EXERGY ANALYSIS OF ENVIRONMENTAL IMPACT MITIGATION PROCESSES

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Abstract. *This study focuses on the sustainability of different technological options for minimizing environmental impact. it is proposed that the cumulative consumption of materials and utilities for construction and operation of environmental treatment systems can be quantified in terms of exergy. in addition, the exergy content of the emissions of a given production process, as well as the exergy of by-products of the treatment process, can be quantified to develop an exergy balance, focused on the treatment process. Furthermore, a methodology is proposed to compare the different process alternatives in two situations: the former considering that the main task of the process is to eliminate the exergy content of a given emission, which is analyzed by the* η_d *coefficient; and the latter considering that the main task of the process is to maximize the utilization of the exergy content of a given emission, which is analyzed by the* η_p *coefficient. Three case studies are presented: air emissions treatment, remediation of a contaminated site and management of solid waste. For each case, three different process alternatives were analyzed, by the proposed methodology. it is concluded that exergy is appropriate to compare the technological alternatives and can be used as a guideline for choosing the most sustainable one.*

Keywords. *exergy analysis, environmental impact, mitigation processes*

1. Introduction

Relationships between the environment in which we live and human activity have been the focus of growing interest in society as a whole and, more specifically, on the part of the scientific community. Understanding of the limited way in which the environment is able to receive and assimilate the waste generated by our civilization has been widely disseminated, both by the media and third sector organizations, whose pressure has been translated, over the years, into ever more restrictive environmental legislation.

The quantification of environmental impact has been effected in many different ways, involving technical, economic and social aspects. Even a technical approach to environmental problems ends up in the need for a complex analysis, involving various scientific disciplines and methodologies Ayres (1995), Ayres (1996).

On the other hand, treatment processes and measures with a view to maintaining emissions within legally established limits have been evaluated, almost exclusively, with respect to their emissions abatement efficiency and economic aspects.

Since environmental issues inevitably require a multidisciplinary analysis, definition of acceptable legal limits regarding the release of waste materials into the environment has been effected through an approach that is not highly systematic, considering physical, chemical, biological, ecological and toxicological parameters, among others. Furthermore, the fact should be emphasized that, in general, legal limits are normally dictated by the most recent developments in treatment technology.

Although suited to the pluralistic nature of environmental problems, the kind of analytical tool normally used ends up relegating the comparison of environmental solutions that attain the same emissions abatement targets, to an economic assessment. Very often, aspects that provide evidence of a lesser global environmental impact of the adopted solution end up being neglected, to the detriment of a local analysis.

In this context, the concept of exergy arises as a powerful tool for analysis not only of environmental impact, but also the measures and processes necessary for mitigating this impact. Since it is a measure of the potential for carrying out work contained in the material (fuel, food or any kind of material), exergy becomes the natural choice for assessing the quantity and quality of resources, instead of other parameters, Gong (1999), Wall (1993) and Dewulf (2001).

Combining the First and Second Laws of Thermodynamics, exergy manages to be a general measure of all streams and stocks of natural resources, including those that are renewable Wall, (1997), Wall & Gong (1997).

Life Cycle analysis is one of the tools used in assessing the sustainability of technological options. It takes into consideration all effects on the ecosystem and population that may put at risk the possibilities open to current and future generations, as well as their survival Cornelissen, (1997), Dewulf, (2001) & Dewulf, (2002).

The concept of cumulative exergy consumption was introduced by Szargut (1988) to express the sum of the exergy of natural resources consumed in all steps of a production process. The exergy content of emissions with respect to the natural environment may cause a potential harming to the environment Szargut (1988).

Using life cycle analysis methodology on an exergetic basis, it is possible to evaluate an environmental impact mitigation process, of the same energy dimension (Joule), in an ordinary facility, with respect to its products and input materials/utilities, irrespective of whether or not these are fuels Gong (1999), Wall (1993).

