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Emergy and exergy analyses: Complementary methods or irreducible ideological options?

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Abstract

The paper discusses the similarities and the incompatibilities between two forms of Energy Analysis (exergy and emergy, 'EXA' and 'EMA' in the following), both of which try to represent the behavior of physical systems by means of cumulative energy input/output methods that result in a double integration over space and time domains. Theoretical background, definitions and balance algebra are discussed first, in a 'statement–counterstatement' format that helps pinpointing differences and similarities.

A significant, albeit simplified, benchmark case (ethanol production from corn) is used to compare the results and analytically assess the merits of each approach as well as possible synergic aspects. Corn production, transport and industrial conversion to ethanol are included in the analysis. First, mass balance and energy accounting are performed in each step of the process, then, exergy and emergy evaluations are carried out separately to lead to a set of performance indicators, the meaning of which is discussed with reference to their proper scale of application.

The Authors underline that each method has its own preferred field of application and conclude that the two approaches appear to be characterized not much as different (and therefore competing) tools, but as different paradigms, whose meta-levels (their 'philosophies') substantially differ. In particular, EXA is found to provide the most correct and insightful assessment of thermodynamic features of any process and to offer a clear quantitative indication of both the irreversibilities and the degree of matching between the used resources and the end-use material or energy flows. EXA combined with costing considerations results in Thermo-Economics (TE), presently the best engineering method for System optimization. One of EXA recent extensions, Extended Exergy Accounting (EEA) includes all externalities in the exergy resource accounting, thus providing a more complete picture of how a process is interacting with its socio-economical environment and with the Biosphere. EMA further expands the evaluation to the larger scale of the Biosphere and properly accounts for the globality of the energy and resource flows supporting complex living systems. Although some conceptual assumptions

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and methodological differences appear irreconcilable, important similarities are also found that may lead to further methodological and practical convergences.

Note: Although a significant confrontation and debate accompanied the development of this paper, contrasting opinions about important features of the two approaches still exist. Therefore, SU takes full responsibility of statements in Sections 2, 4.1, 6.2, 7.1 while ES takes full responsibility of statements in Sections 3, 4.2, 6.1, 7.2. All remaining Sections reflect points of view agreed upon by both Authors.

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1. Introduction

The evermore stringent requirements for a better resource use have led to the compilation and implementation of more and more refined system analysis tools aimed at ‘optimizing’ the conversion of primary resources into final-use energy and commodities. All present theories are based on the premise that neither one of the ‘classical’ process parameters (monetary production cost, labour and capital intensity, and process efficiency) is—by itself—a significant general indicator of the optimality of a production line or design, and that other factors (material flows, resource-to-end-use matching, non-energetic externalities) must be considered (internalized) to provide decision makers with a non-ambiguous set of discriminating indices. Embodied Energy, Emergy Accounting, Life-Cycle Analysis, Cumulative Exergetic Consumption, Exergy Analysis, Thermo-Economics, Extended Exergy Accounting have been discussed and applied to real industrial cases, and there are conflicting claims as of the validity of the one approach over the others. This paper stems from a close confrontation that has emerged in the latest years between supporters of the Emergy Analysis (EMA in the following) and Exergy Analysis (EXA), and is articulated in two distinct parts: the first is a theoretical comparison, and the second is a direct assessment of a specific case (the production of ethanol C_2H_5OH) from corn.

We have chosen to separate the views of the EMA analyst (SU) from those of the EXA analyst (ES): thus, the paper is written in a statement–counterstatement format that, we hope, will facilitate the interpretation on the part of the reader. Beyond our differences, we have a common goal, that clearly surfaces from our often conflicting assertions: there is an urgent need to rationalize resource use, and in spite of some catastrophic views occasionally appearing in the scientific literature, mankind has enough time and resources (cultural, economic, and technological) to remedy the present clearly non-optimal situation of allocation and exploitation of resources. This paper is intended as a contribution towards a common action of all parts involved, be it governmental Agencies, Industry, Labor, or the scientific community. Readers interested in more detailed descriptions of either one of the theories discussed here may consult Ref. [41] for EMA, [34,38,39] for EXA, [54] for CEC, [5,55,57–59] for TE, [52] for EEA.

2. Emergy analysis

The theoretical and conceptual basis for the emergy methodology is grounded in thermodynamics and general System Theory [63]. The first developments can be found in Odum’s book ‘Environment, Power and Society’ [41], while its evolution during the past thirty years is documented in the volume edited by C.A.S. Hall titled ‘Maximum Power’ [29] and finally in Odum’s ‘Environmental Accounting’ [43].

List of symbols

c	specific cost (€/kJ, TE; kJ/kJ (EXA, EEA))
C	capital cost rate (k€/yr)
e	specific exergy (kJ/kg)
E	exergy (kW)
ε	effectiveness (both 2nd Law and emergetic)
ee	specific extended exergy (kJ/kg)
EE	extended exergy (kW)
EEA	extended exergy accounting
EMA	emergy analysis
EXA	exergy analysis
η	efficiency (1st Law)
h	specific enthalpy (kJ/kg)
K	EE conversion factor (kJ/€)
LCA	life cycle assessment
m	mass flow rate (kg/s)
p	pressure (Pa)
s	specific entropy (kJ/(kg K))
T	temperature (K)
TE	thermo-economics
x	molar concentration
U	total solar emergy (seJ)
z	cost rate (TE) (€/s)
Suffixes	
c	chemical
k	kinetic
n	nuclear
p	potential (gravity)
t	thermodynamic
0	reference state

2.1. Emergy: concept and definitions

The central concept addressed by emergy analysts in their works is that of *energy quality*. The emergy concept supports the idea that something has a value according to what was invested into making it along with a generative 'trial and error' process (Maximum Power Principle [35]). The higher the required investment *under maximum power-output selection*, the higher the quality assigned to the item. It is postulated that either a system 'learns' how to maximize its output for success against competing alternatives or is displaced. Implicit in this concept is a thermodynamic approach to natural selection and evolution patterns.

In order to measure the required investment on a common basis, Odum [42,43] introduced the concept of 'form' emergy, i.e. 'the total amount of exergy of one kind that is directly or indirectly required to make a given product or to support a given flow'. We may therefore define an oil emergy, a coal emergy, etc. according to the specific goal and scale of the process. The units of emergy are emjoules (emJ), to distinguish them from joules. This distinction is a matter of principle, and it is a reminder of the different 'quality' of different forms of energy, which cannot be properly expressed solely by their free Gibbs energy.

By introducing the emergy concept, Odum re-directed his focus from the interface between human societies and fossil sources to that between human societies and the environment, identifying the free 'environmental work' as the donor of resources supporting human activities. Such a scale expansion leads to the concept of *solar emergy*, a measure of the total environmental support to processes in the biosphere, including oil production. The *solar emergy* is defined as the sum of all inputs of solar exergy directly or indirectly required in a process [41]. Input flows that are not from solar source (like geothermal and gravitational flows) are expressed as solar equivalent exergy by means of suitable transformation coefficients [42]. The commonly used emergy unit is therefore the *solar equivalent joule* (seJ).

It takes emergy (resources used up) to drive processes and make things. This also applies to processes that are apparently out of the realm of Thermodynamics, like generation of labor, Gross National Product, culture and information. These 'products' are not explicitly expressed in terms of thermodynamic quantities, but they require an investment of resources to be generated and operated. This production cost is adequately measured in emergy terms.

This new point of view accounts for energy concentration through a hierarchy of processes, most of them not under human control, which may therefore follow a different optimization pattern than the one that humans would choose. Human societies try to maximize efficiency, short time-scale return on investment, employment, profit, one-product output. Quite on the opposite, natural processes are stochastic and system-oriented and seem to maximize the utility of the total flow of resources processed through optimization of efficiencies and feedback reinforcement. As environmental conditions change, it appears that the response of the system adapts so that maximum power output can be maintained. In this way, systems tune their thermodynamic performance to the changing environment.

Accounting for required inputs over a hierarchy of levels gives rise to a 'donor system of value', while any purely exergetic analysis and economic evaluation are 'receiver systems of value', where something has a value according to its usefulness to the end user.

It is useful to recall that *emergy is not energy and, therefore, it is not conserved in the way energy is.* Similarly to any other cost measure, the emergy used up is no longer available to drive further transformations. It is embodied in the product, generally in the form of upgraded quality and hierarchical role. This is what emergy analysts mean when they use the words 'emergy content'.

The emergy of a given flow or product is, by definition, a measure of the work of self-organization of the planet in making it. Nature supplies resources by cycling and concentrating matter through interacting and converging patterns. Some resources require a larger environmental work than others, and their use means a larger appropriation of environmental support and services. The emergy content may be therefore assumed as a measure of sustainability and/or pressure on the environment by the system.

2.2. Transformity

The amount of input emergy dissipated (availability used up) per unit output exergy is called *solar transformity* It represents the emergy investment per unit product, and as such it is a measure of the way solar exergy is transformed and degraded. It may therefore be considered a 'quality' factor (as above defined), which functions as a measure of the 'intensity of the biosphere support' to the product under study. The total solar emergy, U, driving a production process of a product, P, may be expressed as

$$U = \sum_i E_i \times \mathrm{Tr}_i = \mathbf{E_I} \times \mathbf{Tr_I} \quad i = 1, \ldots, n \tag{1}$$

where E_i is the exergy and Tr_i is the solar transformity of the ith input flow P_i, U is calculated over all the independent input flows (i.e. flows that are not originated by the same source) and $\mathbf{E_I}$ and $\mathbf{Tr_I}$ are n-dimensional vectors depending on the inputs to the process. The solar transformity Tr_i of the input P_i is in turn defined as follows:

$$\mathrm{Tr}_i = U_i/E_i = \sum_j \mathrm{Ei}_j \times \mathrm{Tr}_{ji}/E_i = \mathbf{E_J} \times \mathbf{Tr_J}/E_i \quad j = 1, \ldots, m \tag{2}$$

In Eq. (2), U_i is the solar emergy driving the production of P_i, while E_{ij} is the exergy and Tr_{ji} the solar transformity of the jth input flow contributing to P_i. This apparently circular definition is made operational by putting Tr_s, the solar transformity of direct solar radiation, equal to 1. Substitution of Eq. (2) in Eq. (1) yields

$$U = \sum_{ij} E_{ij} \times Tr_{ji} = \mathbf{E} \times \mathbf{Tr} \quad i = 1, \ldots, n; \; j = 1, \ldots, m \tag{1'}$$

where $\mathbf{E}$ is the matrix of all indirect exergy inputs supporting the production process and $\mathbf{Tr}$ the matrix of transformities that link each flow to the total emergy U.

The inputs E_i to a process can be locally renewable (R_i), locally non-renewable (N_i), or imported from outside the system (F_i; feedbacks supplied from outside to reinforce the process). Therefore, an equivalent form for Eq. (1) is:

$$U = \sum_i \mathrm{Tr}_i R_i + \sum_j \mathrm{Tr}_j N_j + \sum_k \mathrm{Tr}_k F_k \quad i = 1, \ldots, n; \; j = 1, \ldots, n'; \; \mathrm{k} = 1, \ldots, n'' \tag{1''}$$

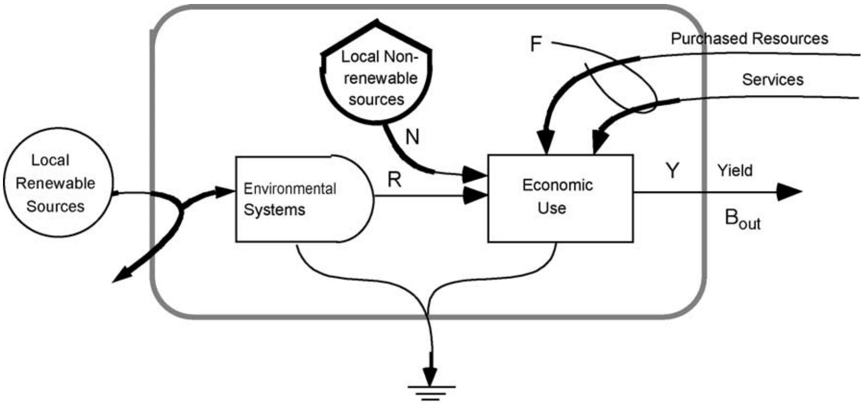
The total solar emergy, U, driving a process is assigned to the output (see Section 4.1.1), as a measure of the resource investment required.

The transformity of the output flow is, therefore (Fig. 1):

$$\mathrm{Tr}_{\mathrm{out}} = \frac{\text{total emergy } U \text{ driving the process}}{\text{available energy (exergy) of the output}} = \frac{\sum_i \mathrm{Tr}_i R_i + \sum_j \mathrm{Tr}_j R_j + \sum_k \mathrm{Tr}_k R_k}{E_{\mathrm{out}}}$$

The solar transformity is measured as solar emergy joules per exergy joule of product (seJ/J). Some flows cannot be easily expressed as exergy and therefore other emergy intensity factors are used (seJ/g, seJ/$, seJ/h, etc) instead of solar transformity. In so doing, all kinds of flows to a system are converted to the same unit (seJ of solar emergy).

