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Journal of Cleaner Production 15 (2007) 1359–1372

Journal of Cleaner Production

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An e*m*ergy evaluation of complexity, information and technology, towards maximum power and zero emissions

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Accepted 12 July 2006
Available online 25 September 2006

Abstract

This paper mostly deals with the role of energy, matter and information flows within both environmental and human-dominated systems. Sustainable growth and development of both kinds of systems require optimum use of available resources for maximum power output, as suggested by Lotka's Maximum Power Principle [Lotka AJ. Contribution to the energetics of evolution. In: Proceedings of the national academy of sciences of the United States of America, vol. 8. 1922, p. 147–50; Lotka AJ. Natural selection as a physical principle. In: Proceedings of the national academy of sciences of the United States of America, vol. 8. 1922, p. 151–5.], recently restated by Odum [Odum HT. Maximum power and efficiency: a rebuttal. Ecol Model 1983;20:71–82; Odum HT. Environmental accounting. E*m*ergy and environmental decision making. N.Y.: John Wiley & Sons; 1996.] as Maximum Em-Power Principle within the framework of his E*m*ergy Synthesis approach. In times of declining resources, this principle translates into increased efficiency and optimum use of any kind of waste and co-products. Ecosystems and any self-organizing systems always apply this strategy and their selection–evolution mechanisms are based on their ability of growing on any untapped resource available. In order to do so, they increase the number of components and patterns for resource degradation in order to optimize the resource throughput and power output. Such a strategy also applies to human-dominated, economic systems, where the ability of dealing with co-products and wastes by means of appropriate designs as well as reuse and recycling processes may lead to "zero-emission" patterns (increased complexity, optimal resource throughput, minimization of emissions, resource exchange among system's components) and be the key for successful and sustainable development. In this paper Life Cycle Assessment and E*m*ergy Synthesis approaches are suggested as joint tools for qualitative and quantitative evaluation of progresses towards industrial symbiosis and more sustainable production and consumption patterns within a zero emission framework.

Keywords: Zero emissions; E*m*ergy life cycle assessment; Maximum power principle

1. Introduction

The biosphere as a whole and component ecosystems are the products of a continuous and never completed process of self-organization, driven and constrained by resource availability. Geologic processes, atmospheric systems, ecosystems, and societies are interconnected through a series of infinitely different and changing relationships. Processes of energy transformation throughout the biosphere build order and degrade energy in the process, and cycle information in a network of hierarchically organized systems of ever-increasing spatial and temporal scales. Understanding the relationships between energy and the cycles of materials and information provides insight into the complex interrelationships between society and the biosphere.

Ecosystems circulate materials, transform energy, support populations, join components in network interactions, organize hierarchies and spatial centres, evolve and replicate information, and maintain structure in pulsing oscillations. It is increasingly clear that all ecosystems are interconnected, each receiving energy and materials from the other, interacting through feedback mechanisms to self-organize in space, time,

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doi:10.1016/j.jclepro.2006.07.008

and connectivity. Energy drives all these processes and energetic principles explain much of what is observed. As energy flows from driving energy sources to higher and higher order ecosystem components, it is transformed from sunlight to plant biomass, to first level consumers, to second level and so forth. At each transformation the second law losses decrease the available energy but the "quality" of energy remaining increases. Human-dominated systems (whole economies, production sectors, technology, etc.) are all supported by primary energy and material flows, through environmental services and ecosystem dynamics (Fig. 1).

Society uses environmental energies directly and indirectly from both renewable energy fluxes and from storages of materials and energies that resulted from past biosphere production. The actions of society, its use of resources and the load this resource use places on the biosphere are of great concern. Clearly it is imperative that insight be gained concerning the interplay of society and environment to help direct planning and policy for the third millennium.

In this paper, a system's view of society and production processes is taken. The interaction and integration among systems components, the internal exchange of resources and services, the identification of matter and energy flows to, from and within a system (LCA), the demand for environmental support (e*m*ergy), and finally the efficiency of resource use for maximum power output and decreased emissions, are discussed and their importance for more sustainable production patterns is highlighted.

