Exergy as a resource efficiency indicator for industries

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Abstract:

A research activity was carried out to identify the most important resource efficiency indicators used at the industry level for five main categories: energy, material use, water use, greenhouse gas emissions and waste generation and management. Fifty eight indicators were found in the literature but only twenty of them were applicable to the process level. Additionally, a detailed analysis was carried out to justify the use of the exergy indicators for industrial processes and the important advantages it has over the use of other indicators. The most repeated limitation among the studied indicators is the inability to measure the quality degradation of the resources, which is one of the most important advantages of the exergy indicators, since exergy not only measures the quantity but also the quality of the resources. Moreover, exergy can also cover the five categories of resources and can be used in the micro as well as in the macroeconomic level. An example of the application of the exergy indicator was developed to support this argument based on an industrial process from a fertilizer manufacturer. This example was modeled using the exergy cost accounting methodology, based on the thermoeconomic theory. Three operation scenarios were proposed in order to quantify how the exergy indicators are able to measure the efficiency in resource use in an industrial process. A global indicator was used for this matter to identify the most efficient scenario (global unit exergy costs) as well as several local exergy indicators (associated to raw materials, to the use of fossil fuels in the process, to CO_2 emissions and to electricity consumption). This analysis represents an effort to highlight the advantages of using exergy and the exergy accounting methodology to assess industries in relation with resource consumption, energy efficiency, waste valorization and re-use.

Keywords: Exergy Indicators, Resource Efficiency, Exergy Analysis, Industry, Fertilizers.

1. Introduction

Natural resources are the basis of our economy. Without them, none of human basic needs could be fulfilled. Studies show that the use of natural resources in a year is already 1.5 times greater than the ability of the earth for regenerating these resources [1]. In order to guarantee the sustainability of human life as we know it and for assuring prosperity of future generations, the use of natural resources needs to decrease drastically in the next years. The sustainable use of natural resources is an important challenge that needs to be addressed by social, economic, ecologic and technical groups.

With the aim of preserving and using natural resources in an efficient way, important efforts have been made in the development of indicators that measure the use of resources in a macro level [2-3]. In this direction, Eurostat published in December 2013, the first scoreboard for Resource Efficiency Indicators. The 30 Indicators mentioned are meant to lead the way to a Resource Efficient Europe. Nonetheless, these indicators are not applicable directly to the industry and are designed principally for policy development.

Industry is one of the main sources of environmental pollution and resource depletion. This is why it is of such an importance to develop indicators that help to measure the efficiency in resource use by the industries. To address this issue, Giljum et al [4], propose a series of indicators of different nature that can be applied in the industry as well as in a country or region level with a life cycle approach. On the other hand Herva et al [5] propose a set of indicators exclusively for the corporate level, to evaluate processes. Other authors concentrate in the study and development of specific indicators like the footprint indicators [6-9], the material flow indicators and the energy related indicators [10-16], among others.

Five main categories of resource efficiency indicators were taken into account for this study, related to energy, material, water use, emissions of greenhouse gases and wastes. Of the fifty eight indicators found, only twenty belonged to one or more of the aforementioned categories and were also applicable to the corporate level. Each one of the selected indicators was analyzed in order to show their strengths and limitations. After doing this, a detailed analysis was carried out to justify the use of the exergy indicators for industrial processes and the important advantages it has over the use of other indicators. An example of the application of the exergy indicators was developed to support this argument. This example was modeled using the exergy cost accounting methodology, based on thermoeconomics theory that connects the Second Law of thermodynamics with economics and uses the input output analysis developed by Wassil Leontieff [17].

This work represents an effort to highlight the advantages of using exergy and exergy accounting methodology to assess industries in relation with resource consumption, energy efficiency, waste valorization and re-use.

2. Methodology

To carry out an analysis of the resource efficiency indicators the first step was to perform an exhaustive review of the different indicators mostly used in the industry. Information from different scientific publications and databases was obtained and analyzed as well as strategic documents from the European Commission, European Environmental Agency and United Nations. Two criteria were used for the selection of the resource efficiency indicators: suitability to one of the studied categories (energy, material and water use, emissions of greenhouse gases and wastes) and the applicability at process level. Only the indicators that fulfilled those two criteria were retained for further analysis.