According to the process efficiencies along a given pathway, more or less emergy might have been required to reach the same result. The second law of thermodynamics dictates that there is a lower limit



Yield (Y) = R+N+F
$\%_R$= Fraction Renewable = R/(R+N+F)
Emergy Yield Ratio = EYR = Y/F
Environmental Loading Ratio = ELR = (F+N)/R
Emergy Sustainability Index = ESI = EYR/ELR

Fig. 1. Diagram for the calculation of transformities. Symbols are explained in Fig. 6. *R*, *N*, and *F* indicate, respectively, renewable, non-renewable and purchased emergy flows into a process. E_{out} is the exergy content of the output (J). $Y=R+N+F$ is the total emergy assigned to the output as a measure of the environmental support needed (seJ). Finally, $Tr=Y/E_{out}$ is the transformity of the output (seJ/J).

below which a product cannot be made. There is also some upper limit above which the process would not be feasible in practice although, in principle, one could invest an infinite amount of fuel in a process and thus have an infinitely high transformity. Average transformities are used whenever the exact origin of a resource or commodity is not known or when it is not calculated separately. It follows that:

(a) Transformities are not constant nor have they the same value for the same product everywhere, since many different pathways may be chosen to reach the same end state.
(b) Emergy is not a point function in the way energy and other thermodynamic state functions are. Its value depends upon space and time convergence, since more emergy is used up over a pathway requiring a higher level of processing for the same product. The emergy value is a 'memory' of resources invested over all processes leading to a product. While the exergy content of a given resource indicates something that is still available, the emergy assigned to a given item means something that has already been used up and depends on the characteristics of processes converging to the product.
(c) Optimum performance for specified external constraints may be exhibited by systems that have undergone natural selection during a long 'trial and error' period and that have therefore self-organized their feedback for maximum power output. Their performance may result in optimum (not necessarily minimum) transformity.

Transformities are a very central concept in emergy accounting. Basic transformities of biosphere processes and primary resource formation have been calculated by Odum and his group [41,43]. Transformities of manufactured products are available in the scientific literature on emergy.

When a large set of transformities is available, other natural and economic processes can be evaluated by calculating input flows, throughput flows, storages within the system, and final products in emergy units. After emergy flows to and storages in a process or system have been evaluated, it is also possible to calculate a set of indices and ratios that may be suitable for system design and policymaking [11,12,30, 33,56].

2.3. Valuing resources within a common framework

Emergy provides indicators that expand the evaluation process to the larger space and time scales of the biosphere While the emergy approach is unlikely to be of practical use in making decisions about the price of food at the grocery store or about the way a process should be improved to maximize exergy efficiency at the process scale, its ability to link local processes to the global dynamics of the biosphere provides a valuable tool for adapting human driven processes to the oscillations and rates of natural processes. This may be a useful step towards developing sustainable patterns of human economies. Emergy measures thermodynamic and environmental values of both energy and material resources within a common framework. Transformities provide a quality factor as they account for the convergence of biosphere processes required to produce something. Embodied in the emergy value are the services provided by the environment, which are 'free' and outside of the money-based economy. By accounting for quality and free environmental services, resources are not valued by their money cost or society's willingness to pay, which often are very misleading.

3. Exergy

The word 'exergy' made its first appearance in an archival publication in the late 1950 [45][1], but the concept it subsumed was discussed already in Gibbs' and Maxwell's writings, where the idea that only a well-identified and measurable portion of the energy content of a body or of a stream can be transformed in mechanical work was put forth. In the works of Clausius, Gouy, Keenan, Bosnjakovic, Darrieus, Jouget and Gochstein (for a commented history of exergy, see [53]), direct mention is made of a thermodynamic function, named 'Available energy', or 'Availability', or 'Maximum Potential Work', defined for a homogeneous system in state 1 as:

$$\begin{aligned} e_1 &= e_{1,t} + e_{1,c} + e_{1,k} + e_{1,p} + e_{1,n} + \cdots \\ &= h_1 - h_0 - T_0(s_1 - s_0) + \sum_j [\Delta g_j + RT_0 x_j \ln(x_j/x_0,j)] + .5V^2 + g(z - z_0) + e_n + \cdots \end{aligned} \tag{3}$$

In Eq. (3), following a notation first suggested by Gaggioli and coworkers [13], the global specific quantity 'exergy' has been split into its constituents, i.e. its thermodynamic, chemical, kinetic, potential, nuclear…'components', each one of which can be exactly and deterministically related to the state properties of the system and to a reference 'environment', a macro-system that constitutes a sort of 'zero' reference to be maintained constant for the following calculations to remain congruent.

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[1] For the sake of conciseness, we must omit here the majority of the large body of references on 'exergy'. Interested readers are referred to [53], which contains the largest and most recent update on this topic.

For the sake of simplicity, we shall be concerned here only with the thermodynamic component, defined as:

$$e_1 = h_1 - h_0 - T_0(s_1 - s_0) \tag{4}$$

Eq. (4) clearly expresses the most important attribute of exergy (which was also its original philosophical novelty): for all practical purposes, *the amount of useful work that can be extracted from a certain system is not measured by its enthalpic content*, because in any real (irreversible) process a portion of that energy is devaluated by the unavoidable irreversible entropic degradation. Similar relations apply to the remaining components: *exergy represents the maximum work that we can extract from a system by means of ideally reversible transformations that bring it to a state of complete (statistical) equilibrium with its reference state*, sometimes called therefore the *dead state* (to underline the impossibility of extracting further work from a system in equilibrium with its surroundings). Conversely, the exergy of a substance in state 1 represents the minimum cumulative amount of work equivalent necessarily needed to 'raise' its energy level, both quantitatively and qualitatively, from the dead state to state 1.

It is impossible here in discussing the rich and interesting history of the development of the exergy concept (for a review, see [53]): it is though important to remark that the matter began to be systematically explored in the 1960 [15,17,18,22,25,26,40,49] and was first applied to the systematic design of energy conversion systems only quite recently, in the 1980, mainly due to the efforts of Gaggioli and others in the United States [1,4,28,38] and of Baehr, Schmidt (as quoted in [34,54]) and other European scholars [7,9,34,54,64]. For the purpose of the present paper, it is important to summarise the most important properties of exergy from the perspective of an Energy System Analysis:

(1) Exergy requires the definition of a reference state, which must be maintained fixed for all calculations to remain congruent;

(2) A system **S** in a state *A* (Fig. 2) can deliver a maximum amount of useful mechanical work equal to its exergy e_A; conversely, a system **S** in state *0* can be brought to state *A* by an expenditure

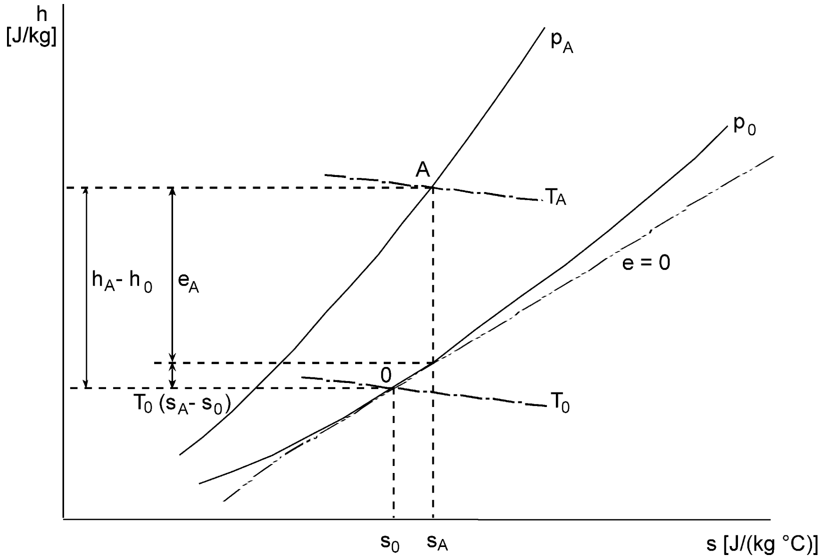


Fig. 2. Exergy definition on the s/T plane.

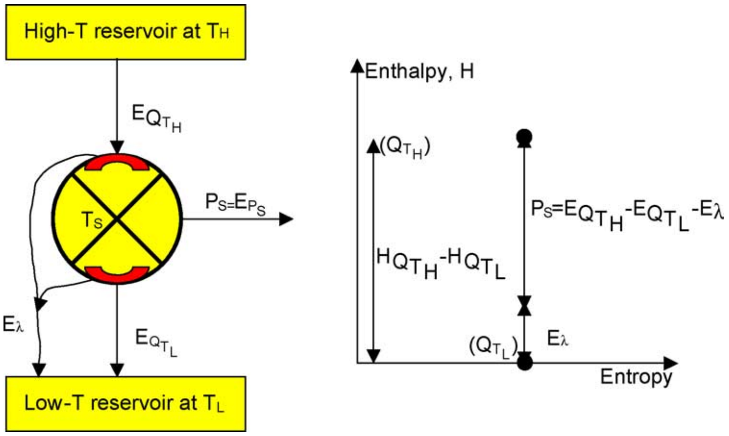


Fig. 3. Maximum work deliverable by a system S operating between two reservoirs at fixed end temperatures.

of mechanical work at least equal to (and for irreversible transformations always larger than) its exergy e_A;

(3) If a system **S** moves from state A to state B, the maximum work that can be extracted in the process is $e_A - e_B$; viceversa, the minimum amount of work to be expended to bring **S** from B to A is $|e_B - e_A|$;

(4) For the 'classical' case of an internally reversible system in thermal contact with two reservoirs, one at T_H and the other at T_L (Fig. 3), the maximum work that can be produced by a continuous process is affected by two types of exergy losses: one at the high end, proportional to $T_H - T_A$, and the other at the low end, proportional to $T_A - T_L$. This is of course nothing more than another statement of the Carnot 'limit' efficiency, and, incidentally, dispenses of all the considerable efforts required by the so-called 'finite-time thermodynamics' treatments;

(5) Exergy is additive: if a stream enters a process **P** with an exergy level e_1, and receives a contribution e_2 in a first component thereof, e_3 in a second component and so on, it exits **P** with an exergy equal to the net (i.e. subtracted of the irreversible exergetic destruction E_λ) sum of the single contributions (Fig. 4);

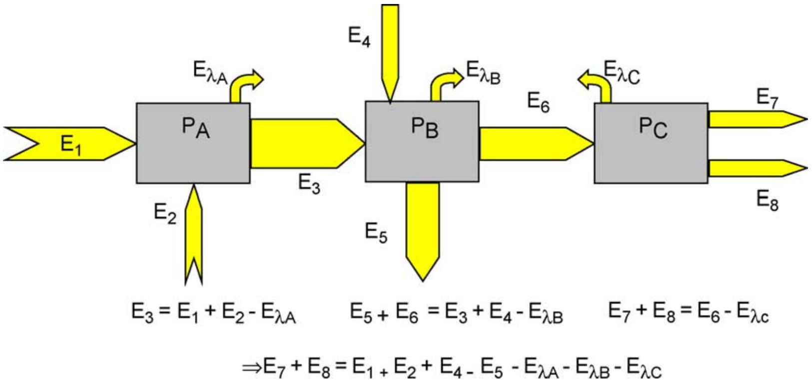


Fig. 4. The additivity of exergy.

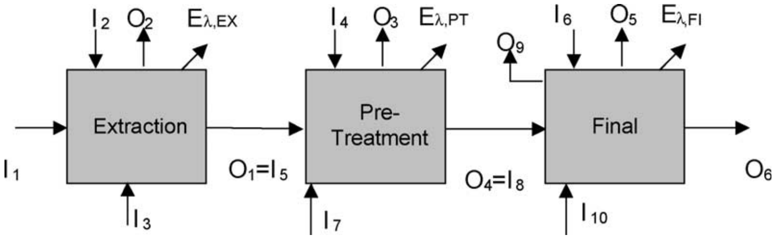


Fig. 5. Exergy 'embodiment' in a product.

(6) As a consequence of the previous point, a 'cumulative exergy content' for a complex process (Fig. 5) can be defined [54] as the sum of all inputs, normalized by the unit mass flow (or exergy content) of the product. By doing this, it is also natural to define the *exergetic efficiency of each sub-process as the ratio of the exergetic content of the useful output to the sum of the expended exergetic inputs* (or, to use Valero's terminology [57–59], of the *product* to the *fuel*);

(7) A material stream can thus be assigned an exergetic content simply by augmenting the initial value of the 'raw exergy' of the pristine input (the material as extracted from the Earth crust) by all the contributions it receives in the course of a specified process. Different databases have been compiled for such 'raw state exergy' values [1,54,60].

