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A general exergy-based environmental impact index †

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Abstract

An ecosystem is a complex system in which biotic and abiotic factors interact and influence each other both directly and indirectly. Each of these factors has to comply with a specific function in the different processes that occur inside the ecosystem, whether transporting or transforming energy or both. When anthropogenic emissions are produced, part of the useful energy of the ecosystem is used to assimilate or absorb those emissions, and the energy spent, loses its function and becomes lost work in accordance with the Gouy-Stodola theorem. Thus, the work that an ecosystem can carry out varies as a function of the lost work produced by anthropogenic sources. The permanency or loss of the ecosystem depends on how many irreversibilities it can support. The second law of thermodynamics through a systematic use of the exergy and lost work is the basis of this paper where a general environmental impact index, based on exergy, is proposed. For the purpose of this work, the ecosystem is divided in subsystems--water, soil, atmosphere, organisms and society--all of them inter-related. The ideal work variation can be obtained from each subsystem within the selected ecosystem, and a global index can be determined by adding the partial lost work of each subsystem. This global index is then used to determine the trend followed by the ecosystem from its pristine, original or environmental line base state. This environmental impact index applicability is presented for a simple combustion example.

Keywords: Environmental impact; Exergy; Entropy

1. Introduction

An ecosystem under normal conditions can be seen as an integrated system, where the flow interactions of material and energy between organisms and the surrounding environment are basically in equilibrium. However, when human beings interact with the environment, by sending or extracting materials to or from the ecosystem, they tend to break this equilibrium by overflowing or over over-extracting goods and in consequence reducing the ability of the ecosystem to transform those goods, thus impeding a continuation of the sustainable cycle. As the ecosystem reduces its capacity to transform energy and mass, we experience the same unavailability, caused by the consumption of those goods that we throw or overexploit, poisoning our own being. Considering each good extracted or sent to the environment, as an amount of available energy to be transported, used or transformed by an element of the ecosystem, every good that is not properly employed will become a loss of the available work, or lost work, which in accordance with the Gouy-Stodola theorem, will become entropy. At the end, the larger the amount of the lost work, the larger amount of the entropy produced and the lower the available energy. Thus, as the available energy tends to zero the ecosystem will tend to die.

Accurately gauging the impact of the society on the environment has become one of the most important goals around the world. A number of attempts can be found in the literature where a set of indicators to assess and manage the beneficial and detrimental effects of human activities on air, water, land, energy use, and waste production are proposed [1]. These indicators are aimed at evaluating its progress and set targets for future legislation, control and economic policies on human activities. Among them, Rosen [2] mentioned that the exergy in the unrestricted waste emissions has the potential to impact the environment. His proposal is based on the fact that there is disequilibrium between the elements of the emissions and the elements in the environment. Similarly, it has been proposed that thermo-economics can be employed as a means to evaluate the environmental impact of industrial processes of the human being. Valero [3], in particular, mentioned that thermo-economics can measure the resources used in thermal power plant systems, and from this proposes that an optimal use of

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resources aimed to reduce flue gas emission can be achieved, thus avoiding damage to the ecosystem.

Around the same time, Torres et al. [4] mentioned that thermo-economics cost accounting methods have placed emphasis on the production process, without bearing in mind the cost of residues. They also establish what is required to know where the residues have been generated, as well as their abatement costs, in order to allocate the cost of products from poly-generation systems. Therefore, there is a process of cost formation of the functional products and there also exists a cost formation process of the residues. This resource consumption is used as a measure to avoid damage to ecosystems.

Seager [5, 6] proposed a way to measure the impact on the environment of flue gases. He defined this measure as the ideal thermodynamic work of chemical separation per mole, necessary to revoke instantaneously a chemical pollutant to its pristine reference condition. Seager used an ideal gas model to evaluate the impact produced by CH_4, CO, CO_2, NO_2 and SO_2. He found that the CO_2 requires less energy per mole to be removed, but the great amount of anthropogenic carbon dioxide in the atmosphere requires much more exergy to revoke such pollutant to a reference state.

