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Research paper

Exergy inefficiency: An indicator for sustainable development analysis

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HIGHLIGHTS

- Present days are a crossroad of our world due to climate and economic problems.
- A new viewpoint must be introduced to support decision makers.
- New indicators are introduced to analyse our energy and productive system.
- These indicators are shown useful also in socio-economic analyses.
- The result is a tool for decision makers.

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ABSTRACT

The present days can be considered a crossroad in the history of our world because the economic, social, and environmental needs do not agree one another. The result is the present socio-economic difficulties, from which it seems very difficult to escape. A new viewpoint must be introduced, but it cannot be based on the usual economic indicators. So, a new viewpoint and a new related approach are required. In this paper we suggest three new indicators based on an engineering approach of irreversibility. They allow us to evaluate both the technological level and the environmental impact of the production processes and the socio-economic conditions of the countries. Indeed, they are based on the exergy analysis and on the irreversible thermodynamic approach, in order to evaluate the inefficiency both of the process and of the production systems, and the related consequences. Three applications are summarized in order to highlight the possible interest from different scientists and researchers in engineering, economy, etc, in order to develop sustainable approaches and policies for decision makers.

1. Introduction

The present days represent a crossroad in the history of humanity, and of the whole Earth. Indeed, the result of the complex dynamics of deepening and growing the poverty distribution on one hand, and of increasing of ecological environmental and socio-economic degradation on the other one, are generating a difficult socio-economic system of despair from which it is very difficult to escape (Hathaway and Boff, 2009). New possibilities for the renewal of the world are coming from real advances in health-care and access to basic services, and the increasing awareness of ecological issues. Humanity began its greater impact on the world ecosystems since Europe began to transform itself into a technological society and expands its power through colonial exploits.

Since 1950, the frequency of exploitation and ecological destruction has accelerated due to the technological, industrial and economic developments, with some consequences on our planet (Hathaway and Boff, 2009):

- The hole in the ozone layer, the protective skin of the planet that filters out harmful ultraviolet radiation;
- The loss of the 65% of once-arable land;
- The conversion of the 15% of the planet's land surface into deserts;
- The input of long-lived toxins chemicals into the air, soil, and water;
- A great number of plant and animal species that disappear each year;
- The global temperature that has already risen an average of 0.5 ° C up to 2.0 °C (Worldwatch Institute, 2007).

Last, from an economic and financial point of view around the richest 20% of the population earns approximately 200 times more than the poorest 80% (Hathaway and Boff, 2009). The consequence is human fluxes from poorer regions to richest ones.

All these facts allow us to highlight that a new approach is required in the analysis of sustainability. Sustainable development is a topic which becomes prominent in everyday life, with respect to the debates around global warming and corporate social responsibility (Corbett, 2009).

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The term sustainable development was introduced into the political and business agenda since the 1980 with the release of the Brundtland report (Steurer et al., 2005; Dyllick and Hocketts, 2002), which named it as the "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). But, we must highlight that in the human history, business activity has always dominated every stage of the value creation and production chain. These activities use a great amount of resources with impact on the natural environment. The present social role for business holds to the development of concept of *corporate social responsibility* (Corbett, 2009; Waddock, 2004) with a strict relation among the Sustainable Development, Corporate Sustainability and Corporate Social Responsibility (Elkington, 1999); indeed, Sustainable Development represents the normative societal concept behind the other two, Corporate Sustainability represents the corporate concept and Corporate Social Responsibility represents the management approach (Corbett, 2009).

Sustainability is an interdisciplinary topic of research, so different approaches have been developed on Corporate Social Responsibility in order to supply the implications of sustainability in relation to the economic value, to the societal and human aspects of business behaviour, to the industry and technological level, to the environmental and resource impacts of products and services. In this context, the Life Cycle Analysis has been introduced, based on the efficient use of resources at each stage of the process for the product or service (Allenby, 1995), analysing design, manufacture, distribution, use, and end-of-life of the products. But, this approach must be linked to Corporate Social Responsibility in order to consider also the economic, environmental and social sustainability, which the business's processes must take into account. Indeed, a realizable environmental sustainability must be related to the company maintenance of its capital with respect to the impact and risk of company processes on the environment. It concerns the use of resources and emissions. But, sustainability must consider also Social sustainability, which is related to the company contribution to the social well-being of the society and workers.