A vast bibliography exists on exergetic analysis of Energy Conversion Systems: it is fair to say that, in general, the method of exergy analysis has improved our understanding of the related physical phenomena in two ways:

(1) At a theoretical level, it resulted in the formulation of an internally coherent, exact, complete and methodologically correct procedure of analysis that generates a clear picture of both the qualitative (type and source) and the quantitative (relative amount) losses occurring in energy conversion processes;

(2) At a practical level, it provided the foundation for more complete and thermo-dynamically correct design methods, which have been proven by literally thousands of analytically comparative applications to known and new components and systems design.

In 1960s and 1970s, almost simultaneously and by independent investigators, the joint application of exergy analysis and engineering economics was proposed, under the name of *Exergo-Economics* (in Europe, [20,32]) and *Thermo-Economics* (in the US, [14,17,22,46]). The basic idea of this method is to apply the usual procedures of Engineering Accounting, linking the prices of components to their operating parameters and to their exergetic efficiency, and pricing not the unit mass, but the specific exergy content of a stream (material or energy). Thermo-Economics (the word was first used by Myron Tribus in his MIT lectures) has been systematised mainly by El-Sayed, Evans, Valero, and Tsatsaronis. An extension to explicitly include into the accounting a modelled set of environmental externalities has been proposed by Frangopoulos and von Spakowski in [19]. Further extensions, to account for unsteady operating conditions and to include life-cycle effects have been proposed in [19] and [54], respectively.

In parallel, studies about the exergy flows in Very Large Complex Systems, like societal Sectors and entire Nations, have been performed [16,37,47,48,54,64,65]: their main goal was that of exploring the resource-to-end-use efficiency of these large systems, and to compare different types of organisations and societal standards [51].

Most recently, an extension of Szargut's Cumulative Exergy Content Method has been proposed [52], in which all externalities are accounted for in exergetic terms: the result is a sort of 'extended Thermo-Economics', which has been properly named Extended Exergy Accounting. Some attention has been given to exergy issues also from a more biologically oriented perspective: thus, Jorgensen and Fath [31] introduce a sort of structural exergy (with the absolute equilibrium as a reference state) designed to account for the internal organization of living organisms. Though this type of approach may have important implications in our understanding of 'ordered' life structures, further experimental proofs are still needed, and a full discussion of this method is outside of the goals of the present paper.

4. Emergy and exergy flows through a system

4.1. Procedure for emergy accounting

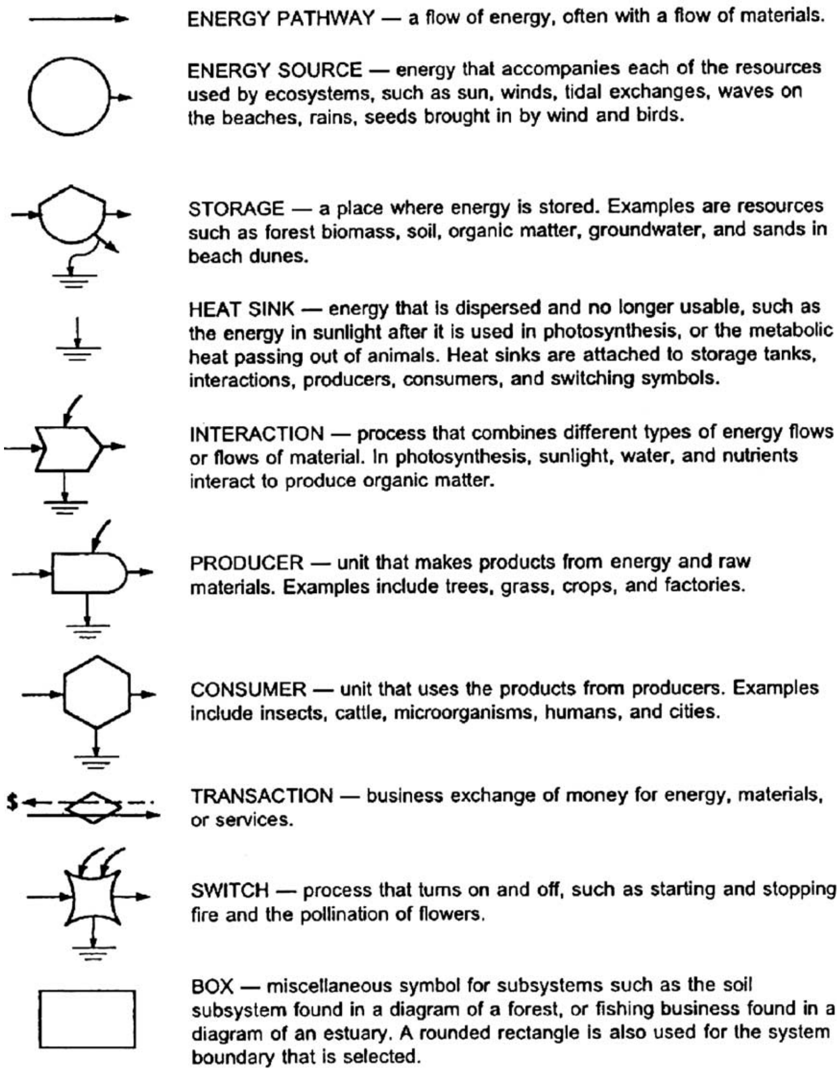
The general methodology for emergy analysis is a 'top-down' systems approach. It can be organized in three steps, as described below. Case studies with numerical examples can be found in [12,30,33,43]

The first step is drawing a detailed energy systems diagram, to gain an initial network overview, combine information, and organize data-gathering efforts. Diagrams must be considered as a 'guide' to organizing one's thinking of the relationships between components and pathways of exchange and resource flow. This is achieved by:

(a) Defining the boundary of the system for a correct inclusion of input flows
(b) Listing the main components believed important on the investigated scale.
(c) Knowing as many possible details about the processes occurring within the boundary (flows, relationships, interactions, production and consumption processes, etc.). Included in these are flows and transactions of money and labor believed to be important.
(d) Drawing the system diagram of the whole system, by means of the symbols described in Fig. 6 (flow addition, interaction, positive or negative feedback, depreciation, etc.). A second system diagram is often drawn that represents an aggregated overview of the system under study. Processes and storages are aggregated to reduce complexity, while retaining overall system integrity and aggregation. Fig. 7 shows an aggregated energy systems diagram of ethanol production from corn. Fig. 8 shows a more detailed diagram of the industrial steps for processing corn to ethanol.

The second step is to construct emergy evaluation tables directly from the diagrams, to facilitate calculation of flows to and from the system. This also permits the identification of the flows of co-products from each phase, some diverging, feeding back and converging within the process, and helps avoid double-counting (see Section 4.1.1). Raw data from preliminary material and energy flow accounting are entered as input flows. They are usually expressed as joules of exergy then they are multiplied by suitable transformities and converted to emergy units. Finally they are summed into a total emergy inflow driving the system. A table for storage reservoirs is also often constructed to place in perspective the emergy content of major system components.

An emergy analysis table usually has the following column headings (Table 1).



ENERGY PATHWAY — a flow of energy, often with a flow of materials.

ENERGY SOURCE — energy that accompanies each of the resources used by ecosystems, such as sun, winds, tidal exchanges, waves on the beaches, rains, seeds brought in by wind and birds.

STORAGE — a place where energy is stored. Examples are resources such as forest biomass, soil, organic matter, groundwater, and sands in beach dunes.

HEAT SINK — energy that is dispersed and no longer usable, such as the energy in sunlight after it is used in photosynthesis, or the metabolic heat passing out of animals. Heat sinks are attached to storage tanks, interactions, producers, consumers, and switching symbols.

INTERACTION — process that combines different types of energy flows or flows of material. In photosynthesis, sunlight, water, and nutrients interact to produce organic matter.

PRODUCER — unit that makes products from energy and raw materials. Examples include trees, grass, crops, and factories.

CONSUMER — unit that uses the products from producers. Examples include insects, cattle, microorganisms, humans, and cities.

TRANSACTION — business exchange of money for energy, materials, or services.

SWITCH — process that turns on and off, such as starting and stopping fire and the pollination of flowers.

BOX — miscellaneous symbol for subsystems such as the soil subsystem found in a diagram of a forest, or fishing business found in a diagram of an estuary. A rounded rectangle is also used for the system boundary that is selected.

Fig. 6. Symbols used in systems diagrams according to Odum [42].

If the table is for flows, it represents flows per unit time (usually per year). If the table is for reserve storages, it includes those storages with a turnover time longer than one year. Dynamic models for storage variation may also be constructed and run [44].

- Column A is the line item number, which is also the number of the footnote in the table where raw data source is cited and calculations shown.
- Column B is the name of the item, also shown on the aggregated diagram.
- Column D is the raw data in joules, grams, dollars or other units, that are shown in column C. Labor inputs are usually given in working time units (years, hours), while services (previous work done to deliver the input flow) are evaluated through the money cost of each flow.

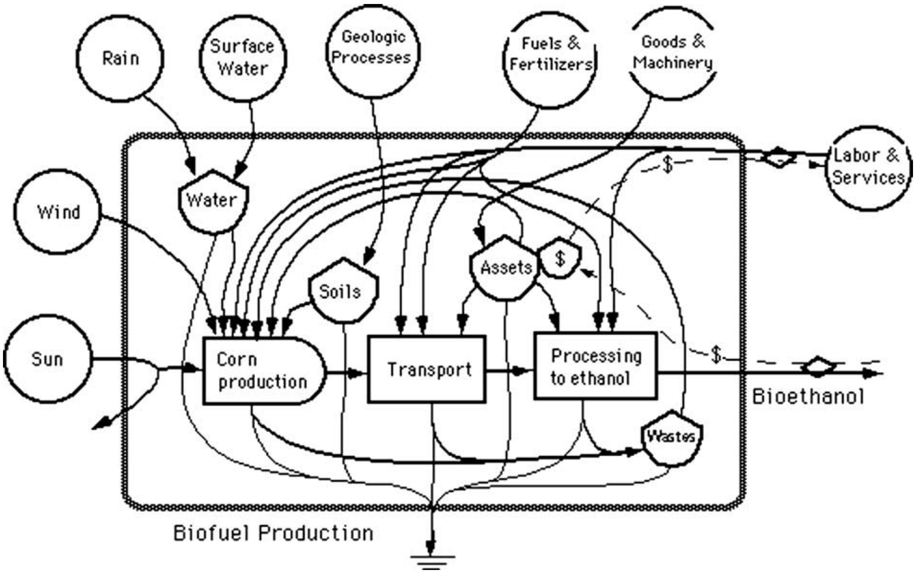


Fig. 7. Diagram of corn production and processing to ethanol. The main steps of the process as well as the main flows driving the system are shown. Flows of degraded energy are also shown as exiting downwards to the heat sink. The flows of agricultural residues fed to the ethanol plant as well as DDGS (Dry Distillation Grains with Solubles), respectively co-produced with corn and ethanol, are not shown, but accounted for in the evaluation.

- Column E is the transformity, or the emergy per unit, used for calculations, in solar emergy joules per unit of raw input (seJ/J; seJ/g). These are obtained from previous studies cited in literature or calculated for the system under study. Converting labor and services into emergy units requires conversion coefficients, C_{lab}, C_{econ}, calculated by means of a previous emergy analysis of a country's economy, for a given year ($C_{\mathrm{lab}}=\mathrm{U/work\ force}$; $C_{\mathrm{econ}}=\mathrm{U/GNP}$). If transformities from other authors are used, source reference should be shown in column F.
- Column G is the solar emergy of a given flow, calculated as raw input times its transformity (column D times column E).

Finally, when the emergy tables have been completed, a third step involves calculating several emergy indices that relate emergy flows of the process or economy with those of the environment, and allow the evaluation of a system's performance as well as predictions of economic viability and carrying capacity.

4.1.1. Emergy algebra

For its special characteristics of being a 'memory' of the exergy invested over the entire process chain, the emergy accounting requires suitable algebric rules, i e. a 'memory algebra' as opposed to the ordinary 'conservation algebra'. The main rules of Emergy Algebra [10,50] are:

(1) When only one product is obtained from a process, all source-emergy is assigned to it.
(2) When a flow splits (originating flows showing the same physico-chemical characteristics), the total emergy splits accordingly, based on the exergy flowing through each pathway.