Stavropoulos [7] proposed a similar index to the one proposed by Seager, but he introduces a damage factors for every type of pollutant species that are sent to environment, and then multiplies them to Seager´s index. The damage factors are employed to give specific weight to a specific substance, thus weighs weighing their effects on global warming or ozone layer depletion. These factors are set arbitrarily and vary from 0 to 1, : for example, water receives a factor of 0, thus limiting limited to evaluate evaluating toxicity or poisoning. Later, Yang [8] continued Stavropoulos' study by introducing an index defined by the ratio of the minimum work needed to revoke pollutants to the incoming exergies from the processes were the flue gas emissions were produced.

Sciubba [9-15] introduced a methodology called extended exergy account (EEA) that is based on an extended representation of the exergy flow diagrams of processes. The fundamental premise of extended exergy accounting is that economic systems are ecosystems that function only because of the energy and material fluxes that sustain human activities. The correct measure for the cost of a commodity or a service is the extended exergetic content, and not capital or material flow or exergy or labor alone. The specific extended exergy is the sum of the physical exergy and of the equivalent exergy of capital, labor and environmental remediation activities.

Rosen [2, 16] evaluated the amount of work required to remove the excess pollutants from the environment. To obtain the excess of pollutants he took as a reference the amount of pollutants limited by standards, and compared them against point measurements. He then evaluated the exergy of reference and measured, from where he estimated the available work required to remove that difference.

As described also by Sciubba [15], the accepted meta-paradigm for the assessment of the state of the environment is:

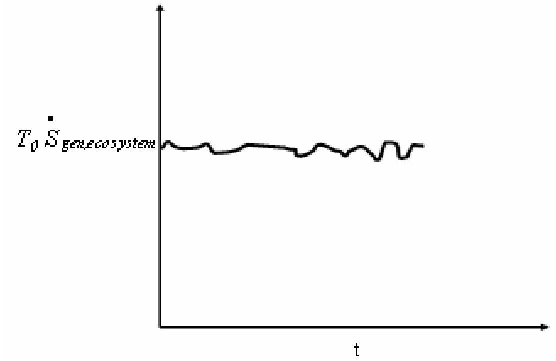

Fig. 1. Behavior of lost work in equilibrium or sustainable.

(a) environmental scientists, engineers, physicists, chemists and biologists have the role of defining, troubleshooting and calibrating a proper set of "decision parameters," called ecological indicators (EI); and (b) National & International Agencies use these EI in their evaluations. Thus a general environmental impact indicator should be based on quantitative terms, to enable one to estimate the harmful effects of industrial operations. As mentioned before, exergy loss or lost work is a concept that contains the elements that permit its use as a measure of reduction and excessive consumption of resources.

The environmental impact index, EII_{LW}, proposed in this work has the capability to identify sustainability and how far from this condition the ecosystem is found, that is, a system will be sustainable for values of unity. It can set the low and high limits where the system can operate under sustainability, as well as the base line. Then, the larger the environmental impact index is, the closest to destruction the system will be. On the other hand, the same separation from the base line defines the amount of exergy required to reverse the contamination plus the amount of exergy required from the same irreversibility of the reversion process.

2. Lost work in an ecosystem

The biotic and abiotic elements contained in the earth, including the sun's energy, form all together a thermodynamic system. In this system the biotic elements are the machines that consume and produce resources for other biotic elements and abiotic elements. At the same time, they are always affected in some way by the energy of the sun [18]. This consumption and production of goods, within the ecosystem that is in harmony, the fluxes of matter and energy remain nearly constants with time, i.e., any outflow of the biotic elements represents available energy for the next biotic element, reducing the amount of energy destruction or lost work to a minimum; thus the entropy generation does not vary drastically with time as described qualitatively in Fig. 1.