2. E*m*ergy and Life Cycle Assessment: concepts and definitions

A framework for environmental assessment of production processes is presented in this paper and the concepts and methods used are defined and described in this Section. The concept of E*m*ergy Synthesis, as a tool for evaluating the environmental support provided by nature to human societies, is firstly summarized. Environmental support, sometimes

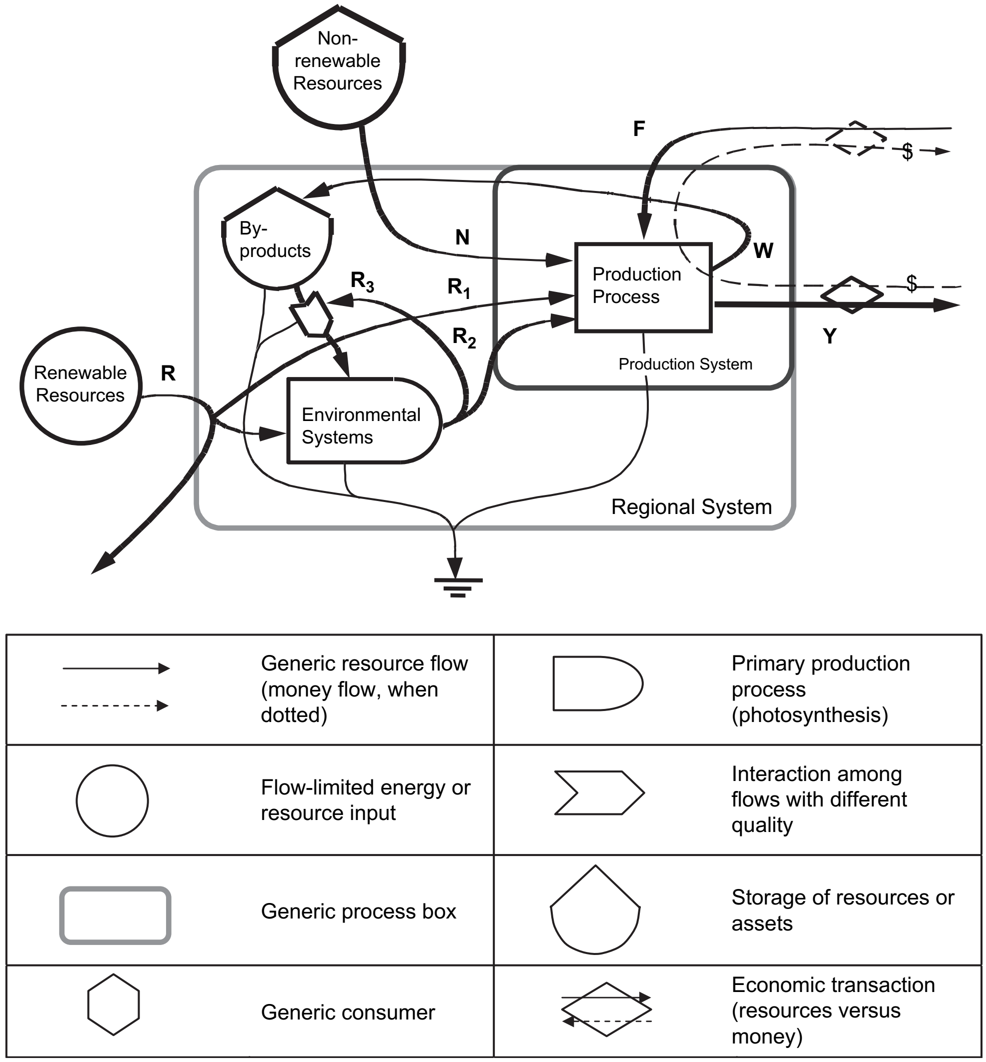

Fig. 1. Generic systems diagram, showing renewable and non-renewable resources driving a production process, with cycling of by-products and interaction of local process with the larger economic system. Renewable resources support environmental systems which in turn support economic systems, directly and indirectly. System's symbols from Refs. [21,24], according to the legend below, that is used in other figures of this paper.

named "ecological footprint", is very often disregarded in conventional economic analyses. How E*m*ergy Synthesis can be synergically coupled to well-known methods for Life Cycle Assessment is also briefly discussed. The rate of resource use and criteria for process optimization are then addressed by means of the Lotka–Odum's Maximum Power Principle (MPP). The concept of Zero Emission Technique and Strategies (ZETS) is presented and discussed and its links to MPP are highlighted. Finally, the concept of information (know-how, culture, etc.), its importance as a key factor for innovative, zero-emission processes, and the cost of generating, testing and disseminating new information, are addressed in the last part of this section. These concepts contribute to the construction of an E*m*ergy Life Cycle Assessment tool, which can be used for environmental policy development.