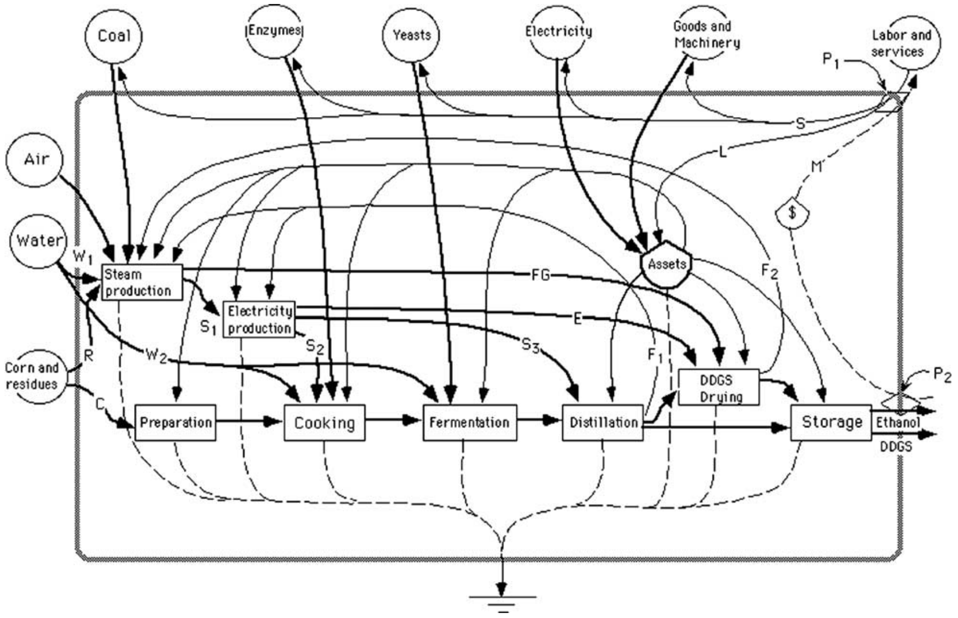


Fig. 8. Detailed flow diagram of the industrial conversion of corn to ethanol. Feedback flows of recycled energy and matter from higher to lower steps are shown. Flows of degraded energy are also shown as exiting downwards to the heat sink. Assets include plant structure (machinery and building, discounted over lifetime) and operation inputs (electricity and labour supplied to plant). A proper fraction of the capital investment is assigned to each process step. *C*, corn fed to the ethanol plant; *R*, agricultural residues fed to the boiler for process heat; W_1, process water for steam production; W_2, W_3, cooling water supplied to the Cooking and Fermentation steps; S_1, high-pressure steam for electricity production; S_2, S_3, low-pressure steam supplied to the Cooking and Fermentation steps; *E*, electricity produced within the plant and used for DDGS drying; FG, flue gases co-produced with steam and used for DDGS drying; F_1, low-pressure water condensate fed back to the Steam Production unit; F_2, hot gases fed back to the Steam Production unit; *L*, labour flux into the process; *S*, services, i.e. labor previously performed for the production and supply of resources and goods used in the process; *M*, monetary flux against the product flow; P_1, purchase price of labour and services; P_2, sale price of ethanol and DDGS.

(3) When two or more co-products (i.e. product items showing different physico-chemical characteristics, but which can only be produced jointly) are generated in a process, the total source-emergy is assigned to each of them. This is because each of them cannot be produced without investing the whole emergy amount.

(4) Emergy cannot be counted twice within a system:
  (a) emergy in feedbacks should not be double counted;
  (b) co-products, when reunited, cannot be summed. Only the emergy of the largest co-product flow is accounted for.

Table 1
A typical emergy accounting table

A	B	C	D	E	F	G
Note	Item	Unit	Amount	Transformity (seJ/J)	Ref. for transformity	Emergy (seJ/yr)
1	CH_4	Joule	···	54,000	[42]	$=D1\times E1$

Under no circumstances should the emergies of the co-products from a process be added together. It would be a violation of rule 4, a double-counting of emergy. Rule 3 creates some confusion at first glance, since it appears that more emergy is output from a process than is input, thus violating the Conservation Law of Thermodynamics. Rule 4 helps avoiding further misunderstandings. However, we already pointed out that emergy is not energy and therefore needs not to be conserved in the way energy does. Giannantoni [23,24] recently developed a mathematical approach and formalism for the emergy algebra, aimed at highlighting the generative processes that make new structures and information to emerge out of less structured inputs. This approach, based on phenomenological data as well as on the assumed uniqueness of the generative process, describes the internal structure of a system in terms of so-called 'incipient' fractional derivatives (an innovative version of the traditional fractional calculus). When this different formalism (equivalent in principle to the previous one) is used, the seeming violation of the Conservation Law is removed.

4.2. Procedures for exergy accounting

4.2.1. Exergy analysis

Exergy Analysis (EXA) requires a procedure very similar in its structure to the one outlined in Section 4.1 above Its basic articulation is as follows (case studies with numerical examples are given in [1,3,5,9,20,22,34,38,54]:

(a) Define the control volume to which the analysis is to be applied. This volume must include the immediate surroundings of the system ([39], see also Section 4.2.3)

(b) Draw a detailed flow chart of the system under consideration, paying particular attention to the proper level of aggregation at which the representation is made. An excessive disaggregation (too much detail) requires more extensive calculations and demands for very detailed data, often not available in practice. An excessively low disaggregation causes the 'lumping' of possibly dissimilar data into a single input or output, invariably leading to the (implicit or explicit) formulation of assumptions that may detract from the reliability of the analysis

(c) Construct a library (or use an existing one) of the components chosen to represent individual processes $\mathbf{P_j}$. For each $\mathbf{P_j}$, identify incoming and outflowing fluxes of mass and energy, separating where possible 'necessary' from 'accessory' inputs and 'useful products' from 'secondary' and 'by-products'. For example, in a Boiler, the combustion air is a necessary input while the bottom ash discharge is an accessory (non-useful) output. In a Gas Turbine, the shaft power is a useful product and the hot exhaust gas, if not used for heat recovery, a by-product.

(d) Identify the thermodynamic state of all fluxes, and quantify their relevant properties (temperature, pressure, enthalpy, entropy, composition and concentration, chemical potentials, etc.)

(e) Perform a mass and energy balance, first at component level and then at system level (too often the two are not consistent). Iterate until exact closures are obtained.

(f) Perform an exergy 'balance' of each component to compute the exergy destruction. Extend to system level. The calculation flowsheet will in general comprise the headings shown in Table 2.

(f) Compute the relevant efficiencies and exergetic costs.

Table 2
Example of exergy analysis flowsheet

Flux	From unit	To unit	T (K)	p (MPa)	T_o (K)	h-h_o (kJ/kg)	s-s_o (kJ/(kg K))	x or c (moles)	Exergy (kJ/kg)	Notes
I	P_f	P_t	300	0.1	288	132	0.15	1 O_2 + 3.76 N_2	88	Air

4.2.2. Thermo-economic analysis

A Thermo-Economic (TE) Analysis requires additional data. Table 2 must be now complemented with another flowsheet that contains the necessary economic database. The goal is to calculate the operating costs pertaining to each component and to allocate them to each stream. An example is provided in Table 3.

(a) The costs pertaining to the operation of each component are now apportioned among the N fluxes, resulting in a monetary costing of the total exergetic content E_n of each flux. Proper rules apply to ‘co-products’ and ‘co-fuels’ [5]: the general idea is to ‘charge’ a stream with a certain cost only if the unit to which this cost pertains has as a goal the increase (or decrease) of the exergy content of that stream [5,55,57].
(b) Perform a cost balance of each component to compute the exergy cost of each stream. Extend to system level (possible iterations are required here).
(c) Compute the relevant unit (in €/J) and global (€/s) production costs.

The *conversion efficiency* of **P** can be computed as the ratio of the exergy of the useful output to the sum of the exergetic inputs that concurred to produce it:

$$\varepsilon_P = \frac{E_{O1}}{\sum_j E_{I,j}} \tag{5}$$

The *exergetic cost of* the output is defined as the total monetary equivalent of the required exergetic input divided by the useful output:

$$c_P = \frac{\sum_j C_{I,j}}{E_{O1}} \tag{6}$$

It can be shown formally [57–59] that:

(a) a compact symbolic representation exists for any conceivable process structure, provided the dimensional homogeneity of inputs and outputs is maintained;

Table 3
Additional economic data flowsheet for thermo-economic analysis

Unit	Power factor (h/8760)	Capital (k€/yr)	Maintenance (k€/yr)	Raw materials (k€/yr)	Labour (k€/yr)	Energy (k€/yr)	Decommissioning (k€/yr)	Other (k€/yr)
1	0.75	500	50	500	400	250	75	100

(b) splits, junctions, recycles and feedbacks can be also handled symbolically, so that proper generalizations of equations 4 and 5 are always computable in closed form.

In the above, we have implicitly expressed the exergetic fluxes in J/s: in industrial engineering studies, it is often convenient to normalise these fluxes with respect to the unit mass flow rate of useful output. If there is more than one product, the mass flow rate (or the exergetic rate in the case of mechanical or electrical work) of the 'main' output can be taken as the normalising quantity. From now on, therefore, we shall deal with specific exergetic contents, expressed in J/kg (in J/J for non-material fluxes).

The procedure may be easily extended to complex chains of technological processes, and can be easily nested as well, i.e. applied at different levels of aggregation in a productive structure [3].

4.2.3. Extended exergy accounting

It is possible to 'internalize' the non-energetic production factors corresponding to Labour and Financial expenses, if we attach an *exergetic equivalent* to the unit of monetary circulation This is really the essence of EEA, the formalism of which is described in detail elsewhere [52]. There is only one additional independent datum that must be inserted in the database: the equivalence factor K_{cap} between capital and exergy fluxes. This is a case- and time dependent coefficient, equal to the ratio between the total exergetic influx in a given Society in a certain year and the corresponding monetary circulation (notice that no reference to the GNP is made here). The calculation proceeds along the same steps as for Thermo-Economics, with the important difference that we can formulate now a transfer function Π that relates only exergetic quantities. In the representation of Fig. 9, Π takes the form:

$$\mathbf{EE}_O = \Pi \times \mathbf{EE}_I + \mathbf{A} \times \mathbf{EE}_O \Rightarrow \begin{vmatrix} EE_{O1} \\ EE_{O2} \\ EE_{O3} \\ EE_{O4} \end{vmatrix} = \Pi \begin{vmatrix} EE_{I_1} \\ EE_{I_2} \\ EE_{I_3} \end{vmatrix} + A \begin{vmatrix} EE_{O1} \\ EE_{O2} \\ EE_{O3} \\ EE_{O4} \end{vmatrix} \tag{7}$$

where the matrix P is the 'process transfer function' and the matrix A contains the allocation coefficients, similar (but not necessarily equal) to those used in TE. Notice that, due to the unavoidable exergy destruction $\mathbf{E}_\lambda$, $\mathbf{EE_O} - \mathbf{EE_I}$ is always negative (i.e., $\mathbf{EE_O}$ is 'charged' with the sum of all of the process physical irreversibilities). The *conversion effectiveness* of $\mathbf{P}$ can be computed as the ratio of the extended exergy of the useful output to the sum of the exergetic inputs that concurred to produce it:

$$\varepsilon_P = \frac{EE_{\mathrm{O1}}}{\sum_j EE_{\mathrm{I},j}} \tag{8}$$

The *extended exergetic cost of* the output is simply the reciprocal of the effectiveness, and it represents the cumulative amount of exergetic resources expended in the fabrication of the product:

$$c_P = \frac{\sum_j EE_{\mathrm{I},j}}{EE_{\mathrm{O1}}} \tag{9}$$

The compact symbolic representation is valid also in this case, though the splits and junctions are handled in a slightly different way [52]: thus, also Eqs. (8) and (9) are always computable in closed form.

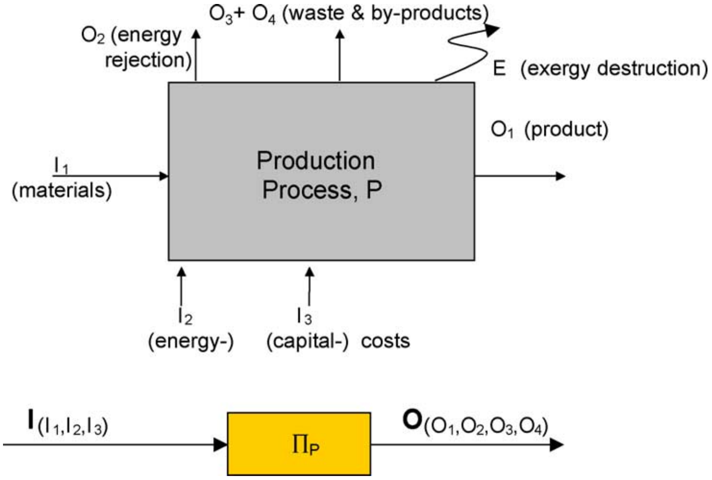


Fig. 9. The concept of ‘process transfer function’.

5. A critique of emergy from an exergist point of view

5.1. Critique

Two fundamental objections can be raised against the emergy approach: first, it is essentially a first-law method, and second, its value scale (the so-called transformities) are difficult to calculate as they represent, at most, well-educated guesses. Let us expand these two points.