The second step was performing a qualitative analysis of the strengths and limitations of each selected indicator according to the resources and substances measured, the calculation methods used and the usability of the indicator, then a comparison was done between the strengths and limitations of the resource efficiency indicators analyzed and the exergy indicators.

Last, an example of the application of five exergy based indicators to a real industry was developed, using three different scenarios. These indicators are calculated using the results of the material, energy, and exergy balances and the exergy cost accounting methodology. This methodology was used to evaluate the amount and quality of energy and material losses in the system in terms of natural resources. It is very similar to the input output theory; the difference is that it uses exergy to quantify flows [18].

Two programs were used for these calculations: EES (Engineering Equations Solver) and TAESS (Thermoeconomic Analysis of Energy Systems Sofware) [19].

3. Exergy as a Resource Efficiency Indicator

3.1. Resource Efficiency Indicators analyzed

The resource efficiency indicators selected for this paper are summarized in Table 1.

Table 1. Resource efficiency indicators found in the industry and analyzed in this study.

Energy	**Material use**	**Water use**	**Emissions of greenhouse gases**	**Waste generation and management**	**General indicator**
- Energy consumption - Specific energy consumption - Exergy - Emergy - Embodied energy	-Material input per service unit (MIPS) - Recycled content - Material flow analysis (MFA) -Exergy related to materials	- Water consumption - Water abstraction - Water footprint of products (WF) - Water recycled/reused -Exergy related to water use	- CO_2 emissions - GHG emissions - Carbon footprint of a product (CF) -Exergy related to GHG emissions	- Generation of waste - Waste treatment and disposal - Generation of hazardous wastes -Exergy cost accounting methodology	- Ecological footprint -Global unit exergy cost

As we can see, there are specific exergy based indicators for each of the categories analyzed in this paper.

The specific exergy, b, of a system is characterized by a set of thermodynamic parameters that define its quality. It is calculated as the sum of the thermo-mechanical exergy, the kinetic exergy, the potential exergy and the chemical exergy as it is shown next[1].

$$b = \underbrace{(u-u_0)+p_0(v-v_0)-T_0(s-s_0)}_{\text{thermo-mechanical exergy}} + \underbrace{\tfrac{1}{2}(C^2-C_0^2)}_{\text{kinetic exergy}} + \underbrace{g(z-z_0)}_{\text{potential exergy}} + \underbrace{(\Delta G_{fi}+r_{j,i}b_{ch\,j})}_{\text{chemicalexergy}} \quad (1)$$

The exergy indicator related to materials is the exergy replacement cost, defined as the quantity of exergy needed, using the best available technology, to replace a material from its surrounding environment and original composition and concentration before extraction [20].

Exergy can also be calculated for water resources. The exergy of any water body represents the maximum mechanical work that can be obtained from it until reaching the complete equilibrium with the reference environment (that is, it is totally diluted into the ocean) [21]. The thermodynamic status of water can be characterized through six parameters: temperature, pressure, composition, concentration, velocity and altitude [22].

The exergy abatement cost is another component of exergy and it is related to GHG emissions and defined as the quantity of exergy needed to reduce the emissions of a specific pollutant to innocuous levels for the environment [23].

Wastes, waste streams and inefficiencies of a system can be calculated using the exergy cost accounting methodology. As we stated before, this methodology uses thermoeconomics that is a general theory of energy saving that connects physics and economics by means of the second law of thermodynamics. It allows evaluating the quality and quantity of energy losses and determining the cost of these losses in terms of resources consumption.

The general indicator, global unit exergy cost, is obtained using TAESS software and it incorporates all categories of resources analyzed, in one single score. This is done by modeling each of the energy and material flows in terms of exergy. There are also other exergy components like the

[1] Term u denotes specific energy; p pressure; v specific volume, ΔG_f gibbs free energy of the given substance, $r_{j,i}$ the number of moles of each chemical species in the given substance and b_{chj} the chemical exergy of the substance. Subindex 0 denotes the reference conditions (usually ambient conditions).

concentration or comminution exergy[2], that can be calculated and incorporated in this indicator and that give important information about the systems.

