proposed by Makarytchev (1997) for a cogeneration plant, in order to define an index of environmental hazard that characterizes the exergy destruction caused by deactivation of process wastes. In this paper, $R_{pol,t}$ is defined by Eq. 2. The total pollution rate may be decomposed into terms of physical and chemical components by splitting appropriately the exergy of the process wastes. The physical pollution rate quantifies a harmful effect of the wastes disposal for temperatures and pressures different from the environment. The chemical pollution rate is a measure of the wastes capacity to react with components of the environment, while they reach the chemical equilibrium with the environment.

$$R_{pol,t} = \frac{B_{Waste} + B_{Deact}}{B_{Product}} \quad \textbf{(2)}$$

where:
B_{Waste} = exergy of waste, which includes the exergies of solid wastes, rejected heat, and emissions.
B_{Deact} = exergy of additional natural resources destroyed during wastes deactivation.
$B_{Product}$ = exergy of the useful effect of a process.

The total pollution rate will be $R_{pol,t} >> 1$, when the term $(B_{Refuse} + B_{Deact}) >> B_{Product}$. This is the case for processes whose emissions and wastes produce a great impact in the environment.

The total pollution rate will be $R_{pol,t} = 0$, when the term $(B_{Refuse} + B_{Deact}) = 0$. This is the case for reversible processes, that don't cause impact in the environment.

The total pollution rate will be between $0 < R_{pol,t} < 1$, when the term $(B_{Refuse} + B_{Deact}) < B_{Product}$. This is the case for processes that present an environmental impact that it is function of the technological limitations of the energy conversion processes.

3. Evaluation of the environmental impact of two Wastewater Treatment Plants

3.1. Plants description.

The analysis of environmental impact was applied to two Wastewater Treatment Plants (WTP), located in the Metropolitan Area of São Paulo, that belong to Tietê River Depollution Program.

A detailed description of WTPs Barueri and Parque Novo Mundo are showed in Mora; Oliveira (2004).

In Fig. 2 , are illustrated the flowchart of WTPs Barueri and Parque Novo Mundo.

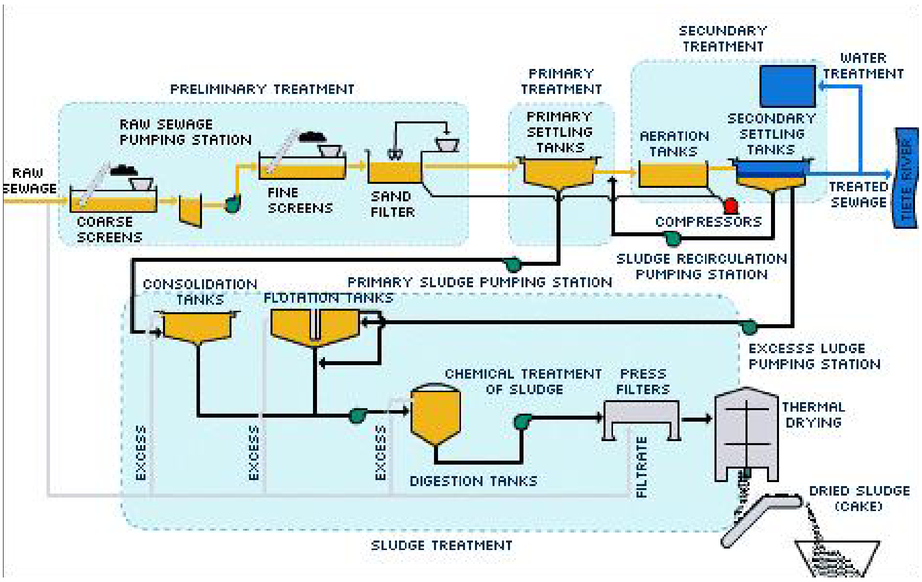

Figure 2. Wastewater Treatment Plant (SABESP (2004))

The plant type illustrated are conventional and secondary activated sludge treatment with organic material removal of 90% Biochemistry Oxygen Demand (BOD). The treatment process that take place in the plants consist of the following stages:

a) The Preliminary Treatment consist of two phases: screening and sand removal. Screening removes large solids, which are retained by the screens. The main reasons for screening are to protect the pumps and tubes, later treatment units and the tanks. In sand removal, the sand is removed by sedimentation. The aims of sand removal are to protect equipment from wear and turbulence, eliminate or reduce the risk of blockages in pipes, tanks, siphons and passages, and simplify the liquid transportation, especially transfer of sludge (see Fig.2).