(A) In its original formulation, emergy was defined as the ‘cumulative amount of calories (or joules) of one kind of *energy* required to make those of another’ [41], {italics added}]. In spite of the ‘exergetic’ reformulation presented in Section 2.1, it is clear both from the remaining of that Section and from an analysis of the actual flowsheets employed in EMA that it is the energy, and not exergy, content of a stream the quantity that matters. Actually, emergy algebra rules prescribe that ‘calories of different kinds {i.e., pertaining to different energy carriers, note by ES} be not added’ [41]: but this is scarcely a Second Law approach. In all applications, leaving aside the emergy jargon, it is clear that the inputs to a system are accounted for on a *purely energetic basis* (no entropy contribution is considered). Different forms of energy flows are in fact accounted for by their transformities, defined as ‘the energy of one kind required to be transformed to make one unit of energy of another kind’ [41]. Again, there is no Second Law concept here: 1 W of heat flux can be added to 1 W of mechanical work only after they have been converted to a common basis on the ground of a backward-tracing process that ends (correctly, from an energy balance point of view) in the original amount of solar influx. But nothing is said about the intrinsic[2] non-equivalence of two amounts of emergy, expressed by the same number of emJoules, but pertaining to different energy carriers (say, heat Q and work W). Trying to quantify the above, we see that, if the transformity of heat is 10^6 seJ/J and that of work 10^9 seJ/J, then a process P_1 whose inputs are

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[2] To prevent a counterargument that is frequently brought up by emergy supporters, this point needs to be clarified. The fact that Q and W may come from different sources, and have therefore different transformities and consequently different seJ values, is not relevant to the issue here: if both were generated by the same fuel cell, they would have the same transformity, but not the same exergy. This is the meaning of the word ‘intrinsic’ in the above statement.

1 W of heat at 300 K and 1 W of mechanical power has a total emergetic input equal to (10^6+10^9) seW. But a process P_2 with inputs of 1 W of heat at 700 K and 1 W of mechanical power will also have a total emergetic input equal to (10^6+10^9) seW. Furthermore, a process P_3 whose inputs are 10^3 W of heat at 300 K and 10^{-3} W of mechanical power will also have the same emergetic input, as long as the transformities remain the same! The issue here is clearly that the Second Law non-equivalence of heat and work is not 'embodied' in the emergy concept.

(B) It may appear that the transformity plays the same role in EMA as the Carnot factor in EXA and of the unit exergy cost in TE. But this is not correct, because very few of the published transformities have been calculated from physical energy balances. The truth is, most transformities are estimated on the basis of *global* emergy balances! Therefore, the system is clearly circular, and the numerical results are heavily affected by the internal system of value-exchange chosen by the analyst, which is completely opaque to the non-specialist reader.

(C) Using as a starting point a statement by Odum that "calories of energy of different kinds are not equivalent in their contribution to useful work" [41,42], some Emergists have claimed that what is really 'embodied' in emergy is available energy, i.e. exergy, and that all of their diagrams ought to be regarded as 'embodied exergy' flow charts. This would make EMA somewhat similar to Szargut's CEC. There are though two fundamental differences:

(i) in CEC, no assumption is made about an 'intrinsic exergetic value' of raw materials. The specific exergy of an ore is *calculated* by means of a simple and closed formula that makes reference to a conventional 'Earth crust equilibrium state' exactly defined by a finite set of state parameters. In EMA, the transformity of an ore is *estimated* on the basis of the assumed contribution to its formation provided by solar irradiation over the geological formation time. With all due respect to the geo-physicists' methods, the values obtained by such an evaluation are hardly 'exact' and universally accepted.

(ii) In CEC, every contribution to the product formation is assessed in terms of its exergy. This means that, roughly speaking, 1 W of heat flux from a natural source at T_1 is assigned an exergy content of $(1-T_0/T_1)$ W. In EMA, the same W is assigned a transformity much higher than 1 (10^4–10^7, depending on the source). There is no a priori assurance that the relative ratios between transformities scale proportionally to their exergetic ratios.

(D) Two of the original claims of EMA are though interesting for exergy analysts as well, and their merits ought to be acknowledged. They are:

(i) The recognition that 'the buying power of money circulation in a society is supplied by the use of a certain quantity of emergy' [41,43]. This is a very important statement in view of Thermo-Economics and especially of Extended Exergy Accounting. The latter has in fact incorporated the EMA statement, reformulating it in terms of exergy: 'the monetary circulation in a Society is supported by, and therefore entirely equivalent to, the total exergetic influx of resources into that Society' [52]. This idea is absent both in CEC and in Thermo-Economics, and represents a major deviation from the presently dominating paradigms of Neo-Classical Economic theory.

(ii) The emergetic transformity of Labour is set equal to the total *pro-capite* emergy consumption in a certain Society. Neither Thermo-Economics nor CEC account for this quantity on an energy-basis. EEA has again borrowed this concept from EMA: in fact, the extended exergy algebra implies that the exergetic equivalent for Labour is proportional to the net *pro-capite* exergy consumption in that Society.

5.2. Counterarguments

(A) Emergy was never defined in terms of ‘energy’ required to make something, but instead always in terms of ‘available energy’ or ‘availability used up’ [42,43] Some analysts actually use energy instead of ‘available energy’ amounts when the difference between the two measures is small or negligible. Inputs to a process are not added on a purely energetic basis (First Law accounting). They are multiplied by transformities, which properly account for the entropy production over the whole chain of processes that generated each input. Therefore: (a) by measuring input flows by means of their exergy (availability) content, emergy calculations acquire a ‘built-in’ ability to account for process scale entropy production; (b) by integrating exergy inputs over time and space for the calculation of transformities, natural trial-and-error processes are also considered, thus taking into account the production of entropy during the ‘metabolic’ pathway(s) leading to the final product through a set of intermediate steps.

Since each input flow is multiplied by its ‘form’ transformity (usually ‘solar’), inputs are all expressed in terms of their ‘solar emergy content’ and therefore are equivalent from the ‘donor-side’ point of view, in the same way all exergy flows are (correctly) claimed to be equivalent from the user-side point of view (the mechanical work that can be extracted from the item).

It is not true that two heat flows characterized by the same power and different temperature have the same emergy content. Generating a heat flow at higher temperature (700 °C instead of 300 °C) requires a higher emergy input (more fuel and materials), which translates into a generally different transformity for the flow at 700 °C ($U_{700}/E_{700}=\mathrm{Tr}_{700}\neq\mathrm{Tr}_{300}=U_{300}/E_{300}$). Transformities do not remain the same, nor they need to, since they are system and technology specific. The same amount of heat at the same temperature might be generated by using different amounts of natural gas or coal, which could translate into a different transformity for the same exergy output.

Finally, rule 3 of the emergy algebra also applies to the production of electricity and heat from the fuel cell in footnote (3), which translates into different values of the transformities, as a consequence of the different exergy of the co-products. Transformities give therefore a clear measure of the intrinsic non-equivalence of two emergy flows (negated in Section 5.1.A) as well as of their role within the larger system where they are supplied or used.

(B) Transformities of global scale environmental flows (rain, wind, deep heat, waves, tides) are calculated as averages, referring to global scale data that are assumed to be relatively constant over time (insolation, heat transfer through the earth crust, etc). This is the same kind of assumption (‘conventional reference state’) that exergy analysts do for their specific exergy evaluations of minerals. Incidentally, there is an ongoing debate about the ‘proper’ reference state among exergy analysts [54,60,61], although there is a general agreement that a conventional reference state is needed there as well.

Global transformities are then used to calculate the transformities of minerals (based on geological data) [8], biomass (based on net primary productivity and ecological data, also on local scale), fossil fuels (again based on local and global data), etc. Finally, all these inputs support the multiplicity of economic processes, whose products have transformities that depend on the location, the technology used, the system in which the process is embedded. The procedure for transformity calculation (reported in Sections 2.1 and 2.2) may appear unclear to a non-specialist reader, but this is true for every field of science. Of course, some transformities may be affected by insufficient knowledge of the process dynamics and depend on the progress of technology. Therefore they need to be revised when significant technological changes occur.

(C) A reply to this criticism was already partially given in the above reply to A. In addition:

(i) Transformity is a measure of unit environmental support, i.e. a unit 'cost factor'. Its calculation depends heavily on the system it is applied to, but also accounts for and embodies environmental support and selection dynamics that cannot be known exactly. Nobody knows exactly the parameters that characterize the environmental dynamics and, therefore, a certain amount of uncertainty cannot be avoided when the scale is expanded. A significant literature is available on 'post-normal science' [2,21], a new way of looking at systems dynamics (be they forests, regions, or whole economies) taking uncertainty into account, as opposed to 'normal science', based on 'exact', linear relations that only apply at local scale. When the scale is expanded, higher order terms and perturbations may become predominant, so that the system dynamics is no longer linear and uncertainty grows. Some methods cannot be made exact, because this is not the goal for which they have been developed. In addition, although being exact on the process scale is a worth effort, the reference to a conventional Earth crust level that does not actually exist in nature (as exergy does) makes results only applicable at the local scale and completely uncertain and unreliable when the scale is expanded (to involve regions, economies and the biosphere). Ecology and Economy are not exact sciences, since they involve large-scale dynamics and sudden pulses (population trends and individual preferences, selection processes, etc). Bank accounting is exact, but only applies within the Bank circuit. The same applies to exergy. It is extremely useful at process scale, but cannot be expanded to address environmental problems, unless it accepts to deal with uncertainty and natural selection. If this happened, emergy and exergy cost methods would converge. Sciubba's extended exergy represents, for several reasons, a step forward. As far as the 'exact' calculation of the transformities of minerals is concerned, they are not 'simply' based on the assumption that geological cycles are driven by solar exergy. Mineral cycles are the result of the complex coupling of earth convective motion driven by deep heat and by surface phenomena (weathering, transport of sediments by rivers, etc), the latter driven by solar exergy [8,43]. The present knowledge about these phenomena is taken into account for transformities calculation, although it cannot be excluded that calculated values may be replaced by more accurate ones, based on new knowledge, when available.

(ii) True. The higher values account for the exergy expenditures over the whole time and spatial scales involved. Consider photosynthesis, whose energy efficiency is only about 0.1%: this means that 1000 J of solar energy are needed for 1 J of biomass. Crude oil is biomass converted to reduced carbon over millions of years, which lowers the efficiency to levels that explain why it takes about 54,000 J of solar exergy to yield 1 J of crude oil exergy. Since natural processes have variable rates and efficiencies, it is impossible to assume any 'a priori' proportionality between transformity and exergetic ratios, due to the evident non-linearity of natural phenomena on the larger scales.

(D) The restatement in exergy terms of the fact that the economy is supported by a resource influx still leaves out the recognition of the environmental support that generates that exergy influx, and therefore does not account for the environmental services that actually support the economy (generation of inputs, dispersal and recycle of pollutants, i.e. the environment as a source and as a sink). It is though a step forward in the direction of a possible convergence of the two approaches.

6. A critique of exergy from an emergist point of view

6.1. Critique

- *Quality* Measuring flows in exergy terms only accounts for one aspect of quality, i.e. the amount of mechanical work that can be extracted from a given resource. While this is perfectly acceptable at the local scale of an energy system, it clearly appears that other kinds of flow (information, culture) are also driving forces of natural societies but cannot be adequately accounted for in exergy terms. An engineer does less mechanical work than a thermal engine. The fuel the engineer uses (food) contains less exergy than the oil driving the machinery. Notwithstanding this, the role of the engineer in the global performance of a power plant is not negligible and cannot be denied. The assessment of the local performance (efficiency, atmospheric emissions) of a power plant does not require to know anything about the engineer who works for it. Instead, the larger scale planning involving economists, government and people requires the indirect flows supporting both the formation of the engineer and the abatement of pollutants to be accounted for as necessary inputs without which also the local scale process would not occur. Emergy analysts calculate the transformities of each flow as described in Section 4 (be it the electricity produced by a power plant or the engineering graduate ‘produced’ by a University), to account for the total support required. Generating, testing, copying and disseminating information also requires emergy inputs to be invested in the process, although quantifying the product is more difficult. The problem here is that information flows (newspapers, TV broadcasting, University formation, etc) carry a small exergy but require a huge emergy in support of their existence.
- *Algebra*. Exergy accounting assigns the total exergy input to the outputs in proportion to their exergy content. In so doing, an ‘exergy cost’ defined as ‘exergy allocated to one unit exergy of the product’ is calculated. This cost comes out to be the same for each different product, when measured as J/J. It would be different, of course, if measured as J/g, but would lose any meaning, since grams of different products do not indicate much about their nature. Therefore, co-products characterized by very different physical characteristics (cogenerated electricity and hot water) would have the same exergy cost and production efficiency. Instead, since the total emergy driving a process is assigned to each of the co-products as explained in Section 4.1.1 (rule 3 of emergy algebra) the transformities (total emergy/exergy of item) may come out very different due to the different exergy content of the products, in so expressing their quality: different position in the thermodynamic hierarchy of the biosphere, different efficiency, etc).
- *Driving forces*. Fuels and materials are not the only driving forces of a system performance. No system can operate without environmental inputs and services. These should be accounted for if the analysis is to represent a real step ahead relative to Neoclassical Economy. Environmental inputs may be direct (e.g. solar radiation driving photosynthesis)) and indirect (labor and services, goods, materials, fuels). Accounting only for commercial input flows, as exergy does, stops the evaluation at the interface between oil companies and the rest of society. Weighting input flows by means of their exergy is not enough to ascertain their real ability to drive a process, by adjusting its speed to the ‘speed’ of the whole system.
- *Thermodynamics*. Both EXA and EMA are rooted in thermodynamics. However, when an analyst tries to describe economic processes, other non-thermodynamic factors need to be taken into account. Thermodynamic analyses cannot be the only bases for policy, nor may they lead to a new theory of

economic value. They can, instead, do something that is much more important. In addition to providing a biophysical basis for economic descriptions, they may help to expand the scope of economics, away from a single numeraire or standard of evaluation toward systems thinking and a multi-criteria framework [36]. From this point of view both exergy and emergy accounting need to perform a step ahead, towards integration with other approaches and systems of value. Instead, trying to refine the exergy or the emergy approach in the hope of making them more comprehensive also outside of their field of definition is not a step ahead, and may lead to useless efforts and loss of possible synergies.