2. Proposed Metodology

All the individual stages of a production process, from the raw material, taken from the environment, to the end product, result in the destruction of exergy. Very often, the final production stage is characterized by a relatively high degree of exergetic efficiency, although the production of intermediary products may occur with very low rates of exergetic efficiency. Therefore, it is both interesting and useful to use the accumulated exergy consumption (AExC) calculation proposed by Szargut (1988) and Szargut & Morris, (1987) , which expresses the sum consumption of the exergy of natural resources throughout the production chain.

A similar method is that of accumulated energy consumption (AEnC), which has already been developed to a significant extent during the 1970s. Nevertheless, the calculation based on exergy is more informative, as it considers the exergy of non-energy raw materials taken from nature Szargut (1988).

Definition of system boundaries is very important, as these have a direct influence on the sum exergy of the calculated stages. With a view to making an exergetic analysis of environmental solutions, considered here is a generic problem with the boundaries shown in Figure 1, where the control volume considered is that which envelops the treatment process. The following exergy flows (defined as B) across the boundaries of this control volume:

- $\mathbf{B}_{\text{materials/utilities}}$: AExC of all the materials and utilities necessary for implementation and operation of the treatment system;
- $\mathbf{B}_{\text{contaminant}}$: Exergy of the contaminant stream generated by human activity and the object of treatment;
- $\mathbf{B}_{\text{waste}}$: Exergy of the waste stream produced by the treatment process, which are discarded into the environment; and
- $\mathbf{B}_{\text{product}}$: Exergy of products useful to society, obtained through the treatment process.

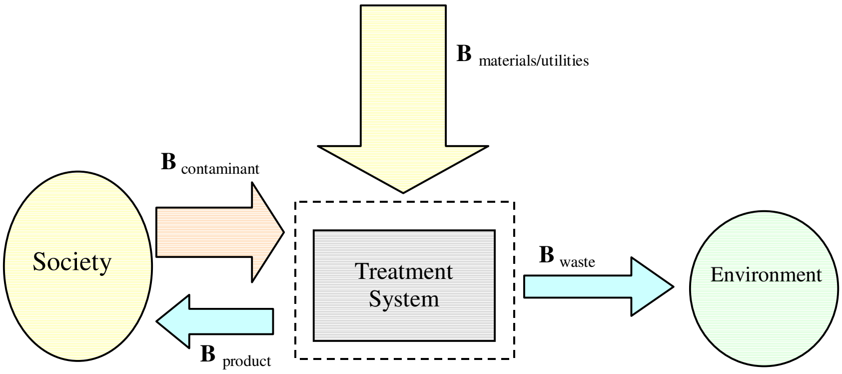

Figure 1. – Boundaries of the considered problem.

Therefore, this study was limited to the analysis of the adopted treatment process and/or environmental solution. In this case, one has the following exergy balance:

$$\mathbf{B}_{contaminant} + \mathbf{B}_{\substack{materials\\utilities}} = \mathbf{B}_{product} + \mathbf{B}_{waste} + \mathbf{B}_{destroyed} \tag{1}$$

From this, it can be seen that one has moved away from traditional focus on exergetic balance of the production process, to assessment of the system for abatement of the emission, waste and/or contaminant that the process generates.

With given or estimated chemical composition of the wastes and contaminants, the specific exergy streams are calculated using the following equation:

$$\bar{\mathbf{b}}^{ch} = \sum_i (\mu_i - \mu_{0,i}) n_i + RT_0 \sum_i n_i \ln(a_i) \tag{2}$$

Where b^{ch} is the chemical exergy, μ_i is the chemical potential of the species, n_i is the number of moles of species i, R is the universal gas constant, T_0 is the reference temperature and a_i is the activity of species i.

With regard to the exergy of input materials/utilities, the methodology employed was that of exergetic life cycle analysis, proposed by Szargut (1988), according to which accumulated exergy consumption (AExC) expresses the exergy sum of natural resources consumed throughout the implementation and operation of this system. The difficulty associated with the use of this methodology lies in calculating the exergy of non-fuel materials, resources and utilities taken from the environment.

