Article

Exergy inefficiency: an indicator for sustainable development analysis

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Abstract: The present days can be considered a crossroad in the history our word because the economic, social and ecological needs don't agree one another. The result is a continuous growth of poverty and an increase of the ecological degradation. This has generated the present difficult socio-economic state, and it seems very difficult to escape. A new viewpoint must be introduced, but it cannot based on the usual economic indicators. So, new indicators must be introduced. They must allow us to consider the technological level, the environmental impact and the socio-economic conditions. In this paper we suggest three indicators based on an engineering approach of irreversibility. Three applications are shown 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.

Keywords: Bioeconomics; Entropy; Exergy; Irreversibility; Sustainability; Thermoeconomics.

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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 poverty on one hand, and of increasing of ecological degradation on the other one, are generating a difficult socio-economic system of despair from which it is very difficult to escape [1]. New possibilities for the renewal of the world are coming from real advances in healthcare and access to basic services, and the increasing awareness of ecological issues. Humanity began its greater impact on the world's ecosystems since Europe began to transform itself into a technological society and expands its power through colonial exploits.

Since 1950, the rhythm of exploitation and ecological destruction has accelerated due to the technological, industrial and economic developments, with some consequences on our planet [1]:

- The hole in the ozone layer, the protective skin of the planet that filters out harmful ultraviolet radiation;
- The loose 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 disappear each year;
- The global temperatures have already risen an average of 0.5°C up to 2.0°C [2].

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% [1]. The consequence is human fluxes from poorer regions to richest ones.

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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 [3].

The term sustainable development was introduced into the political and business agenda since the 1980 with the release of the Brundtland report [4,5], 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" [6]. 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 uses a great amounts of resources with impact on the natural environment. The present social role for business holds to the development of concept of *corporate social responsibility* [3,7] with a strict relation among the Sustainable Development, Corporate Sustainability and Corporate Social Responsability [8]; indeed, Sustainable Development represents the normative societal concept behind the other two, Corporate Sustainability represents the corporate concept and Corporate Social Responsability represents the management approach [3].

Sustainability is an interdisciplinary topic of research, so different approaches have been developed on Corporate Social Responsability 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 [9], analysing design, manufacture, distribution, use, and end-of-life of the products. But, this approach must be linked to Corporate Social Responsability in order to consider also the economic, environmental and social sustainability, which the business's processes must take into account. Indeed, a realisable environmental sustainability must be related to the company's maintenance of its capital with respect to the impact and risk of company's 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 approach 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 optimisation, and able to consider also the social implications. Indeed, indicators perform many functions [10]:

- They can simplify, clarify and aggregate information in order to allow the policy makers to choose better decisions;
- They can incorporate engineering and social sciences knowledge 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 [10], so an effective approach requires requires a subset of indicators which must fulfil three fundamental criteria [10]:

- They must cover issues relevant for sustainable development in most countries;
- They must provide 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 constrains, and it becomes difficult to link the technological to the sustainable indicators. 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 [11], and Bejan introduced a new viewpoint of maximization of power with heat engine models associated to heat

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transfer irreversibility, with the result that maximum power corresponds to to minimum entropy generation rate [12], or maximum entropy generation, which agrees with the Gouy-Stodola theorem [13–15]. So, entropy generation analysis has shown to be a design tool to identify system improvements, but also a measure of sustainability. The process with the lower entropy generation rate is the more sustainable one because it is able to realize the energy conversion more efficiently [16,17].

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

2. Method

2.1. The suggested approach

Irreversibility in the processes developed 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 [18,19]. The analyses of irreversibility in the present thermodynamics is based on the Gouy-Stodola approach, i.s. on the entropy generation [13–15].

Indeed, in 1889, Gouy, and in 1905, Stodola, independently proved that the lost exergy in a process is proportional to the entropy generation [20–22]. Exergy is the maximum amount of work that can be obtained by a system as it comes to equilibrium with its reference environment, which is no more than the system environment [23]. It allows us to quantify the ability of a system to generate changes, related to its non-equilibrium respects with its reference environment [23].