As mentioned, the ecosystem is composed by five subsystems or sphere named: atmosphere, hydrosphere, biosphere, lithosphere and society. In every subsystem the flux of matter may be expressed by Ref. [17]:

$$\left(\frac{dm_{cv}}{dt}\right)_{sphere} = \left(\sum_i \dot{m}_i - \sum_e \dot{m}_e\right)_{sphere} \tag{1}$$

where $\dot{m}$ is the mass flow rate, kg/s; the subscripts cv, i, and e refer to the control volume of a subsystem, inlet and exit, respectively. Following the Darrieuz function, the useful energy or total work for every sphere of an ecosystem is described by:

$$\dot{W}_{u,sphere} = \dot{W}_{\max,sphere} - \dot{E}_{D,sphere} \tag{2}$$

in which the sub index u refers to useful and max to maximum. $\dot{W}_{\max}$ is maximum or ideal available work of each subsystem or sphere, which includes the variation in time of exergy, the exergy caused by heat transfer, the flow exergy, chemical exergy, among others. The term $\dot{E}_D$, defined by the Gouy-Stodola theorem, refers to the exergy destroyed or lost work of each subsystem or sphere, and is given by:

$$\dot{E}_{D,sphere} = T_0 \dot{S}_{g,sphere} \tag{3}$$

where $\dot{S}_{g,sphere}$ is the entropy generation of each subsystem or sphere, and is given by:

$$\dot{S}_{gen,sphere} = \left(\frac{dS_{cv}}{dt} - \sum_j \frac{\dot{Q}_j}{T_j} + \sum_e \dot{m}_e s_e - \sum_i \dot{m}_i s_i\right)_{sphere}. \tag{3a}$$

The total work in the ecosystem can now be seen as the partial sum of the useful work from every subsystem or sphere of the ecosystem. Then the total work can be expressed as:

$$\dot{W}_{u,ecosystem} = \sum_i^m \dot{W}_{u,sphere,i} = \dot{W}_{u,A} + \ldots \\ \ldots + \dot{W}_{u,H} + \dot{W}_{u,B} + \dot{W}_{u,L} + \dot{W}_{u,S} \tag{4}$$

where u refers to useful and A, H, B, L and S refer to atmosphere, hydrosphere, biosphere, lithosphere and sociosphere, respectively. Similarly, the total lost work is given by the sum of the individual exergy destroyed in each subsystem, that is:

$$T_0 \dot{S}_{gen,ecosystem} = \sum_{i=1}^m \dot{W}_{lost,i} = \dot{W}_{lost,A} + \ldots \\ \dot{W}_{lost,H} + \dot{W}_{lost,B} + \dot{W}_{lost,L} + \dot{W}_{lost,S} \tag{4a}$$

and

$$T_0 \dot{S}_{gen,ecosystem} = \sum_{i=1}^m T_0 \dot{S}_{gen,i} = T_0 \dot{S}_{gen,A} + \ldots \\ \ldots + T_0 \dot{S}_{gen,H} + T_0 \dot{S}_{gen,B} + T_0 \dot{S}_{gen,L} + T_0 \dot{S}_{gen,S}\,. \tag{4b}$$

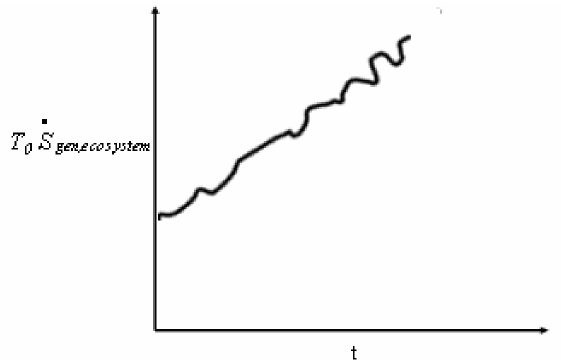

Fig. 2. Increase of lost work in the ecosystem.

Straightforward scenarios can be drawn from Eqs. (2) and (3). First, as the lost work or destroyed exergy increases, the availability to perform any task decreases linearly. Also, for a system to keep doing the maximum amount of work, the term of Eq. (3) should be zero or minimum, since it will never be negative. Bearing this in mind, when a human being – sociosphere – uses irresponsibly the resources from the ecosystem, surplus of output flows of matter and energy are sent back to the rest of the elements of the ecosystem. This surplus cannot be used or transported properly and becomes lost work, which in every cycle will increase as a function of time as described in Fig. 2. It may also be noticed, as seen from Eq. (3), since no ideal process exists in nature, the lost work will always increase.