b) The Primary Treatment consist of primary settling tank which tanks are rectangular or round. Sewage flows slowly through the tanks, allowing suspended solids to gradually settle to the bottom of the tank. This solid mass, called primary sludge, can be consolidated at the bottom of the tank and sent directly for digestion, or can be sent to the consolidation tanks. A large part of these solids is made up of organic matter. Depending on the nature and size of the suspended solids, rotating sieves may be used instead of the screening system or the primary settling tanks (WTP PNM). The aim is to separate the larger suspended solids, by means of flowing them through the moving sieves, from the center to the outside. The retained solids are continuously removed in buckets.

c) The Secondary Treatment is made of three phases. In the aeration tank (phase one), organic matter is removed by biochemical reaction, using microorganisms (bacteria, protozoans, fungi) in the aeration tank. This process relies on contact between the microorganisms and the organic material in the sewage, which forms their food. They convert the organic material into carbon dioxide, water and their own cell structure. The secondary settling tanks perform an important function in the activated sludge process (phase two), being responsible for the separation of the suspended solids present in the aeration tank, allowing a clarified liquid to flow out, leaving sediments solids at the base of the tank, which can be returned in a higher concentration. The effluent from the aeration tanks is settled, so that the activated sludge is separated and returns to the aeration tanks. The return of this sludge is necessary to supply the aeration tanks with a sufficient quantity of microorganisms to keep the feeding process going in sufficient strength to decompose the organic material efficiently. The liquid effluent from the secondary settling tanks is either released directly or conveyed for treatment so that it can be reused internally or sold for uses such as washing streets and watering gardens. In the excess sludge pumping station hapes the third stage of the secondary treatment: the sludge formed from the suspended solids by means of the alimentation of microorganisms must be removed to maintain equilibrium in the system (solids in = solids out). The sludge is extracted and sent for treatment (see Fig.2).

d) The Sludge Treatment consists of five phases: i) Consolidation: this stage takes place in consolidation and flotation tanks. As the sludge still contains large quantities of water, its volume must be reduced. The consolidation process increases the solid content in the sludge, reducing its volume. This process can increase the proportion of solids from 1% to 5%. In this way, subsequent units, such as digester tanks and drying units have less work to do. The most common methods include gravity consolidation and flotation. Gravity consolidation is based on the principle of zone sedimentation, as in the conventional settling tanks. The consolidated sludge is removed from the base of the tank. Flotation involves the introduction of air in a compression chamber. When the solution is depressurized, the dissolved air forms micro bubbles that carry the clumps of sludge to the surface, where they are removed. ii) Anaerobic Digestion: digestion has the following aims: to destroy dangerous microorganisms, to stabilize unstable substances and organic material present in the crude sludge, reduce the volume of the sludge through liquefaction, gasification and consolidation, to enable the sludge to reduce its liquid level, and to allow the use of the sludge – after stabilization – as a fertilizer or soil conditioner. Without oxygen, only anaerobic bacteria survive, which are able to use combined oxygen. Acidogenic bacteria break down carbohydrates, proteins and lipids, turning them into volatile acids. Methanogenic bacteria convert a large part of these acids into gases, principally methane. The stabilization of these substances can also be performed by addition of chemicals, a process known as chemical stabilization. iii) Chemical Conditioning: chemical conditioning results in the coagulation of solids and the freeing of absorbed water. Conditioning is used before the mechanical drying systems, such as filtration, centrifuging, etc. The chemicals used include iron chloride, line, aluminum sulfate and organic polymers. iv) Press Filters: drying in the press filters occurs under high pressure. The advantages of this system include: high concentration of solids in the sludge cake, low turbidity in the filtrate and high solid retention. The resulting proportion of solids is between 30% and 40% for a 2 to 5 hour filtration cycle – the time needed to fill the press, maintain it under pressure, open it, remove the cake and close the press. v) Thermal Drying: thermal drying of the sludge is the process of reduction through evaporation of water into the atmosphere by means of heat, resulting in a proportion of solids between 90% and 95%. This reduces the final volume of the sludge significantly SABESP (2004).