Szargut (1988) and Dewulf (2001) tabulated several values for the specific exergy content of a variety of materials and utilities, ranging from extraction of raw materials from the environment, handling, manufacture and transport, to their construction and operation.

Therefore, the methodology comprised the following system of working:

- Identification and characterization regarding the chemical composition of the environmental contaminant to be assessed;
- Calculation of the exergy of this stream;
- Calculation of the AExC of several treatment, decontamination or recycling processes, determining the materials and utilities necessary for their implementation;
- Calculation of the exergy of the output stream(s) after treatment; and
- Evaluation of yield, in exergetic terms, of the treatment process given by the methodology detailed below.

Depending on the objective of the treatment process, one has two different situations, for which differentiated methodological criteria were defined.

2.1 Processes Involving the Destruction of Contaminant Exergy

The objective of such processes is to reduce the exergy contained in the contaminant stream to a minimum. These are processes used in the treatment of air emissions and liquid effluents, or decontamination of soil and groundwater, in which there is minimal or even negligible product recovery. With respect to these processes, according to the nomenclature shown in Figure 1, an exergetic yield (η_d) was defined for destruction of the contaminant:

$$\eta_d = \frac{\mathbf{B}_{contaminant} - \mathbf{B}_{waste} - \mathbf{B}_{product}}{\mathbf{B}_{materials/utilities}} \tag{3}$$

2.2 Processes Making the Best Use of Contaminant Exergy

The objective of such processes is to maximize the exergy that can be obtained from a given contaminant, through the use of treatment processes that mitigate the impact caused on the environment and produce some kind of product that is of use to society. Such processes include the final disposal of solid or liquid waste materials, which have an elevated specific exergy that can be partially recovered by society. Considering these processes, according to the nomenclature shown in Figure 1, an exergetic yield (η_p) was defined with regard to making best use of the converted product:

$$\eta_p = \frac{\mathbf{B}_{waste} + \mathbf{B}_{product}}{\mathbf{B}_{contaminant} + \mathbf{B}_{materials/utilities}} \tag{4}$$

3. Case Studies

Below are presented three case studies in which the methodology described in the previous section was applied. An attempt was made to consider very different situations, with a view to including the three media that are susceptible to environmental impact, namely: water, air and soil. In this way, case studies were considered involving the problems of air emissions treatment, soil and groundwater contamination, and the final disposal of solid waste materials.

3.1 Air Emissions Treatment

Here we are dealing with a real situation, in which metallic parts are painted using a solvent based paint, in an enclosed painting compartment. A radial fan brings about the removal of air contaminated by volatile organic compounds (VOCs), it being the case that this is the object of treatment in this case. The chemical composition of the exhaust gases is shown in Table 1. For a flow rate of 141 Nm^3/h, and an exhaust gas temperature of 315K, the total exergy rate of the contaminant was calculated as $\mathbf{B}_{contaminant} = 20.060$ kW.

Table 1: Composition of exhaust gases

Contaminant	**Concentration [µg/Nm^3]**
Benzene	24
Toluene	60,162
Xylene	39,015
n-butyl acetate	41,958
Ethyl alcohol	27,972
Acetone	23,310

Three treatment processes were assessed, namely: contaminant incineration, using an afterburner; adsorption onto columns of activated carbon, and biodegradation using a biofilter. The technical characteristics of these processes are summarized in Table 2.