3. Environmental impact index using the lost work in an ecosystem

When an ecosystem is in equilibrium, the use of the resources is maximized and the exergy destruction is maintained to a minimum. This is a desirable state that hopefully can be found in some virgin areas of the earth. In an ideal world, this state offers an opportunity to draw a base or reference baseline from where its evolution can be followed. If the baseline of an ecosystem is changed, then the sum of all the contributions of lost work, as described by Eq. (3), of all the subsystems of an ecosystem will be equal or greater than this baseline, such that:

$$\left(\sum_i \left(T_0 \dot{S}_g\right)_{sphere,i}\right)_{\substack{alterated \\ state}} \geq \left(\sum_i \left(T_0 \dot{S}_g\right)_{sphere,i}\right)_{\substack{pristine \\ state}}. \tag{5}$$

Thus, one may wonder how many times a human being is deviating an ecosystem form sustainability. Bearing in mind that the exergy destruction or lost work is the main variable affecting the capacity of a subsystem to carry out work, then a relationship of the evolution for two given states in time can be constructed, such that:

$$EII_{LW,sphere} = \frac{\left(\sum_i \left(T_0 \dot{S}_g\right)_{sphere,i}\right)_{\substack{Alterated \\ state}}}{\left(\sum_i \left(T_0 \dot{S}_g\right)_{sphere,i}\right)_{\substack{Pristine \\ state}}}. \tag{6}$$

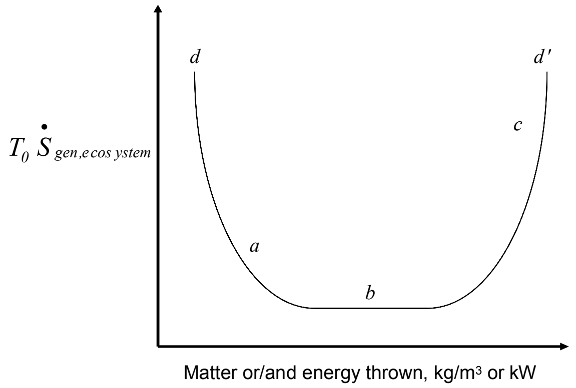

Fig. 3. Entropy production as function of the quantity of matter and energy thrown to an ecosystem.

The behavior of Eq. (6), with the aid of Fig. 3, may be explained as follows:

$EII_{LW} \approx 1$ when the base-line, natural conditions, do not change with time in the ecosystem, i.e. line b.

$EII_{LW} < 1$ when the ecosystem carries a condition that reverts previous effects such that the quantity of loss work or the entropy generation is minimal, i.e., the initial state begins at a or c and is directed to the state b, or c is the baseline state directed to a.

$EII_{LW} > 1$ when the ecosystem carries a condition of existence of loss work or entropy generation, i.e., if b is the baseline state and it moves to a state a or c.

4. Application of the environmental impact indicator

In this section, the IIE_{LW} index is applied particularly to the sociosphere. For this purpose, the flue gases emitted from a flare stack are considered to be sent to the atmosphere and then returned to the sociosphere for a combustion process. Here is evaluated the effect of those emissions that are not absorbed or assimilated by the ecosystem; the exergy destruction behavior is a function of the flue gases concentration in the atmosphere.

The first step in the calculation procedure is the combustion analysis, from a generic combustion engine, under standard environmental conditions. This sets out the baseline, pristine or original concentration of species in the atmosphere. The air characteristics employed for this calculation are: 21 % oxygen, 79 % nitrogen and the average wind velocity of 3 km/hr. The second step is to carry out the combustion analysis for the same combustion engine under non-standard environmental conditions, taking into consideration the effect of the flue gases average concentration of species in the atmosphere caused by the flare. The concentration variation of oxygen and nitrogen for pristine and altered state is shown in Table 1. The first column represents the mass flow rate of emissions coming from the flare; the second column is the average concentration of pollutants in the atmospheric volume; the third and fourth columns are the different gas concentrations as a function of the pollutant concentrations, and the first row represents the base line of the ecosystem.