3.2 Comparison of resource efficiency indicators selected and the exergy indicators

In this section a comparison of the main indicators, summarized in Table 1, with exergy indicators will be done. The indicators in the energy category are all closely linked to each other and they are all suitable for the micro economic level. The main advantage of the exergy indicator is that it gives additional information about the quality of the resources under analysis. Moreover, exergy is able to quantify the quality of all types of resources including mineral commodities or water. Exergy accounting methodology also allows connecting energy with its economic value through thermoeconomics. Its objective is to obtain general equations that relate the behavior of the individual processes of a system with its global behavior and to analyze its cost formation process. One of the disadvantages of the exergy indicator is that the methodology for its calculation is not widely known and is not yet integrated in popular software's. It is worth mentioning that there are programs, like TAESS, that have been developed to apply exergy with the help of thermoeconomics to industrial processes.

Regarding the resource efficiency indicators related to materials, MIPS has the advantage that it allows to compare different products with each other in terms of material use and that it is an adaptable indicator that can be used in the macro-economic or micro-economic level [5]. One of the disadvantages is that this indicator is based on the first law of thermodynamics and therefore cannot discriminate in terms of quality and that the methodology to calculate this indicator does not differentiate between types of masses and adds them all together. It is not sensitive to contamination through heavy metals, radioactive materials and persistent organic compounds and it does not account for material dispersion and depletion or mixing processes [24]. Recycled content indicator depends on information available regarding its origin and it is rarely possible to determine what amount of material is virgin and what amount is recycled.

The exergy indicator related to material use has all the strengths and overcomes all limitations of other material based indicators. Exergy can be used in the micro as well as in the macroeconomic level. It allows comparing products using the exergy cost accounting methodology. Moreover, the exergy indicator does discriminate in terms of quality and it is sensitive to contamination through heavy metals, radioactive materials and organic compounds and it accounts for material dispersion and depletion [24]. The biggest drawback of the exergy indicators is that the cost accounting methodology implies transforming materials and energy consumed into exergy units, for which a detailed knowledge of every single operation unit is required.

The main indicators used to measure the contribution to climate change by an industry are the greenhouse gas (GHG) emission indicators or CO_2 indicators and the indicator carbon footprint of Products. The carbon footprint measures the amount of GHG emissions emitted to the environment and due to the fact that emissions come mostly from fossil fuels it gives an indication of the intensity in its use. This indicator gives useful information to the industries but it cannot track the full palette of human demands on the environment [6]. GHG and CO_2 emission indicators are usually used as indicators at company and national level. They work as measuring tools, allowing comparing climate impact between countries and regions or any industrial activity.

On the other hand the exergy indicator uses GHG emissions accounts and transforms them into exergy to calculate the resources needed to mitigate the emissions produced by a process, a product or a service; this can be done through the exergy abatement cost. As well as the carbon footprint, the exergy indicator can be used to inform internal environmental management about the impact of the process or system analyzed. It can give information to the consumer if implemented as a

[2] Comminution refers to the process of separating particles. Processes like crushing, grinding and milling are typical comminution activities.

standard measurement and can track a wide range of human impacts to the environment using other complementary exergy indicators that have the advantage of using the same measuring units.

The main indicators that measure the efficiency of water use of an activity are based on absolute water consumption, which can be expressed as absolute magnitude or in relation to other parameters, such as time, economic value, output of a process, etc. There are many indicators related to water use, the most significant are mentioned in Table 1. The main drawback of the indicators related to water use is that none of them measure the quality of water resources; they focus exclusively on water use quantities. As an example, the water footprint indicator is considered a resource management indicator instead of an environmental indicator. On the other hand, exergy applied to water allows evaluating water resource degradation by means of a reduction of flow, height or quality. The exergy of any water body represents the maximum mechanical work that can be obtained from it until reaching the complete equilibrium with the reference environment (that is, it is totally diluted into the ocean) [21].