Table 2 – Characteristics of air emissions treatment processes

Process	**Characteristics**
After-Burner	Auxiliary fuel: CH_4 Excess air: 1150% Temp. of gases at outlet: 1295K Fuel consumption: 154.9 Nm^3/h Electrical power consumption: one 5.6 kW axial fan 100% thermal oxidation of contaminants
Activated Carbon	Number of columns: 3 Mass absorption capacity: 0.25 kg of contaminant / kg of activated carbon Electrical power consumption: one 11.2 kW axial fan 100% absorption of contaminants
Biofilter	Dimensions: 20 m x 30m x 2.5 m Volume of substrate: 1250 m^3 Electrical power consumption: one 11.2 kW axial fan 90% of contaminants metabolized

Calculations were made of AExC for each alternative, considering an operational period of 20 years. Also calculated was the exergetic content of waste materials and exergetic yield regarding the destruction of the contaminant, η_d, it being the case that the results obtained are shown in Table 3.

Since the Afterburner alternative increases the exergy content of the emission, due to temperature elevation ($B_{waste} > B_{contaminant}$), η_d has a negative value in this case.

Table 3: Calculation of Exergetic Yield

Parameter	**Units**	**Alternatives** **After-Burner**	 **Activ. Carbon**	 **Biofilter**
$B_{contaminant}$	MJ	2.98E+06	2.98E+06	2.98E+06
B_{waste}	MJ	1.76E+07	0	3.05E+05
$B_{product}$	MJ	0	0	0
$B_{materials/util}$	MJ	7.97E+09	2.06E+08	8.40E+06
η_d	%	- 0.18	1.44	31.90

3.2 Soil and Groundwater Remediation

This case study was also based on a real situation, involving soil and groundwater contamination by petroleum derivative hydrocarbons, which occurred in February 2001. In this occasion, a pipeline assembly fault resulted in a leak of approximately 8,000 L of diesel oil into the soil from an underground storage tank at a gas station located in the interior of the state of São Paulo - Brazil. Table 4 shows an estimate of the distribution of fuel throughout the saturated and non-saturated zones of the soil, according to the fraction distribution model developed by the United States Environmental Protection Agency (USEPA).

Table 4. Distribution of 8,000 L of fuel in an aquifer

Med-ium	Phase	Volume of Contaminant [L]	% of total	Volume Contaminated	% of total
Soil	Free	5,120	64	673	1
Soil	Residual	2,800	35	13,464	20
Water	Dissolved	80	1	53,183	79
Total		8,000	100	67,320	100

Based on information regarding the average composition of diesel oil, and the specific exergy values for each hydrocarbon drawn up in Dewulf, J.; Van Langenhoven (2001), using equation (2), the exergy of the contaminant was calculated as $\mathbf{B}_{contaminant}$ = 328,628 MJ, for the 8,000L of leaked fuel, this being the objecto f elimination (destruction) by the treatment processes.

Three treatment processes were evaluated, namely: pump & treat (P&T), multi-phase extraction (MPE) and removal and incineration of contaminated soil. The technical characteristics of these processes are summarized in Table 5.

Table 5 – Characteristics of soil and groundwater decontamination processes.

Process	**Characteristics**
Pump & Treat	Action: soil, free and residual phases Components: three intrinsically safe pneumatic pumps, oil/water separation tank, and an adsorption system for the phase dissolved in water Installed power: 3.73 kW Efficiency: 64% removal of contamination
MPE	Action: soil, free and residual phases and water (dissolved phase). Promotes *in situ* bioremediation due to soil oxygenation. Components: vacuum pump, vacuum tank, emulsion breaking system, oil/water separation tank, and system for adsorption of phase dissolved in water and air emissions Installed power: 20 kW Efficiency: 100% removal of contamination (considering the levels of decontamination that should be attained according to the risk assessment conducted previously)
Removal and Incineration	Action: soil, free phase and partially in residual phase Removal: Excavation of 26,896 m^3 of soil, transport of 3,026 tons of contaminated soil by truck to an incineration facility Incineration: incinerator with capacity of 100 t/day of hazardous waste material, consuming 6.25 kW_{el}, 60 Nm^3/h of natural gas, and 10 m^3/hr of process water Efficiency: 35% removal of contamination

The AExC value was calculated for each alternative, considering an operating period of 10 months in the case of pumping, 18 months in the case of MPE, and 1 month for soil removal and incineration. Since the processes act on differentportions of the contamination, a remediation efficiency value was also calculated, in order to assess the rate of exergy consumption per unit volume decontaminated. This parameter, as well as the exergetic yield of destruction of the contamination, η_d, are shown in Table 6.