It is clear that sustainable development is an interdisciplinary topic which links together economy, engineering, and social sciences. Of course, these disciplines present specific methodologies and approaches in the analysis of the topic. But, in order to suggest a concrete approach it is fundamental to find a unified approach. To do so, it is possible to introduce an indicator which highlights both the economic needs of analysis and the engineering optimization, and able to consider also the social implications. Indeed, indicators perform many functions (DESA, 2007):

- They can simplify, clarify and aggregate information in order to allow the policy makers to choose better decisions;
- They can include engineering and social sciences information into decision-making, by measuring and calibrating progress toward sustainable development;
- They can highlight possible risks in order to prevent economic, social and environmental setbacks.

In literature there exists a great number of indicators for sustainability (DESA, 2007), so an effective approach requires a subset of indicators which must fulfil three fundamental criteria (DESA, 2007):

- They must cover issues relevant for sustainable development in most countries;
- They must supply critical information for policy decisions;
- They must be calculated by most countries with data available within reasonable time and costs.

The result is a core of more than sixty indicators. From a sustainable engineering point of view it represents a constraint which must be added to the technical constraints, and it becomes difficult to link the technological indicators to the sustainable ones. So, a rational approach to sustainable policies, based on concrete designing and effective results, requires a completely new approach.

Since the '80, optimization of energy and process systems has been reconsidered (Curzon and Ahlborn, 1975), and Bejan introduced a new viewpoint of maximization of power with heat engine models associated to heat transfer irreversibility, with the result that maximum power corresponds to minimum entropy generation rate (Bejan, 1994), or maximum entropy generation, which agrees with the Gouy–Stodola theorem (Lucia, 2013d,a, 2012a). So, entropy generation analysis has shown to be a design tool to recognize system improvements, but also a measure of sustainability. The process with the lower entropy generation rate is more sustainable than others because it is able to realize the energy conversion more efficiently (Kowalski et al., 2013; Hepbasli, 2008).

Moreover, in the analysis of economy and society, thermodynamics has been introduced by many authors (Georgescu-Roegen, 1971; Jørgensen and Mejer, 1979; Jørgensen and Svirezhev, 2004; Jørgensen et al., 1995; Nielsen and Jørgensen, 2015). Thermodynamics presents a great number of applications and an integration of many methodologies for the analyses of both energy and material flows, and economics (Nielsen and Müller, 2009; Kandziora et al., 2013; Zhou et al., 2011; Zhang et al., 2009; Xydis, 2009; Yellishetty et al., 2011; Whittaker, 1976; Warr and Ayres, 2010; Serova and Brodianski, 2004; Herva et al., 2011). Moreover, many applications of exergy analysis have been developed in Cleaner Production, Industrial Ecology and LCA also for the analysis of depletion of resources, activities and production also in transports and building materials, and to conceder and introduce the consequences of new and more sustainable alternatives, like wind and solar power and various forms of bio-fuels (Nielsen and Jørgensen, 2015).

The basic idea of this paper is the application of thermodynamic concepts to socio-economic systems, starting from the analysis of irreversibility. Thermodynamics is a statistical theory for large systems, which is actually based on two corresponding concepts: one approach is based on the first and second laws of thermodynamics and leads to macro-physics of motors, refrigerators and heat pumps, the other is the free energy concept, that leads to microphysics of atomic interactions in physics, chemistry, metallurgy or meteorology. Indeed, the energy analysis takes no account of the energy source in terms of its thermodynamic quality. It enables energy or heat losses to be estimated, but yields only limited information about the optimal conversion of energy. In contrast, the Second Law of Thermodynamics indicates that, whereas work input into a system can be fully converted to heat and internal energy, via dissipative (real) processes, not all the heat input can be converted into useful work. So, the Second Law points out the need for the definition of parameters that facilitate the assessment of the maximum amount of work achievable in a given system with different energy sources. This quantity is the exergy which is no more than the available energy for conversion from a reservoir with a reference to a specified datum, usually the ambient environmental conditions. It represents the thermodynamic quality of a energy, but also the quality of the energy lost in the process considered. Kline argues that the irreversibility, perhaps better denoted by the term exergy degradation or exergy destruction, can be interpreted as the dissipated available energy (or exergy) that ends up as random thermal fluctuations of the atoms and molecules in the exit flow of mechanical devices (Hammond and Winnett, 2009; Hammond, 2004b; Hammond and Winnett, 2006).