Indicators measuring the generation of wastes and their management in an industry only cover wastes and are not able to measure other resources. Additionally, there is a lack of a standard definition of waste and hazardous wastes. On the other hand, by using the exergy indicators it is possible to distinguish thermodynamically between functional products and waste and residues. Residues are remaining flows of matter or energy which are not pretended to yield. These residues are divided into by-products, which could be used in further processes and waste disposals, which require additional resources to reduce its environmental impact. This methodology helps tracing the formation process of residues and locating their origin in the productive diagram. This method distributes the cost of wastes proportional to the external resources consumed to produce the waste.

The ecological footprint (EF) indicator is considered as a general indicator that integrates the use of many natural resources into one single score, however, it has some important limitations. The exergy indicator is a strong competitor of the EF and in comparison with this indicator does account for second law and is able to measure quality of resources, it accounts for all GHG emissions and is not biased to any hemisphere because it is based on thermodynamics.

As it can been seen, there are many resource efficiency indicators that can be applied to the industry. Most of them are very specific indicators that give information only about the use of one type of resource leaving out the consumption of other important resources in the processes analyzed. The exergy indicator, on the other hand, is a general and overreaching indicator that has the advantage of covering all aspects of efficiency measured by the indicators related to energy, materials, GHG emissions, wastes and other indicators like the ecological footprint that are intended to be general indicators to measure resource use. It has nonetheless the drawback that it is not yet accepted or understood by the industry and requires a good amount of input to be built consistently.

4. Development of the exergy indicators

For the case study described in the next section, five exergy based indicators were developed to measure the most important variables of the process. The first is an indicator associated to raw materials (includes the exergy replacement cost), the second measures the GHG emissions of the process (includes exergy abatement cost), the third is meant to measure the electricity consumption, the fourth quantifies the fossil fuel consumption and the fifth is a global indicator called the global unit exergy cost indicator (based on the exergy cost accounting methodology). The exergy indicator related to water was not calculated, due to the fact that the water consumption in this process is negligible. The exergy based indicators are explained in detail next.

4.1. Global unit exergy cost (c_p) and unit consumption (k)

Indicators c_p and k are calculated using the exergy cost accounting methodology. The global unit exergy cost of the product (c_p) accounts for all exergy that is consumed in order to produce a unit of product in a process. It adds up all the irreversibilities generated by upstream processes and that contribute to the exergy cost of the final product. It is the sum of the exergy unit cost of the irreversibilities (c_p^e) and the exergy unit cost of the residues (c_p^r) regenerated along the system. On the other hand the unit consumption (k) of the process is defined as the ratio between the exergy of the fuel and the exergy of the product and it gives information about the exergy efficiency of a device.

The global unit exergy cost takes into account the thermal and chemical exergy involved in the flows of the system, the concentration exergy, the exergy cost associated to the replacement of the materials as well as the exergy abatement cost of the emissions [23], the latter can be incorporated in this indicator by introducing a reduction in the chemical exergy of the fuel. This is a global indicator that is able to give an indication of the efficiency in resource use and that incorporates all categories of resources analyzed.

4.1.2. Exergy indicator associated to raw materials (ERM)

For the calculation of this indicator we need to know the exergy of the raw materials entering the system and compare it with the exergy of the product that is obtained at the end of the process.

$$\mathrm{ERM} = \frac{\text{Exergy of the raw materials entering the system}}{\text{Exergy of the product obtained}} \qquad (2)$$

4.1.3. Exergy indicator associated to fossil fuels (EFF)

This indicator gives information about the amount of fossil fuel that is used in a process compared with the amount of final product obtained; it is a measure of resource efficiency and is calculated as shown.

$$\mathrm{EFF} = \frac{\text{Exergy of Natural Gas used in Boiler}}{\text{Exergy of the product obtained}} \qquad (3)$$

4.1.4. Exergy indicator associated to emission (EEm)

This indicator is based on the calculation of the exergy abatement cost of the CO_2 emissions of the fertilizer plant and compares it with the exergy of the final product obtained.

$$\mathrm{EEm} = \frac{\text{Exergy Abatment Cost (ExAC)ofCO2 Emissions generated in the process}}{\text{Exergy of the product obtained}} \qquad (4)$$

Valero and Valero [21] determined the exergy abatement costs of the emissions of conventional fossil fuels including natural gas. An exergy abatement cost of 1450 MJ/ton [23] will be used for the calculation of the exergy indicator associated to CO2 emissions.