2.1. E*m*ergy, transformities and environmental value

Energy is usually referred to as the ability to do work, based on the physical principle that work requires energy input. Energy is measured in units of heat, or molecular motion…the degree of motion resulting in expansion and quantified in degrees of temperature.[1] Heat energy is a good measure of the ability to raise water temperature. However, it is not a good measure of more complex work processes. Processes outside of the window defined by heat engine technology, do not use energies that lend themselves to thermodynamic heat transfers. Not all energy, matter and information flows are the same and their heat equivalent is a poor measure of their quality. Odum [22] introduced the concept of *emergy* (spelled with an *m*) in the eighties, in order to properly account for the quality of matter, energy and information flows within systems, including their degradation due to second law losses. E*m*ergy accounts for the environmental services supporting a process as well as for their convergence through a chain of energy and matter transformations in both space and time [3,24]. By definition, e*m*ergy is the amount of *available energy* (exergy) of one type (usually solar) that is directly or indirectly required to provide a given flow or storage of energy or matter. The units of solar e*m*ergy are solar emjoules (abbreviated seJ) to distinguish them from actual energy joules (abbreviated J). When the e*m*ergy required to make something is expressed as a ratio to the available energy of the product, the resulting ratio is called (solar) *transformity* and is expressed in solar e*m*ergy joules per joule of output flow (seJ/J).

The total e*m*ergy driving a process becomes a measure of the self-organization activity of the surrounding environment, which makes the process possible. The transformity is an expression of the quality of the output itself, for the higher the transformity the more e*m*ergy was required to make the product flow. For example, the organic matter in forest soil represents the convergence of solar energy, rain, and winds driving the work processes of the forest over many years that has resulted in layer upon layer of detritus that ever so slowly decomposes into soil organic matter.

The e*m*ergy synthesis method is used in the following of this paper as a quantitative measure of the total environmental support to the flows of energy, matter and information involved in a system dynamics. When the focus is on human-dominated systems, e*m*ergy investigation complements and sheds light on results from Life Cycle Assessment (LCA) of processes, identifying patterns characterized by different demands for environmental support and different balance of renewable and non-renewable input resources.

2.2. Combining LCA and e*m*ergy synthesis

LCAs conventionally account for each energy and matter flow to and from a chain of processes from raw material to the final product(s) [1,16,17]. LCA is generally performed based on average values, since the different steps of a process occur in different locations and may be characterized by different performances which are location and technology specific. Yet LCA provides interesting information about the resource and environmental cost of a given product, even if the individual case may differ from the average one due to the existing uncertainty about data collected and processes used. Output flows are also assigned to a specific LCA impact category, in order to better investigate how each flow can potentially affect the surrounding environment. In general, the output of an LCA is a set of indicators related to specific impact categories (contribution to energy resource depletion, global warming potential, rain acidification potential, etc.), which can be used to suggest an appropriate use of each product, for resource use planning as well as for process optimization by means of step-by-step exergy analysis procedures [29]. Advanced and more sophisticated life cycle frameworks also give credit to resources replaced by a process or material as well as to the avoidance of previously unwanted behavior when a new technology or process is implemented. However, LCAs, in general, only account for matter and energy flows occurring under human control. Instead, flows outside of market dynamics (such as environmental services) and flows which are not associated to significant matter and energy carriers (such as labor, culture, information) are not generally included. When sustainability comes into play as major concern, these flows become relevant and cannot be disregarded. E*m*ergy accounting is the only way which can be used to expand the focus of LCA in order to properly account for their contribution to a system/process sustainable dynamics. In fact, by means of e*m*ergy accounting, all resources are referred to the scale of biosphere and their usefulness and quality quantified on the same value basis and then compared with the product(s) generated. In so doing, the most sustainable option (or set of options) can be identified and choices among alternatives facilitated.

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[1] All energies can be converted to heat at 100% efficiency, thus it is relatively easy and accurate to express energies in their heat equivalents. The basic units of energy are the amount of heat required to raise a given amount of water a given number of degrees of temperature. Thus the calorie is the amount of heat required to raise 1 cm^3 of distilled water from 14.5 °C to 15.5 °C at the atmospheric pressure. A calorie is equal to 4.187 J.