6.2. Counterarguments

(a) Quality

It is outside of this author's capability to assess whether 'cultural' and 'biological information' are factors indeed expressed by EMA But it is not irrelevant that we clearly and unambiguously recall that:

(I) EXA *per se* cannot (and never claimed to) include in the analysis factors external to thermodynamic considerations (creativity, consumers' preference, architectonic or environmental pollution, etc.). If such factors are to be considered, LCA or other multi-criteria methods are definitely more appropriate tools. If we want to restrain our analysis to the production factors it is though undeniable that cultural and informational content of a technology cannot be expressed in terms of thermodynamic quantities. Thus, either EMA rejects this view, thereby denying the possibility of a direct methodological comparison, or accepts it, acknowledging that not all 'economic value' factors are amenable to a thermodynamic description.

(II) Both TE and EEA, on the other hand, are capable of internalising the so-called non-energetic factors: TE does this by assigning a monetary cost to the exergy flows, and EEA by converting the externalities into equivalent exergetic content. Thus, Labour, Services, Capital, Transportation, etc. costs are indeed included in TE: there are formulations [19] capable of internalising environmental impact. In EEA, all of the above is systematically internalised. Thus, it is not correct to claim that exergy analyses do not properly account for the global amount of 'resources' invested in a commodity.

(III) As for the claim that information content, flexibility and technological level can be expressed in terms of emergy, there is yet no valid proof that an EMA performed on a realistic system may indeed rely some useful information on these additional production factors.

(b) Algebra

It is incorrect to say that 'products with very different physical characteristics' have 'the same exergy cost and production efficiency'. The exergy input E_{in} (detracted of the losses E_{λ}) is split between the outputs of a process: if there are only two outputs, the balance provides $E_{\text{in}}-E_{\lambda}=E_{\text{product}}+E_{\text{by-product}}$. In specific units,

$$m_{in}e_{\text{material,in}}+E_{\text{energy,in}}-E_{\lambda}=m_{\text{product}}e_{\text{product}}+m_{\text{by-product}}e_{\text{by-product}}$$

In EXA, there is no need for apportioning the input among the outputs: the exergy of both product and by-product are thermodynamics quantities calculated exactly on the basis of material properties and of the selected reference state. In TE, the cost allocation is made on the basis of an explicit *value* choice, on the part of the analyst, who must specify (for each component) which is the product and which the by-product. In EEA, the procedure is in principle the same, though the choice is made somewhat obvious by the peculiarities of the method. To make this point clear: if an exergetic input of 1 kJ produces an output of 0.3 kJ of electricity (exergy factor equal to 1), we say that the process has a 30% effectiveness. If in addition 0.5 kJ of heat at 800 K are generated, and the reference state is at a temperature $T_o = 300$ K, the effectiveness is raised to $\varepsilon = (0.3 + (1 - 300/800) \times 0.5)/1 = 0.61$

It is perhaps worth mentioning that in this latter case the specific emergy content assigned to the hot gases would be substantially higher than its exergetic content.

(c) Driving forces

This critique is ill-placed. again, we must distinguish between EXA, TE and EEA. In EXA (and in Szargut's CEC), the 'environmental services' are accounted for on the basis of the exergy of the inputs (be they material or energy flows). The exergy content of the primary flows is assumed equal to their 'raw' exergy in the Earth's crust: intermediate products may be assessed by a back-tracking procedure. Since both EXA and CEC are thermodynamic tools, non-energetic production factors are explicitly excluded. In TE, all externalities are considered in monetary terms, and the corresponding expenditures increase the cost per unit exergy of the product(s). Provisions exist to attach an additional environmental cost to each output, calculated on the basis of a monetary estimate of environmental damage (both upstream and downstream of the process, see [19]). In EEA, all factors are automatically expressed in exergy equivalents, and the 'ecological footprint' is, so to say, internalised as well.

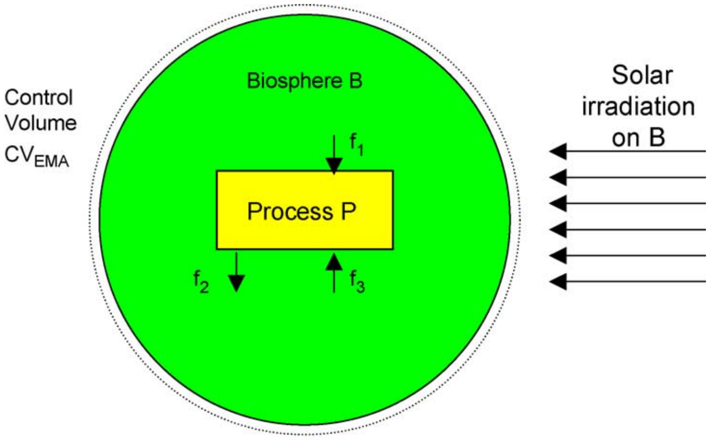
(d) Thermodynamics

There is no doubt that EXA is well rooted in Thermodynamics. As stated in Section 5.1, I maintain that EMA, because of its intrinsic First-Law philosophy, is not entirely consistent in its Thermodynamic foundation. As for the other remark, that both methods 'need to perform a step ahead', we may rightfully say that EXA has already done this when it sprouted first TE, which internalises the non-energetic production factors, and then EEA, which completed the internalisation process by embedding Environmental accounting into a completely exergetic frame. I suspect that the 'necessary step ahead' for EMA may be that of explicitly including Second Law considerations, that would though require not only some modification to its body of algebraic rules, but also a revision of some of its basic assumptions, like for instance the 'maximum power principle'. This is a meta-level issue: since we are unable to describe the Biosphere as a thermodynamic system in a strict sense, then some kind of additional principles are necessary to 'lump' the effects of the extremely intricate patterns of evolution. EXA does not even address this issue, and maintains that the interaction of anthropic systems with the Biosphere can be formulated entirely within the bounds of Classical Thermodynamics, provided we exclude an overambitious 'Thermodynamics of life'.

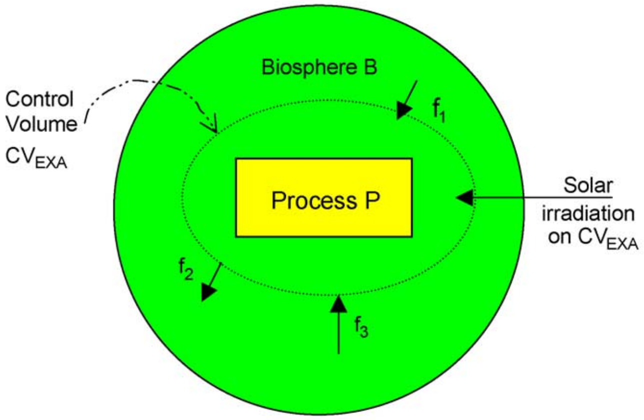
In essence, the two control volumes are different: for EXA and EEA, the interface is a sort of physical membrane constituting the 'inward' skin of the Biosphere; while for EMA, it includes the entire Biosphere. Fig. 10 illustrates this difference.

(e) Some additional remarks on cost apportioning

The costing value assigned by EXA to the unit product is indeed correct: if a process generates m_1 kg/s of product C_1 and m_2 of C_2, the real mistake would be that of assigning equal (or even cost-allocated) *energy* costs to each kilogram of C_1 and C_2, because this would not account for the intrinsic



f_1, f_2, f_3 are flows internal to the system (P+B)



f_1, f_2, f_3 are external flows for P

Fig. 10. The different control volumes for EMA and EXA.

difference in their exergetic contents. The ‘costs’ assigned by the various EXA methods are compared in Table 4: where β and γ are factors representing the allocation of the component ‘costs’ between the two products.

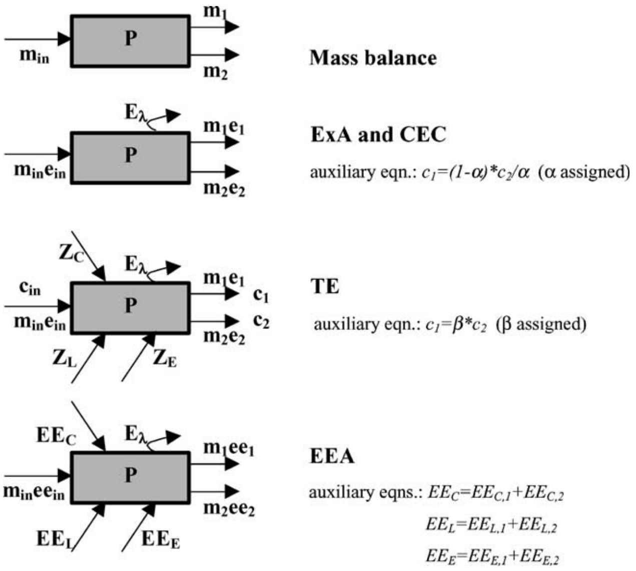
From the above formulae it is clear that C_1 and C_2 can have the same exergetic cost (in J/J or in €/J):

- In EXA, if $m_{C1}e_{C1}=m_{C2}e_{C2}$
- In TE and EEA, if all production factors are equi-allocated or if

$$\frac{\sum_j \alpha_j E_{I,j}}{\sum_j (1-\alpha_j)E_{I,j}} = \frac{m_{C1}e_{C1}}{m_{C2}e_{C2}}$$

Table 4
Efficiency and cost formulae for a two-product process

Accounting method	Process efficiency	Production cost of C_1	Production cost of C_2
Exergy Analysis, EXA and CEC	$\varepsilon_P = \frac{m_1 e_{C1} + m_2 e_{C2}}{\sum_j E_{I,j}}$	$c_{C1} = \frac{\sum_j E_{I,j}}{m_{C1} e_{C1}} \left[\frac{kJ}{kJ}\right]$	$c_{C2} = \frac{\sum_j E_{I,j}}{m_{C2} e_{C2}} \left[\frac{kJ}{kJ}\right]$
Thermo-Economics, TE	$\varepsilon_P = \frac{m_1 e_{C1} + m_2 e_{C2}}{\sum_j E_{I,j}}$	$c_{C1} = \frac{\sum_j \beta_j (Z_j + C_{I,j})}{m_{C1} e_{C1}} \left[\frac{€}{kJ}\right]$	$c_{C2} = \frac{\sum_j (Z_j + C_{I,j}) - m_1 c_1 e_1}{m_{C2} e_{C2}} \left[\frac{€}{kJ}\right]$
Extended Exergy Accounting, EEA	$\varepsilon_P = \frac{m_1 ee_{C1} + m_2 ee_{C2}}{\sum_j EE_{I,j}}$	$c_{C1} = \frac{\sum_j \gamma_j EE_{I,j}}{m_{C1} ee_{C1}} \left[\frac{kJ}{kJ}\right]$	$c_{C1} = \frac{\sum_j (1-\gamma_j) EE_{I,j}}{m_{C2} ee_{C2}} \left[\frac{kJ}{kJ}\right]$



which is of course the correct result Thus, there is no need to introduce a new algebra to assign the total exergetic input to one of the streams, to lower its conversion efficiency, because the conversion efficiency is not the only quantifier of the quality of a stream: the direct and implicit inclusion of entropy into the exergy calculations provides a real measure of the Thermodynamic quality.

(f) The costing of labour

Attaching an ‘exergetic value’ to the human production factor is difficult in simple EXA (see though [3,54]). But both TE and EEA do take into account human work: TE treats it as a (monetary) externality contributing to the cost formation process; and EEA internalises it, expressing it in terms of equivalent exergy. For instance, contrary to the claim made in Section 6.1, the ‘total extended exergetic content’ of an engineering graduate may be computed if enough data are available [6].