4.1.5. Exergy indicator associated to electricity consumption (EEC)

In order to calculate this indicator all electricity consuming devices of the process need to be taken into account.

$$\mathrm{EEC} = \frac{\text{Electricity consumed in the process}}{\text{Exergy of the product obtained}} \qquad (5)$$

Note that electricity consumption could be included in the indicator associated to the consumption of fossil fuels if the values were converted into primary energy. The main disadvantage of doing this is that the conversion factor depends on the country where electricity is produced (i.e. through their energy mix). For the results to be comparable among European industries one would need to use a global energy mix scenario.

It should be also stated that the above indicators can be referred either to the exergy of the product obtained (in which case the result is dimensionless) or to the functional unit expressed in mass terms, i.e. kg of product obtained in a manufacturing industry, kWh of electricity produced for a power plant, m3 of water in a desalination plant, etc… Such option has the advantage of being easier to understand for industry and policy makers in general.

5. Case study

In this section, an industrial process from a Spanish company is analyzed using the exergy cost accounting methodology. With the information obtained from this analysis, three operation scenarios were proposed in order to quantify how the exergy indicators are able to measure the efficiency in resource use in industrial processes. Of the five products that the Spanish fertilizer manufacturer produces, the process that has been chosen for the analysis is the one that corresponds to the granulated fertilizer; its physical structure is shown in Figure 1.

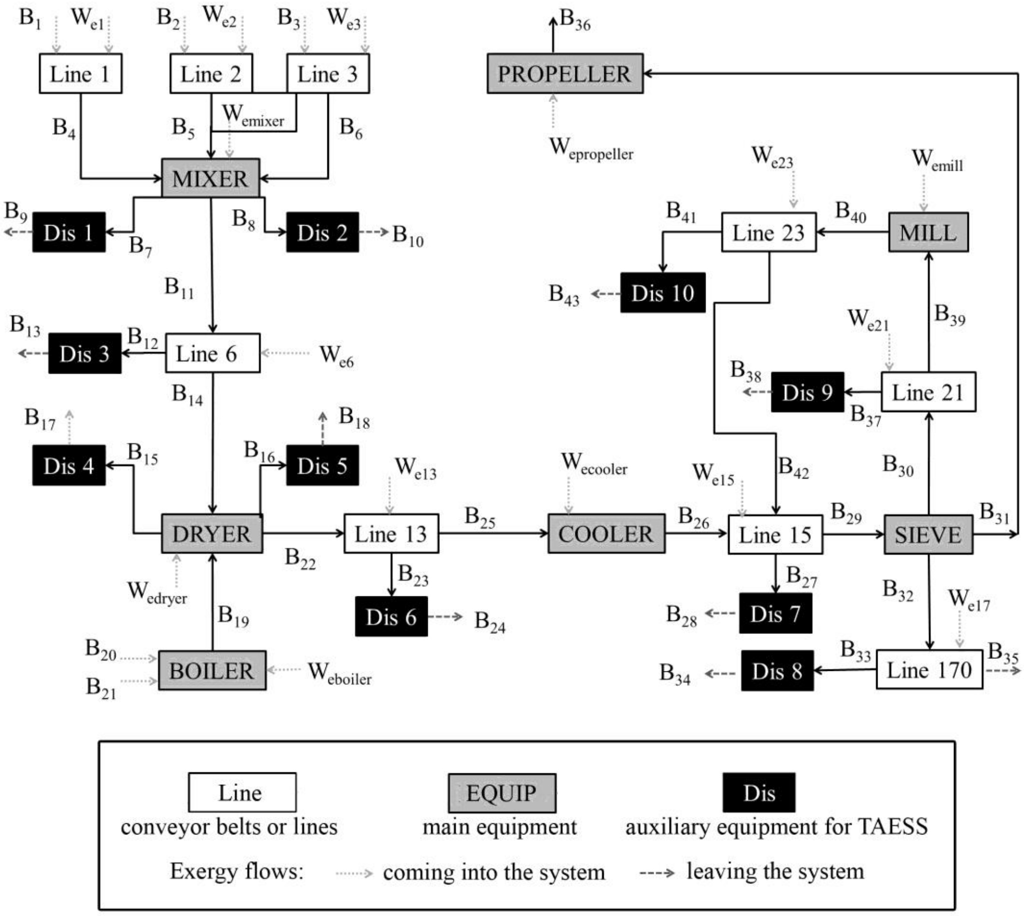

Fig. 1. Physical structure of the granulation process.