3.2. Exergy evaluation of the environmental impact of the WTP

The analysis of the environmental impact was realized for the Wastewater Treatment Plants Barueri and Parque Novo Mundo (PNM). Based on the data supplied by SABESP (São Paulo Wastewater Treatment Co.), an exergy analysis of the two WTP was realized considering operation in steady state conditions. The chemical exergies of the substances were determined according to data presented by Szargut et al. (1988). With the information generated by this exergy analysis, the environmental exergy efficiency and the total pollution rate were determined and compared.

In Fig. 3 and Fig. 4, are presented the exergy balance for the two Wastewater Treatment Plants (PNM and Barueri).

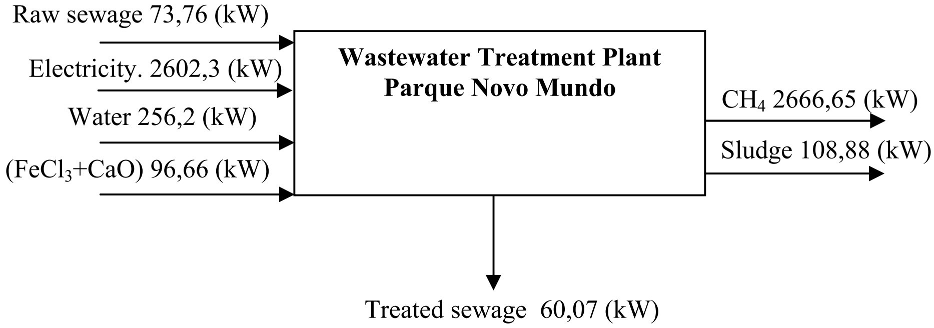

Figure 3. Exergy balance of the Wastewater Treatment Plant Parque Novo Mundo

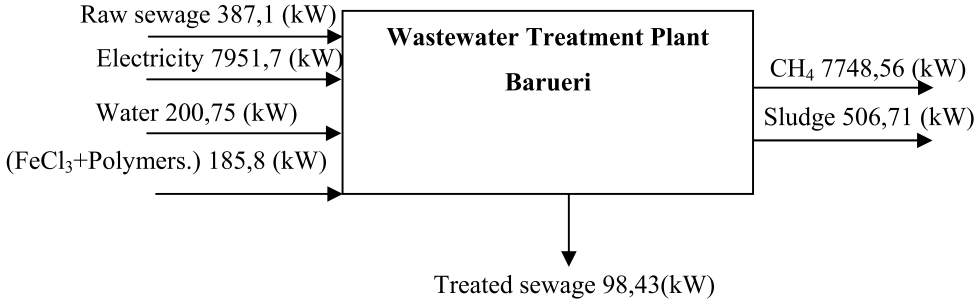

Figure 4. Exergy balance of the Wastewater Treatment Plant Barueri

In Tab. 1. are presented the results of the exergy balance realized for the two Wastewater Treatment Plants (PNM and Barueri).

Table 1. Values of the input, output, destroyed and lost exergy flows for the Wastewater Treatment Plants of Parque Novo Mundo and Barueri

Exergy / **Process**	**Input (kW)**	**Output (kW)**	**Destroyed and lost (kW)**
WTP Parque Novo Mundo	2932.3	60.1	2872.2
WTP Barueri	8539.5	98.4	8441.1

In Tab. 2. are presented the values of the exergy indexes calculated starting from the results of the exergy balance. These indexes were used in the evaluation of the environmental impact of the two Wastewater Treatment Plants.

Table 2. Values of the environmental exergy efficiency and total pollution rate for the Wastewater Treatment Plants of the Parque Novo Mundo and Barueri

Environmental index / **Process**	$\eta_{env,exerg}$	$R_{pol,t}$
WTP Parque Novo Mundo	0.02	47.8
WTP Barueri	0.01	85.8

In this Table is observed, in agreement with the exergy indexes ($\eta_{env,exerg}$, $R_{pol,t}$), that the process that causes the smallest impact in the environment is the Wastewater Treatment Plants Parque Novo Mundo, since it presents the largest $\eta_{env,exerg}$ (0.02) and the smallest $R_{pol,t}$ (47.8).

The low values obtained for the environmental exergy efficiency ($\eta_{env,exerg}$) were due to the high consumption of electricity for the small generated product. The electric power consumption represents 93.1% and 88.7% of the flow of input liquid exergy respectively in WTP Barueri and PNM.