7. A benchmark case: emergy and exergy analysis of bio-ethanol production

To practically assess our differences and similarities, we needed an example of an industrial process that could be evaluated by both EMA and EXA. The process must be complex enough to have practical significance, and must involve extensive interactions with the Environment to make it a proper benchmark. We have chosen ethanol (C_2H_5OH) production from corn, for which an extensive database exists [27]. In spite of the apparent abundance of data, it became soon clear during the evaluation that several assumptions were required to properly close the balances: we have made these assumptions whenever needed, and we offer no further justification for them, besides the obvious one that the mass, energy and exergy balances have to be correct for our analyses to be meaningful.

7.1. The system

The process is represented in Figs 7 and 8. With some adjustments, all data are consistent with those provided by the original source [27]. Fig. 7 describes the main steps of the process: corn production, harvesting and transport to plant, processing to ethanol. Fig. 8 offers a partially disaggregated representation of the industrial process, starting from corn and agricultural residues fed to the plant together with coal, electricity, water, and smaller amounts of other chemicals. The diagram also shows secondary material inputs as well as labour inputs. Corn is processed to ethanol and DDGS (Distillers Dried Grains with Solubles) to be used as animal feed. Agricultural residues may or may not be used as a source of process heat. If they are, additional energy and material inputs to the agricultural phase (harvesting, replacement of nutrients in soil) must also be accounted for. The diagram also shows heat-recycling patterns from higher to lower steps of the process, which decrease the demand of high quality fuels and electricity for corn cooking, ethanol distillation, and DDGS drying.

7.2. The mass-, energy-, and exergy-flow diagrams

The operative flow sheets of the ethanol production are shown in Figs. 11–14. Standard process engineering procedures were applied in their derivation. The cost data actualization and other adjustments have been performed according to the factors reported in Table 2.

From a material balance point of view, some flows are particularly important at process scale. For instance, if only coal-generated process heat is used: (a) about 9 g of topsoil are eroded and oxidized per g of ethanol produced, and (b) about 7 g of CO_2 are released per gram of ethanol produced versus 8 grams absorbed by the photosynthetic process. If agricultural residues are instead harvested and used to replace at least a fraction of process coal, the performance is reversed: soil erosion may even double, while CO_2 emissions slightly decrease. The most important result concerns water: for each g of ethanol 4340 g of water are required, mainly in the agricultural step, and 9 g of industrial wastewater are released.

Energy input–output flows on the process scale do not offer any insight on the actual process efficiency. If life-cycle flows are accounted for (including production of components and abatement of pollutants) an interesting overall energy cost evaluation is though obtained. About 0.11 g crude oil are needed to produce 1 g of corn in field, which translates into an energy return of about 3.8 J per joule invested. Instead, 0.67 g of oil are required per gram ethanol produced, equivalent to an energy return of 1.72 J/J. If residues are used as source of industrial process heat but no credits are assigned for DDGS use, a lower ratio of 1.25 is calculated. If residues are not used but DDGS credit is accounted for, this ratio drops to 0.63. Finally, a ratio of 0.55 is obtained if both residues and DDGS are not accounted for. Since the recycling of residues (high volumes, high moisture content, need of storage) is

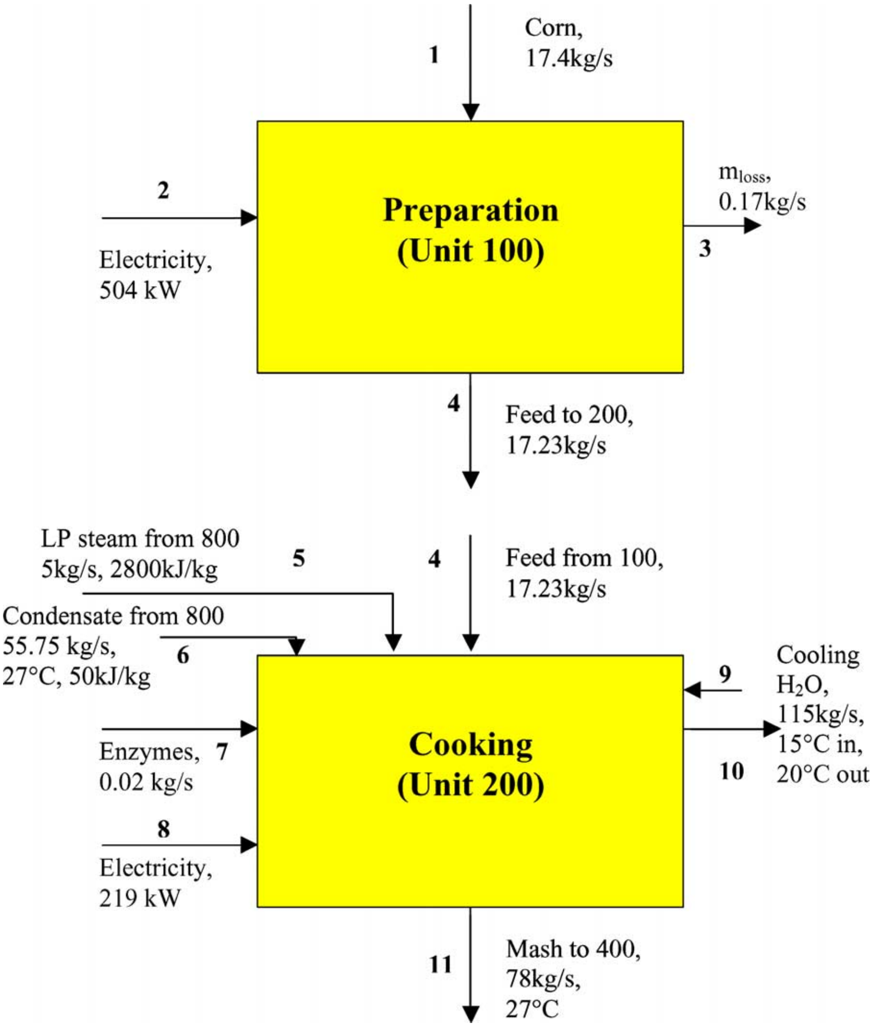


Fig. 11. Ethanol production from corn: preparation and cooking (unit numbers refer to [27]).

not always easy and the use of DDGS is also problematic, ethanol from corn does not appear as an energetically interesting option. From an energy point of view, the use of agricultural residues as a substitute of coal appears important. When only coal is used, the direct energy investment amounts to 76% of the total energy use, while goods and machinery account for 24%. If residues are used instead, the direct energy expenditure amounts to 41% while the indirect energy, embodied in goods and materials, is about 59% and becomes a significant factor.

7.3. Emergy analysis

Results from emergy analysis, calculated under the assumption that agricultural residues can replace a fraction of input coal for process heat, are shown in Table 5 and Fig. 15a. The latter shows the variation

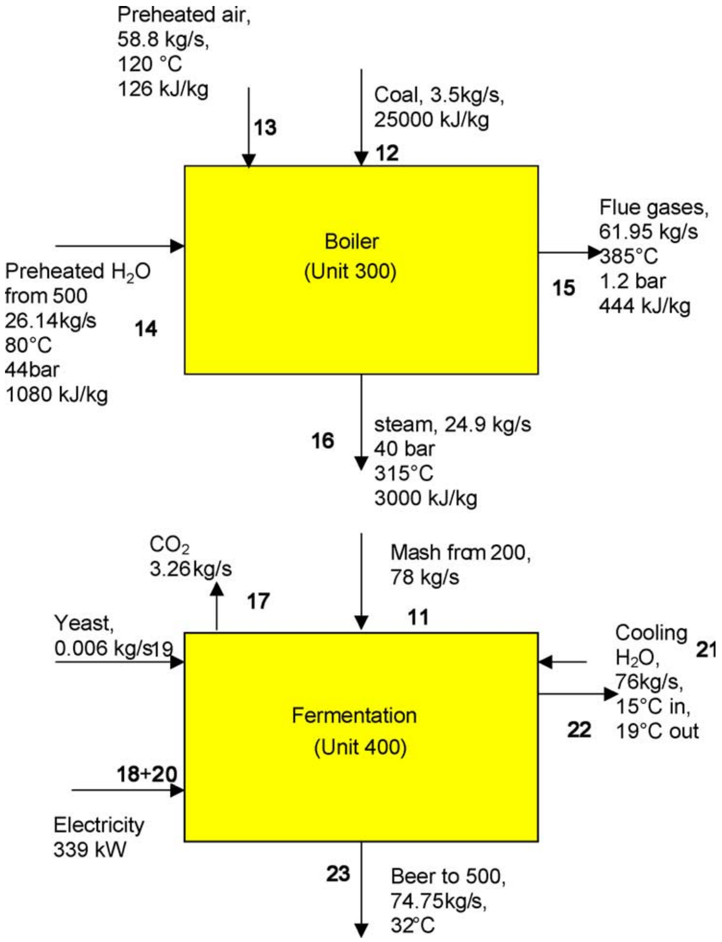


Fig. 12. Ethanol production from corn: steam production and fermentation (unit numbers refer to [27]).

of the emergy intensity (emergy/mass, seJ/g, instead of transformities, seJ/J, for easier comparison) in the different steps, from agricultural production to ethanol storage. Values increase in correspondence with additional inputs and lower amounts of matter transferred to the next step, and decrease when huge amounts of low quality inputs are added (e.g. water). The agricultural phase yields corn and residues, for which transformities, respectively, of 6.18×10^{8} and 5.67×10^{8} seJ/g are calculated. Instead, ethanol and DDGS are produced in the industrial phase, with transformities, respectively, of 4.35×10^{9} and 3.93×10^{9} seJ/g. Indicators are calculated both for corn production and for ethanol production, without focusing on the intermediate steps. Transformities significantly increase from the value for corn to the value for ethanol. The other performance indicators show a higher environmental loading of the whole process compared to the agricultural step alone. Instead, the use of agricultural residues as substitute of a fraction of coal does not change the picture as much as expected. This is because: (i) coal only represents about 12% of total emergy use and therefore does not play a significant role in determining the emergy intensity (only think of the 14.6% of fertilizers); (ii) the use of residues requires harvesting and

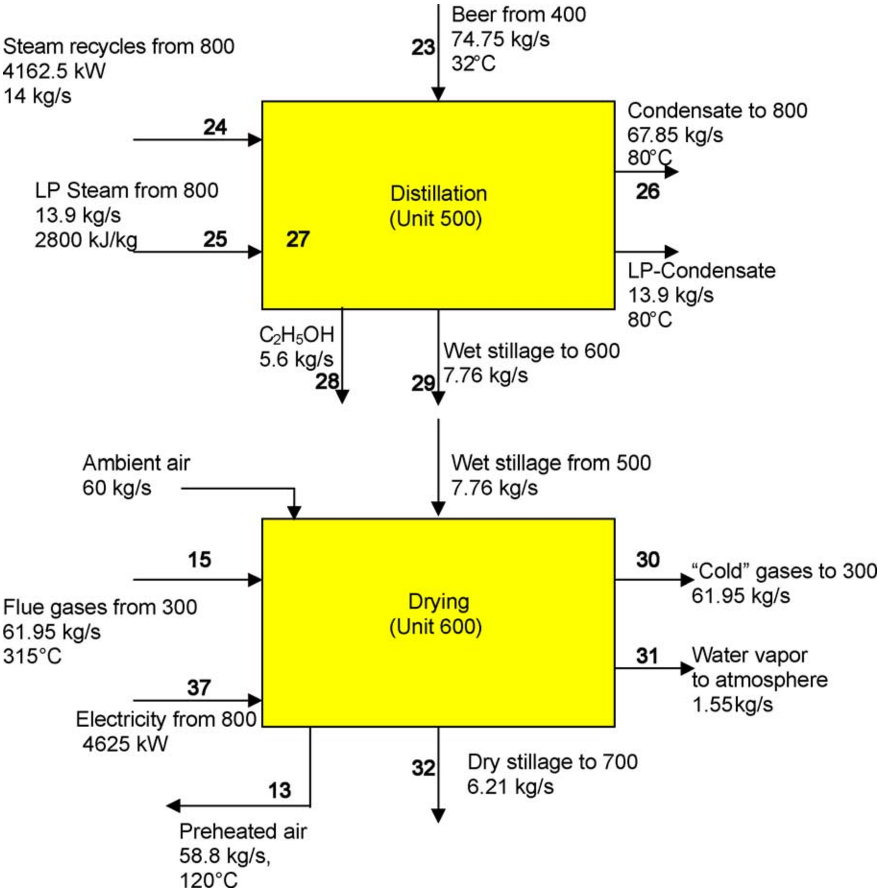


Fig. 13. Ethanol production from corn: distillation and drying (unit numbers refer to [27]).

additional agricultural practices, which partially offset the advantage of coal saving. It might be worth noting that environmental inputs amount to the 11% of total emergy use; fuel and electricity (including coal) amount to 22%, labor and services to 22% and finally goods and materials (including fertilizers and machinery) amount to the 45%. This means that direct fuel use is not the main input driving the process, as it could be inferred from a pure energy or exergy analysis. The role of free environmental inputs (agricultural phase and dilution of pollutants in the industrial phase) as well as of the indirect inputs supporting labor, services, fertilizers, chemicals and machinery is much more likely to affect the global performance of the process and calls for increased attention.