Light grey arrows represent the exergy flows coming into the system boundaries and all dark grey arrows represent exergy flows leaving the system and going into the environment. The main equipment (mixer, dryer, boiler, cooler, sieve, mill and propeller) is represented with gray boxes. White boxes represent the conveyor belts or lines, needed to move material from one stage of the process to another. Black boxes refer to auxiliary equipment with the task of dissipating energy and matter to the environment. These devices do not belong to the process itself, but they have to be incorporated for the modeling with TAESS software. Letter B represents the exergy of the different flows and W represents the electricity consumed by each device and by the conveyor lines.

The most important equipment participating in this process is:

- The mixer or granulator: where the raw materials are mixed and homogenized and where the granulation process takes place.
- The dryer: where the volatile substances are removed to obtain a dry and solid product.
- The boiler: where natural gas is burned and the combustion gases are used for the drying process mentioned in the previous point.

- The sieve: where the granules are separated according to their size. The fines are re-circulated to the beginning of the process and the bigger granules are sent to the mill.
- The mill: is in charge of reducing the size of the granules that are bigger than 600 μm.

This process is based on the chemical reaction of phosphoric acid (H_3PO_4) [3] with calcium carbonate ($CaCO_3$)[4]. These components come together in the mixer at ambient temperature, where the reaction takes place, obtaining as products calcium phosphate ($CaHPO_4$), H_2O and carbon dioxide as gas ($CO_{2,\,g}$).

$$H_3PO_4 + CaCO_3 \rightarrow CO_{2\,g} \uparrow + CaHPO_4 + H_2O \quad (R1)$$

This is a wet process that uses a liquid agglutinate for the formation of the granule. The critical variable at this stage is the liquid-solid ratio; the higher this ratio, the higher the production, until a maximum value, where the possibility of excess moisture is critical due to the formation of oversize granules.

Wet granules leaving the mixer at 60°C and with a 13% of humidity enter the dryer in order to finish their formation process. The dryer uses hot gases from the combustion of natural gas to eliminate humidity until it reaches a value of 1%. The combustion gases enter the dryer at 450°C. The main variable in this stage is the drying speed, because the size of the particles increases with the decrease in drying time. Drying temperature, surface exposed and pressure are also important variables that affect the water elimination.

The granules leave the dryer at 80°C and then enter the cooler and exit at ambient temperature. In this stage, the rotating speeds of the drum as well as the inlet temperature are the critical parameters. The finished material is then passed through a sieve where the lumps with the right size (200 - 600μm) are packed as finished material. Lumps with bigger sizes are taken to a mill where they are broken into smaller pieces and are passed through the sieve again. Particles with sizes smaller than 200 μm are re-circulated and re-enter at the beginning of the process.

The process described above is considered as the normal operation process. For the calculation of the exergy indicators, three scenarios of the granulated fertilizer process will be analyzed:

- **Scenario 1:** normal operation process with recirculation of fines (as described above).
- **Scenario 2**: operation with same amount of raw materials but without recirculation of fines. This scenario is a hypothetic case where the recirculation of fines is not possible due to a problem with the propeller. All material with sizes smaller than 200μm is lost and considered waste. Due to the loss of recirculation, B_3 does not enter the process but the same amounts of raw materials need to be available to maintain the production quantity, this additional raw material will be entered through line 2.
- **Scenario 3:** operation of optimized process where the product is always under specifications. This scenario is based on the assumption that the process has been optimized to the point where 100 percent of the product entering the sieve passes quality check and therefore has sizes between 200-600μm. Neither the mill nor the propeller and the associated conveyor belts will be required in this scenario.