Table 6: Calculation of Exergetic Yield

Parameter	Units	Alternatives P&T	 MPE	 Incineration
Volume decont.	m3	673	67.320	2,522
% of total	%	1	100	4
AExC	MJ	1.02E+06	9.06E+05	3.03E+06
Remediation Efficiency	MJ/m3	1,516	13	1,201
$B_{contaminant}$	MJ	3.29E+05	3.29E+05	3.29E+05
B_{waste}	MJ	1.18E+05	0.00E+00	2.14E+05
$B_{product}$	MJ	0	0	0
$B_{materials/util}$	MJ	1.02E+06	9.06E+05	3.03E+06
η_d	%	21	36	4

3.3 Final Disposal of Urban Solid Waste Materials

For the purposes of this study, consideration was given to a specific assessment according to the mass of the following materials present in domestic refuse: paper, cardboard, polyethylene (PE), polypropylene (PP) polyvinyl chloride (PVC). Chemical exergy, as well as the accumulated exergy consumption of the analyzed materials are shown in Table 7 (Szargut (1988) , Dewulf, J.; Van Langenhoven (2001).

Table 7: Characteristics of materials analyzed

Product	Exergy of Raw Material [MJ/kg]	AExC [MJ/kg]
Cardboard	19.50	70.84
Paper	16.50	69.16
PE	46.50	86.00
PP	46.40	85.20
PVC	19.70	67.00

Table 8: Characteristics of urban solid waste treatment processes

Process	Characteristics
Landfill	Capacity of landfill: 100 t/day Average density of waste: 8 t/m^3 Installed power of systems for treating percolate and making use of biogas: 63.04 kW Work demand: 420,000 t.km Quantity of soil moved: 495,000 m^3 Co-generation: 1.1 MW$_{el}$ + 109 kW$_{th}$ [14]
Recycling Triage	Capacity: 2 t /day Manual segregation system Installed power: 23.5 kW
Plastics Recycling	Installed power: 25.36 kW Gas consumption: 30 m^3/t
Paper/Cardboard Recycling	Installed power: 34.69 kW Gas consumption: 30 m^3/t
Incineration	Capacity: 100 t/day Air consumption: 653,240 kg/day (100% excess) Energy input: 8x10^5 MJ/day Entalpy of exhaust gases: 6.3x10^5 MJ/day Ash production: 25.26 t/day Installed power: 91 kW

With regard to solid waste treatment, three alternatives were considered, namely: sanitary landfill, recycling and incineration. Table 8 shows the main characteristics of the processes that were analyzed.

The AExC value was calculated for each alternative, considering an operating period of 20 years. Also calculated were the exergetic content of the waste materials and the exergetic yield for obtaining the products, η_p. The results are shown in Table 9.

Table 9: Calculation of Exergetic Yield

Alternatives / Product	$B_{materials}$ **[MJ/kg]**	**Product**	$B_{product}$ **[MJ/kg]**	η_p (%)
Landfill				
Cardboard	1.15	Heat & Elet.	1.04	5
Paper	0.47	Heat & Elet.	1.04	6
PE	0.21	Heat & Elet.	0.00	0
PP	0.23	Heat & Elet.	0.00	0
PVC	0.15	Heat & Elet.	0.00	0
Recycling				
Cardboard	18.09	Cardboard	19.50	52
Paper	18.09	Paper	16.50	48
PE	12.62	PE	46.50	79
PP	12.62	PP	46.40	79
PVC	12.62	PVC	19.70	61
Incineration				
Cardboard	0.54	Heat & Elet.	7.12	36
Paper	0.54	Heat & Elet.	6.88	40
PE	0.54	Heat & Elet.	18.91	40
PP	0.54	Heat & Elet.	18.64	40
PVC	0.54	Heat & Elet.	9.87	49