7.4. Exergy analysis

Ethanol production is a rather inefficient process both from an energetic and an exergetic point of view. A First Law Analysis of the industrial step only indicates that approximately 34 MJ are needed to produce 1 l of Ethanol. A similar calculation based on exergy leads to a value of 28 MJ of exergetic input

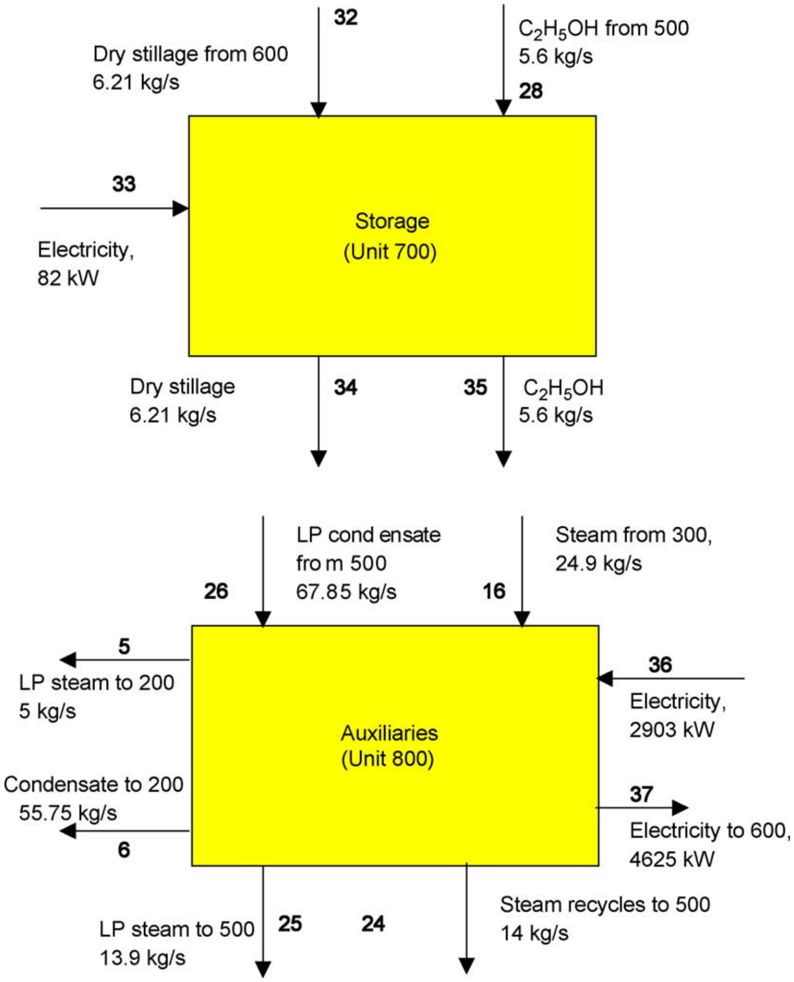


Fig. 14. Ethanol production from corn: final storage and auxiliaries (unit numbers refer to [27]).

per liter.[3] The rather high ratio (0.82) between the two values indicates that 'high quality energy' (carried by high-T steam, chemical additives and electrical current) represents a major contribution to the input streams. This clearly appears in each step of the process (Figure 15b). On a monetary basis, the production cost of 1 l of C_2H_5OH is equal to 0.164 €/l. An EEA analysis modifies somewhat the picture: taking as a basis the total exergetic yearly input into the country (data for Italy 1998 [37]), the exergetic resource consumption amounts to 35.5 MJ/l (16.9 if the extended exergy equivalent of the proceeds from the sale of by-products is included in the balance). Since the Italian economy in that year had a capital equivalence factor $K_{cap} = 18.2$ MJ/€, the equivalent monetary cost, recalculated from the extended exergy invested in the process, is now much higher and equal to 1.95€/l (0.93 with byproducts

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[3] These values were computed assuming that the specific energy content of the corn delivered to the plant site was equal to the cumulative energy content calculated by EMA. Lack of reliable data has prevented us from performing a more precise calculation using Szargut's CEC method.

Table 5
Emergy flows, indices and ratios for corn and ethanol production

Source of process heat	→	Coal	Coal + residues	
Emergy flows (including the emergy associated to labor and services as well as to the abatement of airborne and waterborne pollutants)				
R1	Local renewable inputs, R1, to the agricultural phase	$5.58\times10^{+14}$	$5.58\times10^{+14}$	seJ
N	Locally non-renewable inputs, N	$2.39\times10^{+14}$	$2.39\times10^{+14}$	seJ
F1	Purchased inputs to the agricultural phase, F1	$3.90\times10^{+15}$	$3.90\times10^{+15}$	seJ
Y1	Total emergy inputs to the agricultural phase, Y1 = (R1 + N + F1)	$4.70\times10^{+15}$	$4.70\times10^{+15}$	seJ
R2	Locally renewable inputs to the industrial phase, R2, for abatement of pollutants	$5.91\times10^{+14}$	$3.41\times10^{+14}$	seJ
F2	Purchased inputs to industrial phase, F2	$2.61\times10^{+15}$	$1.96\times10^{+15}$	seJ
Y2	Total emergy inputs to industrial phase, Y2 = (R2 + F2)	$3.20\times10^{+15}$	$2.30\times10^{+15}$	seJ
Y	Total emergy input to the process, Y = (Y1 + Y2)	$7.90\times10^{+15}$	$7.00\times10^{+15}$	seJ
Corn production				
Tr	Transformity of corn	$4.22\times10^{+04}$	$4.22\times10^{+04}$	seJ/J
EYR	Emergy yield ratio of corn = Y1/F1	1.20	1.20	
ELR	Enviromental loading ratio of corn = (N + F1)/R1	7.42	7.42	
ED	Empower density of corn (Y1/area)	$4.70\times10^{+11}$	$4.70\times10^{+11}$	seJ/m^2
EIS	EYR/ELR of corn	0.16	0.16	
Ethanol production				
Tr	Transformity	$1.83\times10^{+05}$	$1.70\times10^{+05}$	seJ/J
EYR	Emergy yield ratio = Y/(F1 + F2)	1.21	1.19	
ELR	Environmental loading ratio = (F1 + F2 + N + R2)/(R1)	13.15	11.55	
ED	Empower density = (Y/area)	$7.90\times10^{+11}$	$7.00\times10^{+11}$	seJ/m^2
EIS	EYR/ELR	0.09	0.10	

recovery). Current accounting techniques *underestimate* the commercial production cost of ethanol by 1.5–3 times! Such a result is surprising, and can be only partially explained by the fact that the economics of the plant are distorted by the agricultural incentives that encourage the recycling of corn overproduction, contributing in practice to ‘subsidize’ the biomass-to-ethanol process.

8. Conclusions

Aside from the discussion of the relative merits and demerits of EMA and EXA, discussed at length in Sections 5 and 6, and assuming that ethanol production is a process that can be taken as a viable benchmark for these analyses, we can conclude that:

(1) Material balances are useful indicators of both local and global ‘effects’ of the process on the environment (soil erosion, global warming, water demand and pollution). Their usefulness is though limited in the assessment of a process per se. At most, this technique may be used to compare two

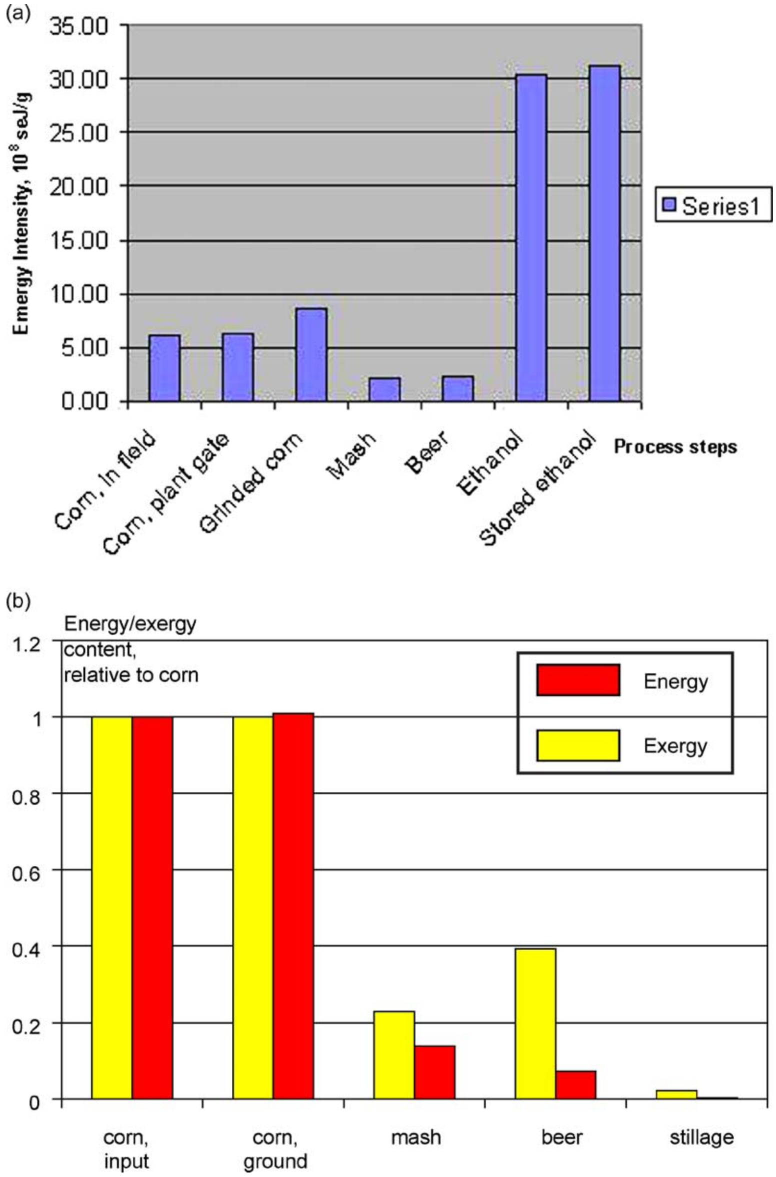

Fig. 15. (a) Variation of the emergy intensity (emergy/mass, seJ/g) from lower to higher steps of the process. Values increase in correspondence of additional inputs and lower amounts of matter transferred to the next step, and decrease when large amounts of low quality inputs are added (e.g. water) and higher mass (mash, beer) is transferred. (b) Exergy allocation for the various phases of the process.

similar processes: but since a material balance does not include any ‘energy’ measure, it is of limited relevance.

(2) A First Law analysis is not only incomplete but also misleading, because it distorts the real resource consumption quantifiers, overestimating the low exergy (high entropy) fluxes.

(3) An exergy analysis offers useful insights for the correct assessment of the process itself: it identifies and quantifies the sources of irreversibility, and allows for an immediate comparison of different process structures. Furthermore, it provides a clear indication of the resource-to-end-use matching, thus allowing for a more proper resource allocation. Its inability to account for externalities though limits its usefulness for a broader picture.

(4) Extended exergy analysis (EEA) overcomes this latter limitation, and provides a complete picture of how the process is interacting with the biosphere and with the societal environment.

(5) Emergy analysis (EMA) is a top-to-bottom approach, in that it looks at the process from the perspective of the Biosphere. As such, it is at present the only method that directly includes in the balance (i.e. in the product 'cost') the effects of non-commercial fluxes like rain, solar irradiation, wind, deep heat etc.

(6) Both EEA and EMA explicitly include in their costing procedures the so-called externalities (labour, capital, environmental effects, information). They adopt though two basically different approaches: EEA restricts its analysis to the deterministically measurable quantities, avoiding all uncertain issues about the complex and non-linear dynamics of the interaction process/environment. EMA, on the contrary, expands its control volume to the entire Biosphere, trying to account for all of the environmental dynamics. This introduces by necessity a degree of uncertainty in its quantification: one may say that this uncertainty is the price EMA pays to include all of the large-scale interactions.

(7) The results of the case study presented here are paradigmatic: they clearly show that the information provided by the two methods is complementary rather than competing, and that the respective results are characterized by different degrees of uncertainty (not necessarily smaller for EEA). The two methods display 'optimal fields of application': EEA is best suited for constructing a 'corrected' production function, while EMA provides a better assessment of the interconnection between the examined process and the environmental dynamics.

(8) Undeniable and rather fundamental differences exist between the two methods (both in the analysis of the data and in the relevant algebra of the process representation, see also [62]), but they seem to pertain to a meta-level and therefore do not exclude a compatibility in an extended sense.

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