It is important to state that the results presented in the following sections take into account the exergy involved in the replacement, extraction and processing of the raw materials entering the process as B_1, B_2 and B_3. All other exergies of the system, like the exergy of the fossil fuels and the exergy of electricity have their boundaries located at the plant; they only incorporate the chemical and thermal exergies.

5.1 Procedure

The first step to calculate the indicators is to define the boundaries of the system and the physical structure of the process. The physical structure defines energy and material flows coming in and

[3] $\dot{m}_1\ H_3PO_4 = 1.055\,kg/s\,, humidity = 0.35, \dot{m}_1 = 1.624\,kg/s$

[4] $\dot{m}_2\ CaCO_3 = 1.128\,kg/s\,, humidity = 0.07, \dot{m}_2 = 1.213\,kg/s$

leaving each device as shown in figure 1. With the help of the physical structure of the process, all material and energy balances where defined and the equations solved in ESS Software. For each of the aforementioned scenarios the five main exergy indicators mentioned in section 4 were calculated: global unit exergy cost, exergy indicator associated to raw materials, exergy indicator associated to fossil fuels, exergy indicator associated to emission and exergy indicator associated to electricity consumption.

In the case of the exergy indicator associated to raw materials (ERM), the exergies of the raw materials (B_1, B_2 and B_3) have been calculated so that they take into account the thermal and chemical exergy, the exergy replacement cost as well as the exergies associated to extraction, concentration, smelting and refining. The exergy of the product, for all indicators, considers the thermal as well as the chemical exergy and varies depending on the scenario analyzed.

To calculate the exergy indicator associated to fossil fuels (EFF), we only used natural gas data since in the fertilizer plant it is the only fossil fuel that is directly used. The combustion gases of natural gas are used to remove the humidity of the granules in the dryer. The exergy of natural gas was calculated considering only its chemical exergy, as well as for the raw materials no other exergies associated to concentration, extraction or processing where considered.

The sources of pollution in the fertilizer plant are mainly due to the chemical reaction that takes place in the mixer (flow B_9) and due to the combustion of natural gas in the boiler (flow B_{18}). Assuming complete combustion, only CO_2 emissions will be taken into account to calculate the exergy indicator associated to emission (EEm).

The calculation of the exergy indicator associated to electricity consumption is a given value of the plant.

5.2. Results

If we intent to develop indicators to measure the resource efficiency of a process it is necessary to understand their meaning and the results we obtain. In the process analyzed the only indicator that incorporates all factors affecting the system is the global unit exergy cost indicator (c_p). As its name suggests it is a global indicator that can be used to compare this process with another one with a different configuration and still be able to identify which of them is the most resource efficient. We are able to state that the higher the value of this indicator, the less efficient the process.

Apart from the global indicators, it is usual to have local indicators evaluating changes in a same process and ERM, EFF, EEm, and EEC are examples of this type of indicators. They have been calculated with respect to the exergy of the final product and this is a value that can vary significantly depending on the process analyzed. One cannot say that a process is more or less resource efficient by calculating only one of these indicators; we need the help of a global indicator that covers all the processes affecting the system.

Table 2 summarizes the results of the calculation of the exergy indicators for the three scenarios considered in this study.

Table 2. Results of the calculations of exergy indicators for the three operation scenarios (most efficient first)

Scenarios	cp (Global)	ERM (Materials)	EFF (Fossil Fuels)	EEm (Emissions)	EEC (Electricity)
Scenario 3: Optimized operation	7.10	5.79	1.19	0.74	0.12
Scenario 1: Normal Operation	7.23	6.55	1.40	0.75	0.25
Scenario 2: No recirculation	8.43	6.79	1.40	0.87	0.24

All the indicators were able to identify scenario 3 as the most efficient one. In Figure 2 we can see the efficiency increase of scenarios 2 and 3 with respect to scenario 1, which is the normal operation process.