2.3. Lotka–Odum's Maximum Empower Principle

Designs are reinforced that maximize power output possible from the resource available, as suggested by Lotka's Maximum Power Principle [19,20]. Successful systems develop structures that maximize useful resource consumption and production, also by feeding back matter and information. In order to take quality of flows into account, Odum [21,24] restated Lotka's principle via the *em*ergy concept as Maximum Empower Principle. The revised statement is as follows:

> *Systems that develop the most useful work with inflowing emergy sources by reinforcing productive processes and overcoming limitations through system organization, will prevail in competition with others.*

or, in other words,

> *In self-organization patterns, systems develop those parts, processes, and relationships that maximize useful empower.*

It is important that the term "useful" is used in these two statements. For example, drilling oil wells and then burning off the oil may use oil faster (in the short run) than refining and using it to run machines, but it will not compete, in the long run, with a system that uses oil to develop and run machines that increase drilling capacity and ultimately the rate at which oil can be supplied.

Within a Maximum Empower and natural selection framework, maximum efficiency as defined in classical textbook thermodynamics is no longer the driving prerequisite. First of all, complex systems adapt to environmental conditions by *optimizing*, and not necessarily maximizing, their efficiency, so that global maximum power output can be achieved and maintained. Maximizing global production is the goal, which is reached by "choosing" the most appropriate efficiency for each of the co-products. As a consequence, resource throughput is also maximized consistently with availability of resources. In this way, systems tune their thermodynamic performance according to the surrounding environment.[2] In general, when resources are abundant, the advantage goes to the system which is able to draw them in faster than others, in spite of their use efficiency. When resources decline, efficiency must grow, in order to generate the maximum possible product within the existing constraints based on smaller throughput, although an efficiency increase is generally achieved at the expense of process speed [25].[3] Societies deplete most of the known and accessible resource storages, on the both source side (reservoirs of non-renewable resources such as oil, minerals, fertile soil) and sink side (clean air and water, ecosystem integrity). Resources become increasingly scarce, due to increased use per person and increased population. Therefore, according to the Maximum Empower Principle, fast consumption is no longer a winning strategy for survival and must be replaced by increased global efficiency (doing more with resources available). This leads to the so-called Zero Emission Technologies and Systems (ZETS).

2.4. Zero emission patterns

Ecosystems recycle every kind of waste. The concept itself of "waste" is no longer appropriate for ecosystems. The products from one component or compartment are always a useful resource for another component or compartment. Ecosystems self-organize in order to maximize the total product (e.g. biomass, stored exergy) by optimizing the resource throughput, according to Lotka–Odum's Maximum Empower Principle. Self-organization for Maximum Empower ensures that all available resources are utilized to the maximum possible extent and no unused resources are left.[4]

The detritus chain in ecosystems is a clear example of this statement. Human-dominated systems should be reshaped according to the same principle, for maximum resource use and zero emissions [26]. In traditional linear production systems resources are processed and passed on to the next step and unused wastes are released to the environment. As a consequence, the energy and material cost of the product is higher and efficiency lower, and a higher emission load is imposed on the environment. Such systems are unlikely to develop maximum-power behavior and therefore be successful in medium and long-term competition, when resources become scarcer.

In an integrated, "zero-emission" strategy, processes are reorganized and clustered in such a way that unused resources become the raw input to new production patterns.

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[2] Photosynthesis, a low energy-efficiency process (0.1%), is an example of such a behavior. Solar energy is abundant and constant, but other resources (water, nutrients) are not generally such. By optimizing its efficiency via a complex, still not completely clear, biochemical mechanism, the photosynthetic process adapts its performance to the amount of available resources. A higher energy efficiency would not fit the availability and appropriate use of needed resources other than solar radiation (e.g. water, nutrients, etc.). The optimum efficiency "chosen" by green plants maximizes their biomass over time within the existing constraints. Moreover, the larger system of biosphere allocates fractions of solar energy to patterns other than the photosynthetic one (wind, water, oceanic currents, etc.) in so maximizing and maintaining the global productivity much more than by maximizing one individual pattern (e.g. rain).

[3] The interplay of available resources, efficiency and power is an important factor affecting a process. For example, the XVIII century industrial revolution in England was driven by large amounts of coal used at less than 1% efficiency (early steam engines). The winning factor in market competition was not just energy, but power (generating products and expanding faster than competitors). When availability of coal was constrained by several other factors (demand, price, competition, social factors, etc.) efficiency increase became more important, in order to make more products out of available resources.

[4] This may not be true for each individual process over a short time scale, but depends on the spatial and time window of interest as well as on the number of interacting processes. For example, fossil fuels (reduced carbon) can be considered as the waste of photosynthesis, a process where production is slightly larger than consumption (respiration). Instead, on the larger geological scales these materials are also cycled by earth's convective processes and are used for the global construction of earth crust. By extracting them, humans boost the process by returning carbon to the biosphere faster than it would have been via natural cycles.