The exergetic analysis is the base of the present engineering in relation to the highest efficiency designing at the least cost, but it allows us also [18]:

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 interactions between the systems and their environment [24–32]; indeed, any change is always consequence of:

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

Any process, interaction, cycle occurs in a proper time τ, named lifetime, and, during this time, the exergy balance can be obtained [32]:

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

where we have the following:

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

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; and the subscripts k, p and ch refer to kinetic, potential and chemical terms, respectively; i and j are related to the number of fluxes of heat and mass, respectively. The following entropy variation, ΔS, of the system occurs and is related to the previous energy variation:

$$\Delta S = \sum_i \frac{Q_i}{T_i} + \sum_j \int_0^{\tau} \dot{m}_i s_i dt + S_g \tag{2}$$

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where T is the temperature of any ith reservoir, s is the specific entropy and $S_g = W_\lambda / T_0$ is the entropy variation due to irreversibility, named entropy generation [24–32]; W_λ is the work lost, and the subscript 0 refers to the environment, while p is the pressure and V is the volume.

The work lost, W_λ, results [30]:

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

where Ex refers to exergy and in and out refer to inflow and outflow, respectively. Thus, the final relation useful for our analysis becomes the following:

$$\begin{aligned} T_0 S_g = \sum_j \int_0^\tau \dot{m}_i \big(h_j + e_{k,j} + e_{p,j} + e_{ch,j}\big)\, dt + \sum_\ell \int_0^\tau \dot{n}_\ell \nu_\ell \big(g_\ell^\oplus - ex_{ch,\ell}^\oplus\big)\, dt - \\ - \sum_i \left(1 - \frac{T_0}{T}\right) Q - W_t - \int_0^\tau \frac{d}{dt}(E - T_0 S)\, dt \end{aligned} \tag{4}$$

where g is the molar specific Gibbs potential, $ex_{ch} = y(\mu - \mu_0)_{T_0,p_0}$ is the molar specific chemical exergy at the reference atmosphere, y is the molar fraction, $\dot{n}$ is the molar flux, ν is the stoichiometric coefficient, and μ is the chemical potential; $\oplus$ refers to the standard conditions.

Moreover, the Gouy–Stodola principle works for real systems, and it has been used by Stodola in designing real machineries; consequently, the fundamental engineering principle is the Gouy–Stodola principle .

The sources of any physical process are the exergy gradients [22], while entropy generation describes its irreversibility [20].

This last relation allows us to evaluate all the dissipations during the process, and to introduce a new indicator, the *exergy inefficiency*, which allows us to measure the technological level of a process in relation to the *unavailability* [18,19]:

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

This quantity measures the technological maturity of a production system or a production sector in a country, because it quantifies just the effect of the process losses. The lower the value of the exergy inefficiency, the more the industrial process is efficient in terms of energy use [18,19,33].

Starting from the thermodynamic results, we can also define the sustainability of a process by using the following indicator, the equivalent wasted primary resource value for the work-hour, defined as [34]

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

where n_h is the working hours and n_w is the number of workers. This quantity allows us to quantify the cost of the wasted exergy required for the support of the work-hours and for capital flow generation. Moreover, the previous relation (Equation (6)) can be modified also in relation to the quantity of product as follows [34]:

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

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

2.2. *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 gasses,

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such as CO_2. Consequently, today, one of the main problem of the industrialized country is just the management of CO_2 [35–38] emissions.

On the other hand, just the CO_2 emission problem could 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 [39,40]. The theoretical work produced when a fuel cell supplies an electric current I is $\dot{W} = E\,I$, with E electromotive force. But, the cell potential, and its related efficiency, decreases in increasing of current [41] as a consequence of the any irreversibility [42]:

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 $E_\lambda^{ohm} = r\,I$, 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 [42]:

$$E_\lambda = E_\lambda^{act} + E_\lambda^{ohm} + E_\lambda^{conc} + E_\lambda^{Nernst} \quad (8)$$

and the related molar specific entropy generation:

$$\tilde{s}_g = \frac{E_\lambda}{nF\,T} \quad (9)$$

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. The reference chemical reaction is [43]:

$$C_2H_5OH + 3O_2 \rightarrow 3H_2O + 2CO_2 \quad (10)$$

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 [42] 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 $\text{mol}_{CO_2}^{-1}$. 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 $\text{mol}_{CO_2}^{-1}$ = 1.02 kWh $\text{kg}_{CO_2}^{-1}$.