Table 1. Variation of the average concentration of the atmospheric species as function of the emissions.

kg/s	kg/m^3	O_2 (%)	N_2 (%)	State
0.00	0.0000E+00	79.000%	21.000%	Pristine
35.80	1.9901E-04	79.003%	20.997%	Altered
71.60	3.9802E-04	79.007%	20.993%	
107.40	5.9702E-04	79.011%	20.989%	
143.20	7.6903E-04	79.014%	20.986%	
179.00	9.9504E-04	79.028%	20.982%	

Table 2. Average composition of the burnt gases.

Element	Molar fraction	Element	Molar fraction
C_6H_{14}	0.0077	n-C_5H_{12}	0.0036
C_3H_8	0.0303	N_2	0.4430
H_2S	0.0114	CH_4	0.4152
i-C_4H_{10}	0.0036	CO_2	0.0056
n-C_4H_{10}	0.0113	C_2H_6	0.0654
i-C_5H_{12}	0.0023		

The burned fuel in the flare is taken as a gas mixture and its components are shown in Table 2. The gas mass flow rate into the flare is 21.63 kg/s; and the mass flow rate of air under stoichiometric conditions is 179 kg/s. To determine the spatial distribution of the emissions from the flare, a Gaussian steady state plume model was employed [19]. These results, also shown in Table 1 as altered state, are used as input values for the behavior analysis of the combustion analysis for the internal combustion engine.

In this work two examples of combustion process in the internal combustion engine are compared: i) burning with standard clean air composition, and ii) burning with the air that has been polluted by the emissions coming from a flare. A schematic representation of the process is shown in Fig. 4, the combustion engine is represented by the candle on the bottom, and the elements of an ecosystem to assimilate and absorb emission are represented by a box on the top of the same figure. For the first example, denoted by (a) in Fig. 4, the combustion in the internal combustion engine is carried out for clean air: 21% of oxygen and 79% of nitrogen. Here it is considered that for every cycle, the ecosystem--trees, rain, organisms, etc.--is able to assimilate and process the flue gases, thus working as a cleaning machine. This is represented by the box on top of Fig. 4, and every time the flue gases are emitted to the environment, they will pass through the box, allowing the use of clean air for internal combustion.

For the second case, noted by (b) in Fig. 4, the capacity of the ecosystem as a machine to remove pollutants is superseded. Because flue gases from the flare exceed the assimila-

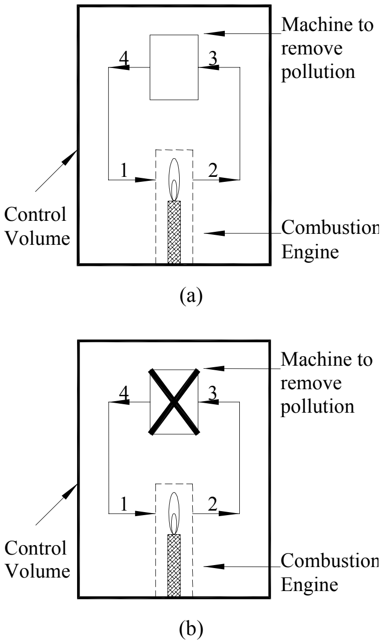

Fig. 4. Relation between society and atmosphere: (a) clean air; (b) dirty air to be used in an internal combustion engine.

tion capacity of the ecosystem, polluted air comes back to the internal combustion engine, thus affecting the combustion process. Then, for every cycle, the available energy contained in the excess flue gas emission will become lost work, and in consequence, the entropy generation will increase.

This can be better explained, for example, by considering an internal combustion engine that burns C_8H_{18}. Also, that the C_8H_{18} is completely burnt with stoichiometric air, and that the engine delivers 37 kW. From Eqs. (3) and (3a), for a steady state and adiabatic process, the exergy destruction in the sociosphere sphere can be expressed by:

$$\frac{\dot{E}_{D,sociosphere}}{\dot{n}_F} = \frac{\left(T_0\,\dot{S}_g\right)_{siciosphere}}{\dot{n}_F}, \tag{7}$$

$$\frac{\dot{E}_{D,sociosphere}}{\dot{n}_F} = T_0\left[\left(\sum_i \dot{n}_i\,\bar{s}_i\right)_P - \left(\bar{s}_F + \sum_j \dot{n}_j\,\bar{s}_j\right)_R\right] \tag{7a}$$

where $\dot{n}_F$ is the molar flow rate, F refers to the fuel, i and j correspond to the respective species products P and reactants R present.