When resources become scarce, this behavior translates into a selective advantage as predicted by the Maximum Empower Principle. While in conventional production the main resources are matter, energy and labor, zero-emission patterns rely to a large extent on knowledge, i.e. on better information about needs of and surpluses from each component as well as about technological tools for resource processing and exchange [12]. The zero emission concept "*represents a shift from the traditional industrial model in which wastes are considered the norm to integrated systems in which everything has its use. It advocates an industrial transformation whereby businesses emulate the sustainable cycles found in nature and where society minimizes the load it imposes on the natural resource base and learns to do more with what the earth produces*" [34].

A significant experience in this regard is the so-called Industrial Symbiosis in the Danish town of Kalundborg [8,9] (http://www.symbiosis.dk/), where careful planning around an oil refinery/coal-fired power plant system and the local waste management agency allows huge savings of energy, surface and ground water (3 million m^3/yr), fuel oil (20,000 t/yr), and decreased SO_2 emissions. Due to the interaction of this industrial complex with other local firms, about 80,000 t/yr of combustion ashes are delivered to local building enterprises for use as additives to cement production; hot water is delivered to a large number of smaller users as well as to the city district heating system; nickel and vanadium are extracted from ashes and exported; and sulphur, fertilizers, enzymes, and recycled materials are also extracted in large amounts and marketed. It is important to underline that the Kalundborg Eco-Industrial Park was not initially designed as such, but gradually it evolved over a number of decades when the participants discovered that the establishment of energy and waste exchanges resulted in economic benefits for all parties involved. Further information about the development of industrial symbiosis experiences and eco-industrial parks can be found in Gertler [10], Heeres et al. [14], and Desrochers [7].

2.5. The information cycle

The importance of knowledge and information as key factors for Zero Emission Strategies were underlined in Section 2.4. Many believe that information is a no-cost resource and that providing new flows of information to a process is a way for improving its performance without increasing the cost of production. This is because little attention is given to the characteristics of the information concept as well as to the way information is generated in natural and economic systems. Information is no doubt one of the concepts which Odum [24] investigated deeper. He pointed out that

> *knowledge and information are found in ecological and economic networks, the result of many complex transformations of energy…Like other structures, information is thermodynamically away from equilibrium, and thus is continuously lost by dispersal and depreciation. Information is maintained by work processes, continually copying, correcting, replacing, and revising. Information is lost when its carrier disperses.*[5] *Living organisms reproduce, copy, repair, revise, and reapply their information.*

Due to the second-law processes, self-organizing systems may develop erroneous information, i.e. information unable to drive system's operations within the surrounding environment. The survival strategy that maximizes empower is making extra copies (i.e. sharing information), discarding those that develop errors, and reinforcing those that still work by making copies of these. Therefore, the only way to maintain information is keeping it in operation, making copies, test them for survival and discontinuing those copies that do not work (Fig. 2).

In Odum's words "*…a closed circle of information processing is necessary to maintaining one unit of information. It takes emergy to support the whole cycle: very little emergy to make copies, more emergy to extract information in a form that can be disseminated (e.g.: spores, seeds, CDs), even more emergy to sustain shared information (i.e. maintaining information by maintaining the whole population where this information is duplicated, selected and reproduced).*[6] *Finally, it may take even much more emergy to develop new, useful information from its precursor (i.e. the emergy needed to maintain a population for the time required to the new information to be generated). As a consequence, the transformity of information copies is much smaller than the transformity of one unit of shared information or one unit of new information. The evolution of life and its forms is strictly interconnected with the information cycle, driven by the emergy needed to copy, disperse, use, test and select the existing information as well as to generate new information units*" [24].

Since Maximum Empower/Zero Emission Strategies are significantly dependent on information for optimum use of resources, the cost of generating, testing, disseminating and storing information is of paramount importance for sustainability. For example, the information carried by DNA in living systems is no doubt generated and supported by direct and indirect solar emergy flows. The information carried by books, software, money, and expertise is also generated and supported by direct and indirect emergy flows, but this is always disregarded in conventional Life Cycle Assessment procedures. The problem is that the information content of a specific input, design, or tool is very difficult if not impossible to quantify as such. The large effort performed for information accounting since Shannon first introduced a quantitative expression of this concept did not lead to

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[5] Information carriers are books, floppy disks, DNA, paintings, people, etc. All of them degrade out over time and thereby lose ability to carry information.