4. Conclusions

This study proposes a scientific methodology, with well defined criteria for quantifying the performance of technological alternatives regarding the mitigation of environmental impact, based on one single aspect: exergy. In this way, it is possible to compare the exergetic cost of implementing and operating a given process with the exergy of the contaminants that are to be eliminated. The method of analyzing the accumulated exergy of the processes involved, allows the evaluation not only instantly but also throughout an operating period. Emphasis should also be given to the flexibility of scenarios and situations to which this methodology is applicable, with the possibility of comparing the environmental damage and cost of very different scenarios. Such a characteristic allows for an assessment of environmental impact and its cost for society in a more consistent manner, even making it possible, as proposed by Gong (1999), Wall (1993) to demand corresponding sanctions and rates, according to a suitably defined criterion.

The proposed merit criteria, exergetic yield for destruction of the contaminant and conversion into product, showed results consistent with those technological options that are the most notable in terms of ensuring the sustainability of environmental solutions.

With respect to all the alternatives evaluated, the input materials/utilities consumed during the operation had a preponderant part to play in calculating accumulated exergy in each process, with special emphasis on the utilities gas and electricity. The exergy consumed in installing the processes had less significant orders of magnitude.

Case studies involving the treatment of air emissions and the remediation of contaminated soil and groundwater, respectively, were assessed according to η_d rate, as the main focus of these processes was that of eliminating the exergy contained in the contaminants. None of the processes in question showed any kind of by-product that is of use to society. Even though in some of them good use was made of thermal wastes, as would be possible in the afterburner process, or pyrolysis for activation of the saturated activated charcoal, involved in both studies, the resultant products would be of less importance when compared with the main objective of these processes. Nevertheless, the methodology used in calculating η_d would show the distortion of providing lesser yields for those processes in which some kind of useful product is returned to society. This particular aspect could be further investigated and corrected in a continuation of this study.

In situations where the objective was that of destroying the exergy of the contaminant, processes involving biological activity were those that showed the highest yields, for example, use of a biofilter (32.7%) and MPE (36%). On the other hand, those involving thermal destruction through the consumption of input materials/utilities (mainly natural gas) showed the lowest yields, such as the removal and incineration of soil (4%, second case study), use of the afterburner (0.18%) , and adsorption onto activated carbon (1.48% first case study).

The second case study showed a unique situation, in which the available processes that were evaluated act on a different medium and portion of the contamination. Therefore Table 6 shows the specific remediation efficiency per volume decontaminated. The yield η_d calculated in the same table confirms the actual raking that is observed, which has MPE (η_d =36%), as the most sophisticated and efficient technology, concerning decontamination levels, followed by pump & treat (η_d =21%). Soil removal (η_d =4%) shows to be the less usual alternative, due to its partial solution of the problem and its high costs.

Urban solid waste treatment processes were the only ones assessed based on product yield rate, η_p, in view of the fact that these processes manage to return products that are of use to society, such as process heat, electrical power and recycled materials.

The differences obtained using η_p, which identifies recycling as the best alternative and sanitary landfill as the worst, was highly consistent with the notion of sustainability that environmentalists and government institutions have been trying to disseminate. The highest exergetic content and consequent added value of recycled products explain the high figure obtained, even if this process involves a higher consumption of exergy. At the opposite extreme, landfill seems to be an alternative of low specific exergy consumption, however, on the other hand, it provides little or no useful product to society.

Currently, choices of alternatives regarding processes for the mitigation of environmental impact are principally focused on cost, very often ignoring the sustainability of the technologies employed. With the use of exergy, the concept of sustainability gains a very valuable quantitative nature for conducting more technical, rational and universal analyses of environmental solutions.

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