The exergy destruction for the combustion analysis on a combustion engine under standard environ-mental air composition, as shown in Table 1, can be obtained from Eqs. (6) and (7), such that for the pristine state this is:

$$\left(\frac{\dot{E}_{D,sociosphere}}{\dot{n}_F}\right)_{\substack{Pristine\\state}} = T_0\left(8\bar{s}_{CO_2} + 9\bar{s}_{H_2O} + 47.023\bar{s}_{N_2}\right)_P - \ldots \tag{8}$$
$$\ldots - T_0\left(\bar{s}_{C_8H_{18}} + 12.5\bar{s}_{O_2} + 47.023\bar{s}_{N_2}\right)_R,$$

$$\left(\frac{\dot{E}_{D,sociosphere}}{\dot{n}_F}\right)_{\substack{Pristine\\state}} \approx 1{,}240{,}856 kJ/kmol_F. \tag{8a}$$

Since the ecosystem cannot cope with the combustion gases exerted, the amount of oxygen decreases, increasing the amount of nitrogen based gases. Then, for the following cycle state, i.e., for non-standard environmental or polluted condition, the atmospheric air composition is 79.003 % of N_2 and 20.997 % of O_2.

Similarly, the lost work or exergy destroyed in the altered state then becomes:

$$\left(\frac{\dot{E}_{D,sociosphere}}{\dot{n}_F}\right)_{\substack{Altered\\state}} = T_0\left(8\bar{s}_{CO_2} + 9\bar{s}_{H_2O} + 47.032\bar{s}_{N_2}\right)_P - \ldots \tag{9}$$
$$\ldots - T_0\left(\bar{s}_{C_8H_{18}} + 12.5\bar{s}_{O_2} + 47.032\bar{s}_{N_2}\right)_R,$$

$$\left(\frac{\dot{E}_{D,sociosphere}}{\dot{n}_F}\right)_{\substack{Altered\\state}} \approx 1{,}240{,}969 kJ/kmol_F \tag{9a}$$

and finally the EII_{LW} will be:

$$EII_{LW,sociosphere} = \frac{\left(\sum_i \left(T_0\,\dot{S}_g\right)_{sociosphere}\right)_{\substack{Altered\\state}}}{\left(\sum_i \left(T_0\,\dot{S}_g\right)_{sociosphere}\right)_{\substack{Pristine\\state}}}, \tag{10}$$

$$EII_{LW,sociosphere} = \frac{\left(\frac{\dot{E}_{D,sociosphere}}{\dot{n}_F}\right)_{\substack{Altered\\state}}}{\left(\frac{\dot{E}_{D,sociosphere}}{\dot{n}_F}\right)_{\substack{Pristine\\state}}}, \tag{10a}$$

$$EII_{LW,sociosphere} = \frac{1{,}240{,}969 kJ/kmol_F}{1{,}240{,}856 kJ/kmol_F} = 1.00009, \tag{10b}$$

$$EII_{LW,sociosphere} > 1. \tag{10c}$$

Then, and in accordance with the IIE_{LW} when it takes values above 1, it means that the ecosystem carries a condition of existence of lost work. For the others' altered state the same procedure is carried out: the results of the lost work or exergy destruction and their EII_{LW} index of those altered state are given in Table 3.

5. Results and discussion

The exergy destruction and exergy variation as a function of pollutant concentrations are shown in Fig. 5. It can be seen that as the pollutant concentration increases, the exergy destruction or lost work increases, increasing at the same time

Table 3. Entropy generation and exergy used, and environmental impact index.

kg/s	$\dot{E}_D/\dot{n}_F$, kJ/kmol$_F$	EII_{LW}	State
0.00	1240856	1.00000	Pristine
35.80	1240969	1.00009	Altered
71.60	1241087	1.00019	
107.40	1241200	1.00028	
143.20	1241323	1.00038	
179.00	1241436	1.00047	