Over the past twenty years or so environmental economics has moved from being a fringe activity to become one of the most active fields of economic research. It is now a major, even dominating, influence within significant areas of policy debate, including global issues such as climate change and biodiversity loss. It formulates and analyses the two key issues of concern: the valuation of ecological assets and the design of policy instruments to manage those assets. These are brought together in the contemporary study of sustainable development. Thus, environmental economics is essentially a branch of applied welfare economics. The various methods that have been proposed for valuing external costs and benefits are all open to criticism (Hammond and Winnett, 2009; Hammond, 2004b; Hammond and Winnett, 2006).

In this paper we suggest a holistic approach related to the synthesis of bio-economics and thermo-economics, an industrial thermodynamic approach which can be named bio-thermo-economics.

2. Materials and methods

Irreversibility in open systems represents a fundamental topic of investigation for engineering thermodynamicists for the optimization of the design and development of the industrial devices and processes (Lucia, 2016b; Lucia and Grisolia, 2017). Today, the analyses of irreversibility is based on the Gouy–Stodola approach, named the entropy generation approach (Lucia, 2013d,a, 2012a) which states that the lost exergy in a process is proportional to the entropy generation (Lucia, 2012b, 2016a, 2013e). Exergy is the maximum shaft work which can be obtained by a system in relation to its specified reference environment. The reference environment is considered infinite and in equilibrium. The reference state is well known in relation to its temperature, pressure and chemical composition (Dincer and Cengel, 2001). We stress that the fundamental step for the evaluation of exergy is just the definition of the reference state. Exergy allows us to quantify the ability of a system to generate changes, related to its non-equilibrium with respect to its reference environment (Dincer and Cengel, 2001).

The exergetic analysis is the basis of the present engineering in relation to the highest efficiency designing at the least cost, but it also allows us (Lucia, 2016b):

1. To take into account the impact on the natural environment;
2. To evaluate the more efficient use of the energy resources, and the magnitude of wastes and losses.

But, the cause of any impact is no more than the interaction between the system and its environment (Lucia, 2007, 2013c; Bejan, 2000, 1982, 1995; Bejan et al., 1996; Bejan and Lorente, 2004, 2010; Bejan, 2006a); indeed, any change is always consequence of:

1. Flows of matter through the system boundary (money included);
2. Heat flow through the system boundary;
3. Work developed by or on the system.

Any process occurs in a proper time τ, and, during this time, the exergy balance can be obtained as follows (Bejan, 2006a):

$$W = \Delta B + \sum_{\alpha} J_{ex,\alpha} + \sum_{\beta} Ex_{Q,\beta} - T_0 S_g \tag{1}$$

where:

- W is the net work done during the process;
- $\Delta B = E + p_0 V - T_0 S$ is the accumulation of nonflow exergy;
- $J_{ex} = \int_0^{\tau} \dot{m}\left(e - T_0 s\right) dt$ is the transfer exergy due to mass flow;
- $Ex_Q = Q\left(1 - T_0/T\right)$ is the exergy transfer due to heat flow;

and Q is the heat exchanged, W is the work done; $\dot{m}$ is the mass flow, h is the specific enthalpy, e is the specific energy, s is the specific entropy and $S_g = W_\lambda / T_0$ is the entropy variation due to irreversibility, named entropy generation (Lucia, 2007, 2013c; Bejan, 2000, 1982, 1995; Bejan et al., 1996; Bejan and Lorente, 2004, 2010; Bejan, 2006a, 1996; Chen et al., 1999; Chen and Sun, 2004; Andersen, 2011; Ge et al., 2016), and the subscripts 0 means reference environment, α and β are related to the number of fluxes of heat and mass, respectively. The entropy variation ΔS of the system, related to the previous exergy variation, results:

$$\Delta S = \sum_{\beta} \frac{Q_\beta}{T_\beta} + \sum_{\alpha} \int_0^{\tau} \dot{m}_\alpha s_\alpha dt + S_g \tag{2}$$

where T is the temperature of any βth reservoir, W_λ is the work lost due to irreversibility, dissipation and frictions, and p is the pressure and V is the volume.