Now, considering the mean value of the cost of the kWh in EURO-area as 0.22 EUR kWh^{-1} [44], we can obtain the following cost of production 0.01 EUR $\text{mol}_{CO_2}^{-1}$ = 0.23 EUR $\text{kg}_{CO_2}^{-1}$. 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 in order to provide 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 [45], for a 100 W Direct Ethanol Fuel Cell (DEFC) we can evaluate 23.8 EUR of cost for the CO_2 environmental impact.

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2.3. Application 2: Comparison between fuels production

In relation to the fuel production this approach has been used in Reference [34]. 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 [46].

This result highlight how the biofuels could be 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.

2.4. Application 3: policy considerations

The analysis of the exergy balance for Italy has been developed by Wall, Sciubba and Naso [47]. 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 summarised 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 [18]. The total exergy inflow results 6,678 TJ and exergy outflow results 2,216 TJ, with an exergy lost of 4,462 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.

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

3. Results

Today, growth is aim of the present economic system. But, there exists a link between energy and economic development, because energy use affects development [48], and the promotion of the economic growth [49]; indeed, just energy is an essential factor of any production system and the economic processes, even if the economic analyses of growth considers only capital and labor.

Nowadays, in industrialized countries, the management of CO_2 emissions represent 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 introduce 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 uses of these indicators.

4. Discussion

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 base of the national policies is the detached approach that what is good for the market is good for Gross

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Domestic Product, and *viceversa*. Consequently, the economists use it for the measurement of profit of the production in any country, and of the economic, social, and environmental welfare.

But, indicators can be classified in four different, but related one another, pillars [10]:

- Social: 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:
  - Economic development,
  - Global economic partnership,
  - Consumption and production patterns,
- Environmental:
  - Natural hazards,
  - Atmosphere,
  - Land,
  - Oceans, seas and coasts,
  - Freshwater,
  - Biodiversity,
- Institutional:
  - Natural hazard,
  - Governance hazard,
- Technological:
  - 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 comprehensive approach.

The Significant methodological work is needed to develop good, measurable and internationally accepted indicators on other aspects of governance.

So, recently, two other alternative indicators, related to sustainability, have been introduced:

- The Measure of Economic Welfare [37];
- The Economic Aspects of Welfare [50];
- The Index of Sustainable Economic Welfare [51];
- The Genuine Progress Indicator [51].

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.

5. Conclusions

In relation to the sustainable development, science and technology play a fundamental role; consequently, scientific knowledge and technological improvement can be consider 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 thermodynamic approach for the whole system, and by taking into account all its interactions both internal to the process and external towards the environment and society [18], 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 [52].

In order to evaluate the sustainability of industrial processes, some indicators have been introduced. Every companies use 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)" [52], 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 [52]. The indicators must satisfy some properties [18]:

- They must be evaluated using unambiguous and reproducible methods under a well defined set of fundamental assumptions;
- They must be expressed by a numeric 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 analyzed a great number of indicators and highlighted their limits which can be summarized as follows [52]:

- 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;
- The tranformity: 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.

The exergy of a system is the maximum shaft work obtainable by the system in relation to its specified reference environment, which is considered infinite, in equilibrium, and it is specified by fixing its temperature, pressure and chemical composition [23].

Exergy is a quantity that allows the engineers to design system with the aim of obtain the highest efficiency at a least cost under the actual technicnology, economic and legal conditions, but also considering ethical, ecological and social consequences; indeed

- It allows the evaluation of the impact of energy resource utilization on the environment;
- It allows the evaluation of more efficient energy-resource use, and of the locations, types, and magnitudes of wastes and losses;

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- It is an efficient technique to evaluate if it is possible to design more efficient energy systems by reducing the inefficiencies in existing technologies.

but:

- The exergy of a system in complete equilibrium with its environment is null;
- Exergy doen't follow any conservation law;
- A system carries exergy proportional to the level of disequilibrium with its environment;
- Any loss of energy quality results in consumption of exergy.

On the other hand, all the real systems operate on irreversible thermodynamic processes which take place in a finite proper time [22]. 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 form a technological and from a socio-economico point of view.

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