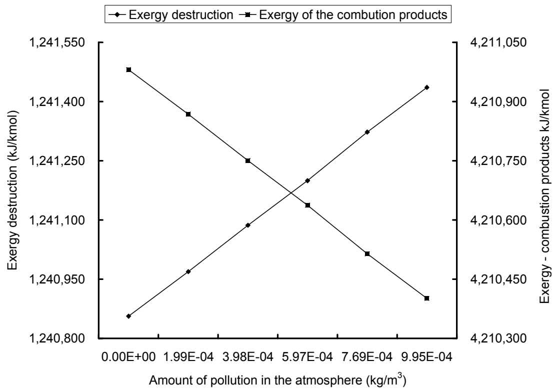

Fig. 5. Exergy destruction and the exergy behavior as function of the pollutants concentration.

the entropy generated and a decrement on the available energy or exergy. It can be noticed that the lost work varies 0.0091% for a variation of 0.017% of the O_2 concentration in the atmospheric air; and the relation between the pollutant concentration and the exergy destruction is 1:0.5.

In regards to the main objective of this study, the values obtained for the environmental impact index based on the lost work for the sociosphere are shown in Table 3. The first column is the lost work, the second column is the environmental impact index based. The first line is the baseline state, which takes a value of one. It is also noted, because of the direct dependence, that as the exergy destruction increases, the environ-mental impact index also increases. The trend that might be described by the environmental impact index as a function of time then becomes an interesting tool to understand the behavior of a certain fraction of an ecosystem and provides elements for decision making.

The behavior of the environmental impact index is shown in Fig. 6. Here it is seen that the lost work increases in an ecosystem as emissions exceed the atmosphere's capacity to absorb or assimilate those emissions. The value of the index represents the quantity of useful energy that is not used by the ecosystem sphere under study, in this case the sociosphere.

Here the environment impact index took small values, as also did the exergy destruction as shown in Table 3; but this value was only for one engine that must deliver 37 kW. In other words, for each 10 kW of useful energy spent, 0.0047 kW of this energy is not used correctly. In the case of large

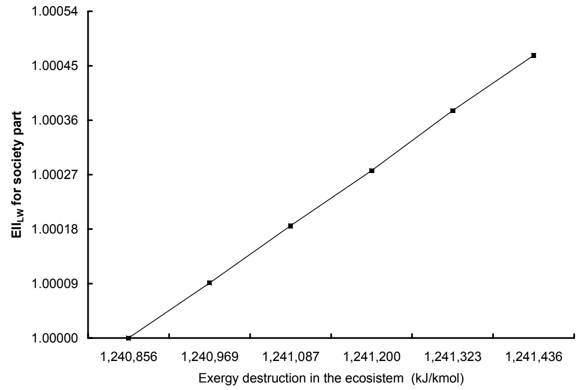

Fig. 6. Environmental impact index based on the work for the society as function of the loss work.

cities, the exergy destruction due to lost work produced by the air polluted represents 4700 kW for 1 million of cars, and for México City with an 8 million automobile population becomes 37.6 MW.

6. Conclusions

The environmental impact index exergy based presented in this work can be a useful tool for assessing the environmental impacts of emissions of materials into the environment. This determines the storage capacity to do work by two systems in non-equilibrium. Also it can be used to analyze thoroughly the waste of resources in the activities of society. An important addition that this method offers is the advantage to establish quantitative and qualitative guidelines for saving and efficient use of natural resource

The useful energy decreases when there is an increment in the loss work and the decrement is a function of the capacity of the ecosystem to revoke the emissions. After the capacity of depuration of the ecosystem is exceeded, the exergy destruction increases for every cycle; thus the lost work in an ecosystem can be used as a measure of the reduction and excessive consumption of the resources when human activity is out of control. This work confirms those results.

When the proposed environmental impact index, EII_{LW}, takes values above 1, Table 3, there will be an alteration of the baseline state of the environment, resulting in an inefficient use of resources. The values of EII_{LW} must be close to unity when there is no change in the environment as shown in the same table.

Although the environmental impact index presented in this work can evaluate change in each part of an ecosystem, there is plenty of work to identify all the necessary indexes to measure all kinds of situations, equipment, surroundings and reactive systems.

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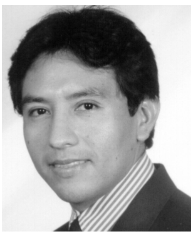

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