The work lost, W_λ, due to irreversibility, dissipation and friction results (Bejan and Lorente, 2004):

$$W_\lambda = \frac{Ex_{in} - Ex_{out} - W}{T_0} \tag{3}$$

where Ex refers to exergy and *in* and *out* refer to inflow and outflow, respectively. So, we can obtain the explicit relation for the entropy generation, the entropy variation related to irreversibility:

$$\begin{aligned} T_0 S_g = & \sum_{\alpha} \int_0^{\tau} \dot{m}_\alpha \left(h_\alpha + e_{k,\alpha} + e_{p,\alpha} + e_{ch,\alpha}\right) dt \\ & + \sum_{\ell} \int_0^{\tau} \dot{m}_\ell \left(g_\ell^{\oplus} - ex_{ch,\ell}^{\oplus}\right) dt \\ & - \sum_{\beta} \left(1 - \frac{T_0}{T_\beta}\right) Q - W - \int_0^{\tau} \frac{d}{dt}\left(E - T_0 S\right) dt \end{aligned} \tag{4}$$

where g is the specific Gibbs potential, $ex_{ch} = y\left(\mu - \mu_0\right)_{T_0, p_0}$ is the specific chemical exergy at the reference atmosphere, y is the molar fraction, $\dot{m}$ is the mass flux, and μ is the chemical potential; $\oplus$ refers to the standard conditions, and the subscripts k, p and ch refer to kinetic, potential and chemical terms, respectively.

The sources of any physical process are the exergy gradients (Lucia, 2013e), while entropy generation allows us to evaluate its irreversibility (Lucia, 2012b; Bejan and Lorente, 2016, 2008; Bejan, 2018, 2006b; Chen, 2012; Chen et al., 2019) and dissipations during any process, so we can introduce a new indicator, the *exergy inefficiency*, with the aim to measure the technological level of a process in relation to its *unavailability* (Lucia, 2016b; Lucia and Grisolia, 2017):

$$\varepsilon_\lambda = \frac{T_0 S_g}{Ex_{in}} \tag{5}$$

It allows us to quantify the effects of the process losses, so the lower the value of the exergy inefficiency, the more the industrial process is efficient in terms of energy use. Consequently, it allows us to quantify the technological maturity of a production system or a production sector (Lucia, 2013b, 2016b; Lucia and Grisolia, 2017).

Moreover, in order to obtain information on the sustainability of a process, we can introduce also another indicator, the equivalent wasted primary resource value for the work-hour, defined as (Lucia and Grisolia, 2018)

$$EI_\lambda = \frac{T_0 S_g}{n_h n_w} \tag{6}$$

where n_h is the working hours and n_w is the number of workers. It quantifies the cost of the wasted exergy required to support of the work-hours and to generate capital flow generation. Moreover, the previous relation (Eq. (6)) can be modified also in relation to the quantity of product as follows (Lucia and Grisolia, 2018):

$$EI_\lambda = \frac{T_0 S_{g,PS}}{\dot{m}_{CO_2}} \dot{m}_{\text{product}} \tag{7}$$

where $\dot{m}_{\text{product}}$ represents the mass produced in a day and n_{CO_2} is the moles of CO_2 wasted.

3. Results

In relation to the sustainable development, science and technology play a fundamental role; consequently, scientific knowledge and technological improvement can be considered a resource for a new economic growth, in accordance with the social and environmental requirements in order to avoid the present unsustainable conditions.

The technological processes can be analysed by using a holistic approach based on thermodynamics, and by taking into account all its interactions both internal to the process and external towards the environment and society (Lucia, 2016b), obtaining a quantitative evaluation of the flows of matter and energy through the border of the system considered, and of the related consumption rate of the available resources (Sciubba, 2009).

In order to evaluate the sustainability of industrial processes, some indicators have been introduced. Every company uses different processes for their production, with different related carbon emissions and environmental consequences. So, each indicator must be considered "an aggregate, a quantitative measure of the impact of a 'community' on its surroundings (environment)" (Sciubba, 2009), so:

- The ecological indicators must be applicable to any "community";
- They are aggregated because it cannot be limited to a single individual;
- They consider only the effects produced on the environment that surrounds the community under examination.

The community and the environment are considered separate, but interacting systems (Sciubba, 2009). The indicators must satisfy some properties (Lucia, 2016b):

- They must be evaluated using unambiguous and reproducible methods under a well defined set of fundamental assumptions;
- They must be expressed by a numerical expression whose results can be ordered in an unambiguous way;
- They must be calculated on the basis of intrinsic properties of the community and of the environment;
- They must be normalized in order to compare different communities or environments;
- They must be defined on the basis of the accepted laws of thermodynamics.