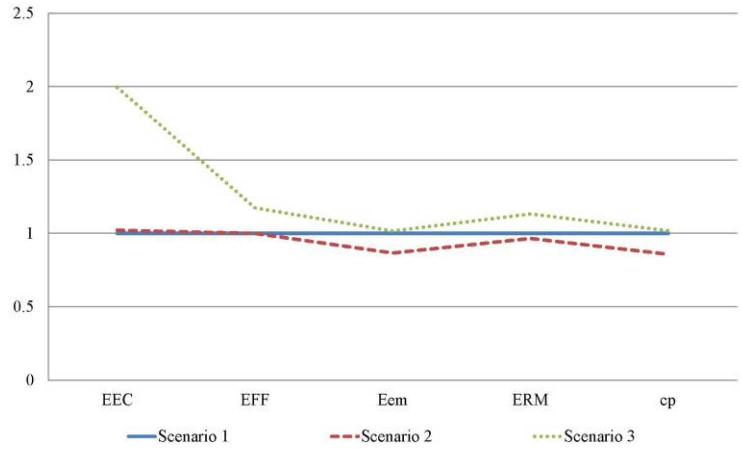

Fig. 2. Comparison between the three scenarios proposed: efficiency increase with respect to Scenario 1.

Scenario 3 is more resource efficient than scenarios 1 and 2 and the efficiency increase varies depending on the resource measured. We know, for example, that scenario 1 is more resource efficient in general terms than scenario 2, but if we compare the EFF and EEC indicators, we will see that scenario 1 has the same efficiency regarding fossil fuels and less efficiency regarding electric consumption than scenario 2.

If we decide to compare two different processes using the local indicators, the result will not be able to give us information about the overall resource efficiency. It is not possible to guarantee that the exergy of the product, or that the exergy abatement cost, or the exergy of the fossil fuels will always be smaller or higher that the exergy of the raw materials entered. Nonetheless, if we evaluate the same process operating under different conditions, using local indicators, they will give us valuable information on resource use.

The global unit exergy cost indicator (c_p), is valuable at the industry level to compare resource efficiency within an industry, it is useful to benchmark different processes that produce the same product and it has enormous potential to help evaluate resource efficiency among sectors and even among countries, thanks to its ability to measure the efficiency in the use of different types of resources. It can also be proposed as a tool to evaluate the Best Available Techniques compiled in the Reference Documents published by the European Commission.

6. Conclusions

In this project a detailed research has been carried out to identify the resource efficiency indicators applicable to the industry and belonging to one or more of the following five categories: Energy, Material, Water use, Emissions of Greenhouse Gases and Wastes. The strengths and limitations of the twenty indicators that fulfilled the criteria of selection were compared with the strengths and limitations of the exergy indicator. One of the most repeated limitations among the indicators found is the inability of most of them to measure the quality degradation of a resource. This is the most important advantage of the exergy indicator; it not only measures the quantity but also the quality of the resources. Nonetheless, exergy and exergy cost methodologies are complex and less intuitive than other methodologies.

As stated before, there are different exergy components that can be used to determine efficiency in the use of resources. The exergy indicators are able to measure energy consumption and use, evaluating quantity and quality. For material flows including water it allows to transform mass units to exergy units and evaluate the resource taking into account intensive properties like temperature, pressure, composition, concentration, velocity and altitude. In terms of waste and residues, exergy cost accounting methodology allows analyzing production systems to evaluate the best configuration (components and interconnections) to reduce waste flows and take advantage of the exergy available in residues. Regarding emissions, the exergy abatement cost measures the quantity of exergy needed to reduce the emissions of a specific pollutant to innocuous levels for the environment. We are able to conclude that exergy and all its components are readily available tools for the evaluation of resource consumption.

The case study allowed validating the use of the exergy indicators obtained through the exergy cost accounting methodology and to measure resource efficiency in a real process. The analysis of the usefulness of the indicators revealed that we are dealing with two types of indicators, global and local indicators. The Global Unit Exergy Cost indicator (c_p), is considered as a global indicator because an increase in its value will always mean an increase in resource consumption, a decrease in resource efficiency and therefore more sacrifice of resources, independent from the system analyzed. The other four indicators calculated are categorized as local indicators because the relationship between their value and the increase or decrease in resource efficiency is not always the same; it depends on if we are comparing two operation states of the same process or two different processes, that is way special attention needs to be taken when using these indicators. Nonetheless, both types of indicators are highly relevant and contribute significantly to the analysis of systems.

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