Another important term in the calculation of the exergy indexes is the exergy associated to the wastes of the processes (produced gas and dehydrated mud). If all this exergy was associated to an useful exergetic effect, the values of the $\eta_{env,exerg}$ for WTP Barueri and PNM would increase significantly. These values are presented in Tab. 3.

Table 3. Values of the environmental exergy efficiency and total pollution rate for the Wastewater Treatment Plants of Parque Novo Mundo and Barueri with the use of the produced gas and dehydrated mud.

Environmental index / **Process**	$\eta_{env,exerg}$	$R_{pol,t}$
WTP Parque Novo Mundo	0.97	0.00
WTP Barueri	0.98	0.00

4. Conclusions and Recommendations

The present work proposes a scientific methodology with an exergy based criteria to evaluate and quantify the environmental impact of energy conversion processes. In this way, it is possible to compare and characterize the environmental exergy performance, and the destruction of the exergy of these processes in the environment. It should also be emphasized the flexibility of the types of processes to which this methodology is applicable, being able to compare environmental damages of very different scenario.

In this work, the environmental exergy efficiency is proposed as an index of environmental impact that contains the aspects of exergy efficiency and environmental impact of the energy conversion processes.

The evaluation of the environmental impact through the environmental exergy efficiency ($\eta_{env,exerg}$) is complemented with the calculation of the total pollution rate $R_{pol,t}$. Tab. 4. presents a comparative summary of the exergy indexes for the case studies analyzed in this work.

Table 4. Comparative summary of the values of the environmental exergy efficiency and total pollution rate for the case studies analyzed

Environmental index / **Process**	$\eta_{env,exerg}$	$R_{pol,t}$
WTP Parque Novo Mundo	0.02	47.80
WTP Barueri	0.01	85.80
WTP Parque Novo Mundo (considering the methane and the mud of WTP as useful effect)	0.97	0.00
WTP Barueri (considering the methane and the mud of WTP as useful effect)	0.98	0.00

An overall comparison of the results obtained through the calculation of the indexes of environmental impact ($\eta_{env,exerg}$, $R_{pol,t}$), (see Tab. 4), shows that the process that causes the smallest impact in the environment (not considering the cases where the methane and the mud of WTPs are useful effects) is the Wastewater Treatment Plant Parque Novo Mundo, since it presents the largest $\eta_{env,exerg}$ (0.02) and the smallest $R_{pol,t}$ (47.8). In this comparison it is also observed that in agreement with the $\eta_{env,exerg}$ values, (0.01), and $R_{pol,t}$ (85.8), the process that causes the largest impact in the environment is the Wastewater Treatment Plant Barueri, if the by-products (methane and mud) are not considered as useful effect.

The low values of the environmental exergy efficiency ($\eta_{env,exerg}$) for two WTP , are due mainly to the high consumption of electricity for the small generated product, besides the great amount of methane and mud wasted. The electric power consumption represents the largest percentage of the input exergy in the WTP.

Another important fact to be considered in the low values obtained in the environmental exergy efficiency of WTPs, is that the exergy contained in the by-products generated (methane and the mud) is not being used at the moment. If that exergy was considered as a part of the useful effect of the processes of WTP, the values of the $\eta_{env,exerg}$ for WTP Barueri and PNM would be 0.98 and 0.97, and the values of the pollution rate ($R_{pol,t}$) would be zero. From the analysis of these last results, it is observed the great potential improvement that these processes would have, by using the mud for agricultural purposes and the methane as a fuel.

From the analysis of the exergetic indexes results of the environmental impact for the analyzed case studies, it can be observed that in spite of the limitations of the exergy concept with respect to the toxicity and the biological quality of any substance, it is an useful tool in the quantification of the environmental impact of the energy conversion processes, from the point of view of the processes environmental performance ($\eta_{env,exerg}$), as well as in the characterization of the required exergy to deactivate the process wastes ($R_{pol,t}$).With the obtained results of that evaluation and quantification, it can be made the optimization of the environmental performance of the process, what is reflected directly in its economical analysis.

To complement this work, it is proposed to include a thermoeconomic analysis in the methodology presented for the environmental evaluation of energy conversion processes that take place in wastewater treatment plants.

5. Acknowledgement

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