Sciubba analysed a great number of indicators and highlighted their limits which can be summarized as follows (Sciubba, 2009):

- MTA (Material Throughput Analysis or Material Inventory Analysis): it is based on the hypothesis that the lifestyle of a community can be measured by the global equivalent material flow used to produce the commodities on which it thrives;
- EEn (Embodied Energy): it allows us to obtain a direct measure of environmental impact, by evaluating the amount of energy used to obtain a product, in terms of resources and work done;
- Transformity: it consider only the conversion of the solar energy conversion into any other form of energy of the Emergy Analysis without taking into account any other flows of matter and energy.

Real systems operate on irreversible thermodynamic processes which take place in a finite proper time (Lucia, 2013e). Entropy and entropy generation in non-equilibrium processes represent the bases of the modern engineering thermodynamics.

The indicators here proposed introduce the entropy approach to the economic considerations. The three applications developed shows how these indicators could represent an engineering approach to sustainability, both from a technological point of view and from a socio-economic one.

Now, three applications are summarized in order to show the use of the indicators here introduced.

3.1. Application 1: CO_2 emission cost in DEFC technology

Progress has always been associated with the economic growth and with a related increase of the energy production needs. Up today, the energy production have been made by the combustion of fossil fuels, with a related increased of the air pollution and the emission of greenhouse gas, such as CO_2. Consequently, today, one of the main problem of the industrialized country is just the management of CO_2 emissions, one of the present problems of the production systems (Chicco, 2010; Hammond, 2004a; Nordhaus, 2008; Sciubba, 2005).

But, just the CO_2 emission could also represent an opportunity for the promotion of high-efficiency design of both conventional and new technological plants. Among the new technologies, one of the most promising one is the fuel cell (Bagotsky, 2012; Calise, 2011). The theoretical power produced when a fuel cell supplies an electric current I is $\dot{W} = EI$, with E electromotive force. But, the cell potential, and its related efficiency, decreases in increasing of current (Li, 2007) as a consequence of any irreversibility (Lucia, 2014):

1. Activation polarization E_λ^{act}, due to the irreversibility of the electrochemical reactions and evaluated by the Tafel relation $E_\lambda^{act} = a + b\ln I$, with $a = -RT/(\alpha nF)$, where α is the electron transfer coefficient, and $b = -a$ is the Tafel slope obtained by the plot of E_λ^{act} as a function of I;
2. Ohmic polarization $E_\lambda^{ohm} = rI$, due to electrical resistance r in the fuel cell. The resistance r is the total resistance of the fuel cell, sum of the electronic, R_{el}, ionic R_{ion} and contact, R_{conct}, effects: $r = R_{el} + R_{ion} + R_{conct}$;
3. Concentration polarization E_λ^{conc}, due the overaccumalation of products in the reaction area, expressed as $E_\lambda^{conc} = b\ln(1 - I/I_L)$, with I_L the limiting current, a measure of the maximum rate at which a reactant can be supplied to an electrode;
4. Nernst loss $E_\lambda^{Nernst} = (RT/nF)\,ln(k_{out}/k_{in})$, with R universal constant of gas, k equilibrium constant for partial pressure evaluated for the inlet and outlet gas composition, due to the spontaneous adjustment of the lowest electrode potential by the cell;

with the resultant exergy lost (Lucia, 2014):

$$E_\lambda = E_\lambda^{act} + E_\lambda^{ohm} + E_\lambda^{conc} + E_\lambda^{Nernst} \tag{8}$$

and the related molar specific entropy generation:

$$\tilde{s}_g = \frac{E_\lambda}{nF\,T} \tag{9}$$

where n is the number of moles of fuel, F is the Faraday constant and T is the temperature.

In order to evaluate the equivalent wasted primary resource value for quantity of product, we consider a Direct-Ethanol Fuel Cell, i.e. a PEMFC. The reference chemical reaction is (Lamy, 2017):

$$C_2H_5OH + 3O_2 \rightarrow 3H_2O + 2CO_2 \tag{10}$$

For this reaction the standard (temperature = 25 °C and pressure = 1 atm) molar specific enthalpy variation $\Delta\tilde{h}$ is -286 kJ mol^{-1} at 60 mW cm^{-2} electric power density at $E_0 = 1.145V$ electric potential. Following Fleischer and Ørtel (Lucia, 2014) it is possible to evaluate the value of $T_0\tilde{s}_g$ as $\sim$ 109 kJ mol^{-1}. Consequently, EI_λ results 164 kJ mol$^{-1}_{CO_2}$. In order to assign an economic value comparable with other energy resources the indicator EI_λ can be expressed in kilowatt-hours, obtaining 0.045 kWh mol$^{-1}_{CO_2}$ = 1.02 kWh kg$^{-1}_{CO_2}$.

Now, considering the mean value of the cost of the kWh in the EURO-area as 0.22 EUR kWh^{-1} (EUROSTAT, 0000), we can obtain the following cost of production 0.01 EUR mol$^{-1}_{CO_2}$ = 0.23 EUR kg$^{-1}_{CO_2}$. Considering that the bioethanol enthalpy is 261 kJ mol^{-1} the inefficiency of the process results $\epsilon_\lambda = 0.41$.

As an application we can consider that the fuel cell can be designed as auxiliary power units to supply hotel loads of up to 100 W or integrated into vehicles. The auxiliary power units market is consider a growing field of production because fuel cells offer a low-emission and low-noise technology. So, using the data collected in literature (Saisirirat and Joommanee, 2017), for a 100 W Direct Ethanol Fuel Cell (DEFC) we can evaluate 23.8 EUR of cost for the CO_2 environmental impact.

3.2. Application 2: Comparison between fuels production

In relation to the fuel production this approach has been used in Reference Lucia and Grisolia (2018).

Photosynthesis is a process that leads to complex organic molecules starting from simple molecules and by absorbing solar radiation (Lucia and Grisolia, 2018). We consider the following chemical reaction for cyanobacteria *Spirulina platensis*:

$$6CO_2 + 12H_2O \rightarrow C_6H_{12}O_6 + 6H_2O + 6O_2 \tag{11}$$

So, we must evaluate the entropy generation. We consider the Sun, the photosynthetic organism and the Earth as different systems. Fluxes occur among them. The process under study can be analysed in four steps:

1. light comes from sun to the photosynthetic organism without any work carrying an energy (and exergy) flux. The Sun emits a gas of photons which follows an adiabatic expansion, with a related dilution of photons, along the path from the Sun to the Earth. Consequently, the Sun can be considered as a grey-body at temperature T_S = 5762 K in radiative equilibrium with the Earth. The Earth absorbs all the radiation, consequently, it behaves as a black body at atmospheric temperature T_E = 298.15 K. The first law holds:

$$\begin{aligned} \varepsilon\sigma T_S^4 &= \sigma T_E^4 \\ \varepsilon &= \frac{R_S^2}{R_O^2} \end{aligned} \tag{12}$$

   with σ = 5.67 × 10^{-8} Wm^{-2}K^{-4}, ϵ emissivity, R_S Sun radius and R_O Earth radius. The entropy generation during the process can be evaluated as:

$$S_{g,SE} = \frac{4}{3}60N_A h\nu\left(\frac{1}{T_E} - \frac{1}{T_S}\right) \tag{13}$$

   with $\nu = c/\lambda$ frequency, c light velocity and λ wave length, h = 6.626 × 10^{-32} Js the Planck's constant and N_A = 6.022 × 10^{23} mol^{-1};
2. the photosynthetic organism absorbs the light from their environment, and the entropy generation results $S_{g,la} = 0$ J K^{-1}, because it happens at constant temperature ($T_{PO} = T_E$, where PO means photosynthetic organism) without any work;
3. glucose is produced by the photosynthetic organism by using the exergy absorbed from the light, and the related entropy generation results:

$$S_{g,gp} = -\frac{\Delta G_{PO}}{T_{PO}} \tag{14}$$

   where PO means photosynthetic organism;
4. the remaining heat is exchanged by the photosynthetic organism with the Earth, with the related entropy generation $S_{g,POE} = 0$ J K^{-1}, because it happens at the same temperature without any work.

Consequently, the entropy generation for the photosynthesis process results:

$$S_{g,PS} = S_{g,SE} + S_{g,la} + S_{g,gp} + S_{g,POE} = \frac{4}{3}60N_A h\nu\left(\frac{1}{T_E} - \frac{1}{T_S}\right) - \frac{\Delta G_{PO}}{T_{PO}} \tag{15}$$

The consequent reaction efficiency can be evaluated as:

$$\eta = \frac{\Delta G^0}{60N_A h\nu} \tag{16}$$

So, for *Spirulina platensis* it has been evaluated the energy involved in the production as 2187 MJ kg$_b^{-1}$ = 607.5 kWh kg$_b^{-1}$, with the related cost of production of 133.65 EUR kg$_b^{-1}$. The result has been compared with the one evaluated for the crude oil extraction by the steam injection for thermal enhanced oil recovery which requires 1990–2330 MJ m^{-3} of energy per unit volume of oil extracted with a related cost of 132.00 EUR m^{-3} for the crude oil extract (Brandt, 2011).

This result highlight how the biofuels obtained by *Spirulina* is competitive with the oil extraction, but with a sustainable result. This consideration could allow the companies and the government to consider the biofuel production with cyanobacteria as a new resource for the environment and the economy.

3.3. Application 3: policy considerations

The analysis of the exergy balance for Italy has been developed by Wall et al. (1994). The reference year for the exergy analysis of Italy is the year 1990. The population of Italy was 5.77 × 10^7 people. The result obtained can be summarized in the inflow exergy of resources as 140 GJ/capita (1 GJ/capita = 16.0175 TWh), while the output exergy as 25 GJ/capita and the electric work produced was 13.55 GJ/capita. The related unavailability percentage results 72%, pointing out that in 1990 Italy did not use technologies in an efficient way, with the consequent present economic results.

Now, we can use the same approach to analyse an Italian town, the district of Alessandria. The reference year for the exergy analysis is the year 2004 (Lucia, 2016b).

In relation to the data available, we can consider only the flows of exergy from energy resources, neglect of the flows of products and services (Lucia, 2016b). Alessandria is an italian district of Piedmont region, and we analyse only the municipality of Alessandria, which covers 204 km^2 with a population of 93,922 people. We consider the following exergy flows only related to the city management in order to obtain information from the energy management of the city administration:

- The exergy inflow from the tertiary sector: it is distinguishing trait mainly from consumption of building heatings, water systems and electrical appliances, from electricity you obtain low temperature heat, from fuels, which consists of Electricity 712 TJ (85% for low temperature heat) and Fuels 559 TJ, with a total amount of 1271 TJ;

- The exergy outflow from the tertiary sector uses: Electricity 289 TJ (low temperature heat 182 TJ, other uses 107 TJ) and Fuels 148 TJ, with a total amount of 437 TJ;
- The exergy inflow from the residential sector: the consumptions of this branch are mainly for residential use for residential lightening, heating, etc.: Electricity 309 TJ and Fuels 2825 TJ, with a total amount of 3134 TJ;
- The exergy outflow from the residential sector uses: Electricity 125 TJ (low temperature heat 79 TJ, other uses 46 TJ), and Fuels 992 TJ, with a total amount of 1117 TJ;
- The exergy inflow from the public transport: This sector receives in input fuel and in output mainly produces mechanical power: Electricity 14 TJ and Fuels 29 TJ, with a total amount of 43 TJ;
- The exergy outflow from the public transport: Electricity 0 TJ, and Fuels 10 TJ, with a total amount of 10 TJ;
- The exergy inflow from the private transport: This sector receives in input fuel and in output mainly produces mechanical power: Electricity 0 TJ and Fuels 2230 TJ, with a total amount of 2230 TJ;
- The exergy outflow from the private transport: Electricity 0 TJ, and Fuels 652 TJ, with a total amount of 652 TJ.

The total exergy inflow results 6678 TJ and exergy outflow results 2216 TJ, with an exergy lost of 4462 TJ. So, the unavailability percentage results 66.8%. It pointed out a result very closed to the same of Italy in 1990. It means that in 14 year the use of the technologies and the energy remains approximately the same. Indeed, in 2012, a financial failure occurred for the Alessandria city.

Now, we can consider a possible policy decision of the city administration, as follows:

- Introducing the district heating: it would reduce
  - The exergy inflow for tertiary sector of electricity uses to 107 TJ for the electricity and to 0 TJ for the fuels;
  - of the 90% of fuels for the exergy inflow and outflow from the residential sector;
- improve the public transportation: it would:
  - Improving, for public sector, the exergy inflow to 100 TJ and the exergy outflow to 34 TJ;
  - Decreasing, for private sector, the exergy inflow to 1400 TJ and the exergy outflow to 409 TJ.

The result of these two energy management decision is to reduce the exergy inefficiency to 0.338, with a better energy management.

This result highlights how the use of these new indicators could be interesting also for policy considerations for municipalities or states.

4. Conclusions

The aim of the paper is to suggest a new approach to sustainability, in order to change slowly the present productive systems, but reducing the impact on the environment with an increase of working position. “Slowly”means that we can change the impact without any inertia from the great companies. Indeed, any change is a cost for the companies. In order to achieve the aim, three new indicators are suggested, by using an engineering approach of irreversibility.

These indicators allow one to evaluate both the technological level and the environmental impact of the production processes and the socio-economic conditions of the countries.

They were based on the exergy analysis and on the irreversible thermodynamic approach, in order to evaluate the inefficiency both of the process and of the production systems, and the related consequences.

In Economy, Gross Domestic Product is an economic indicator used to evaluate the results of the national policies because its increase is related to the increase of the nations well-being. The present bases of the national policies is the detached approach that “what is good for the market is good for Gross Domestic Product, and *vice versa*”. Consequently, the economists use it as the indicator of profit of the production in any country, and of the economic, social, and environmental welfare.

But, indicators can be classified in four different, and related, pillars (DESA, 2007):

- Social pillars: equity (income, sanitation, drinking water, energy access and living conditions) and Global economic partnership (trade and development financing) included:
  - Poverty,
  - Governance,
  - Health,
  - Education,
  - Demographics,
- Economic pillars:
  - Economic development,
  - Global economic partnership,
  - Consumption and production patterns,
- Environmental pillars:
  - Natural hazards,
  - Atmosphere,
  - Land,
  - Oceans, seas and coasts,
  - Freshwater,
  - Biodiversity,
- Institutional pillars:
  - Natural hazard,
  - Governance hazard,
- Technological pillars:
  - Designing optimization,
  - Optimization of production processes,
  - Energy saving and reduced environmental impact of power production.

This multi-dimensional nature of the indicators highlights just how sustainable development is a complex topic and how these pillars must be related in a holistic approach, so, recently, two other alternative indicators, related to sustainability, have been introduced:

- The Measure of Economic Welfare (Nordhous and Tobin, 1972);
- The Economic Aspects of Welfare (Zolotas, 1981);
- The Index of Sustainable Economic Welfare (Daly and Cobb, 1989);
- The Genuine Progress Indicator (Daly and Cobb, 1989).

In particular, these last two indicators have been described as more accurate than the Gross Domestic Product for the measurement of well-being and progress in relation to a concrete sustainable economics and to new nation strategies for policy decisions, because they take into account factors that affect the quality of life and the nation ability to sustain it into the future, as pollution, crime, family breakdown, and community involvement. So, while Gross Domestic Product evaluates the total monetary valuation of all production transacted in the marketplace, the Index of Sustainable

Economic Welfare, and the Genuine Progress Indicator evaluate the effect of the production to humans for improving the quality of life, by including non-market goods and services useful to humans.

The indicators here introduced could represents a new approach to the analysis of the sustainability. Indeed, they introduce an engineering approach to sustainability and evaluate it also in economic costs. In this way, a link between technological level and economic value occurs.

Growth is aim of the present economic system. But, there exists a link between energy and economic development, because energy use affects development (Toman and Jemelkova, 2003), and the promotion of the economic growth (Stern, 2010); indeed, just energy is an essential factor of any production system and the economic processes, even if the present economic analyses of growth considers only capital and labour.

Nowadays, in industrialized countries, the management of CO_2 emissions represents one of the present compelling issue. Indeed, the improvement of the energy efficiency and its rational use can be considered a fundamental economic strategy for the sustainable development of the industrialized countries.

So, we have introduced new indicators related to the inefficiency in order to evaluate:

- The equivalent primary wasted resource value,
- The technological level,
- The advanced level of industrial processes,

with the result of linking the exergy cost to the inefficiency of the systems, and considering the cost of the wasted exergy used to sustain the processes themselves.

Some applications have been developed in order to highlight the possible use of these indicators.

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