[6] e.g. by keeping a forest in good health, so that the information cycle works and information can be tested, selected and duplicated (comment of the Authors, not originally in Odum's quote).

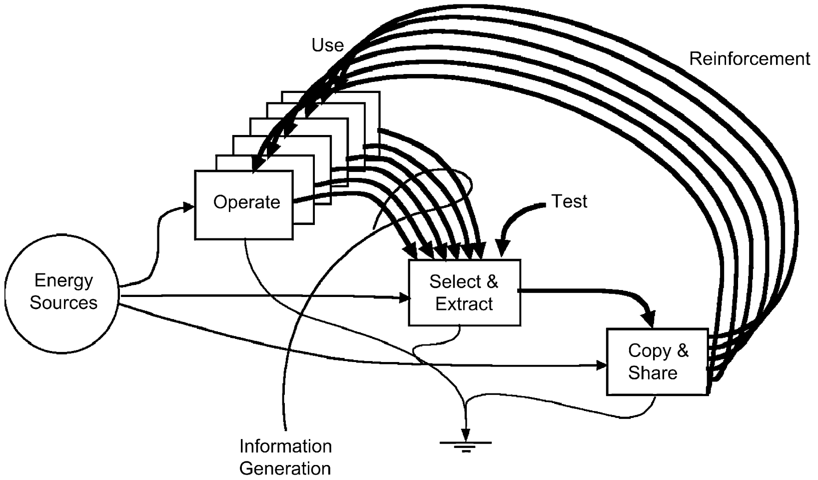

Fig. 2. The main features of an information maintenance circle, including depreciation, extracting, copying, operating, testing, and selection [24].

consensus on information measures, especially when complex systems (ecosystems, societies, culture) are involved [2,27,30]. Instead, the amount of resources supporting the generation of information, i.e. how much it takes to support labor, generate innovation, make new technologies, test and spread new solutions and designs, can be quantified in e*m*ergy terms. For example, Odum [23] explored the e*m*ergy needed to support a University system (i.e. to support undergraduate, graduate and PhD students as well as ongoing research activity), and calculated average values (order of magnitudes) of e*m*ergy intensities per hour or joule of applied educated labor.

Several e*m*ergy analysts calculated the total e*m*ergy driving national economies for the generation of their Gross National Products (see Refs. [5,6,13,15,18,28], among others). Their data can be used to assess the e*m*ergy intensity of one unit of GDP generated (e*m*ergy intensity of currency, seJ/GDP). Since information in socio-economic systems is very often carried by currency and labor for human artefacts and designs, then e*m*ergy intensities of currency and labor can be used to convert hours of educated labor, money of earner income, and financial investments into information-related e*m*ergy inputs to a process. Moreover, since labor and know-how cannot be applied without using additional technological devices, we should also recognize the e*m*ergy cost of the latter as part of the cost of providing and using information. For example, the e*m*ergy cost of material infrastructure for heat exchange between two firms adds up to the e*m*ergy supporting labor and services for design, construction and operation of such an infrastructure. Both of them are e*m*ergy investments required to increase the interaction among different parts of a system and improve their performance by minimizing resource use and prevent misuse. Although these quantitative estimates are, of course, still affected by many uncertainties, yet they provide an interesting first-order assessment of the share of information within the total resource budget driving a system/process.

If e*m*ergy accounting procedures are used to expand the focus of LCA, such an integrated approach becomes a valuable tool for developing, monitoring and improving sustainable production patterns in economic systems, based on Maximum Empower, decreased emissions and a new role for knowledge and information.

3. Strategies for zero emission patterns

Zero Emission Strategies clearly indicate the way for Maximum Empower to be achieved in human-dominated systems. Self-organization of technology and economies for optimum use of resources makes them more similar to natural systems without humans and increases success probability in a scarce resource world. The result of such a Maximum Empower/Zero Emission Strategy is multifold:

(a) Fewer resources are required to drive the global multi-product process than would be needed if each sub-process were driven individually (think of co-generating electricity and hot water).
(b) Fewer resources are released unused and are potentially able to drive desired environmental transformations; as a consequence, smaller loads burden on the environment are generated or fewer resources need to be invested for safe management of wastes.
(c) Synergic effects (i.e. increase of benefits) become possible, due to exchange and collaboration links among components; and
(d) The total output is maximized, since additional products are generated by usefully employing still usable resources, instead of releasing them unused.

Comparing the total e*m*ergy used and the amount of products generated (energy, goods, services) over the whole chain of processes offers a way to calculate their global scale

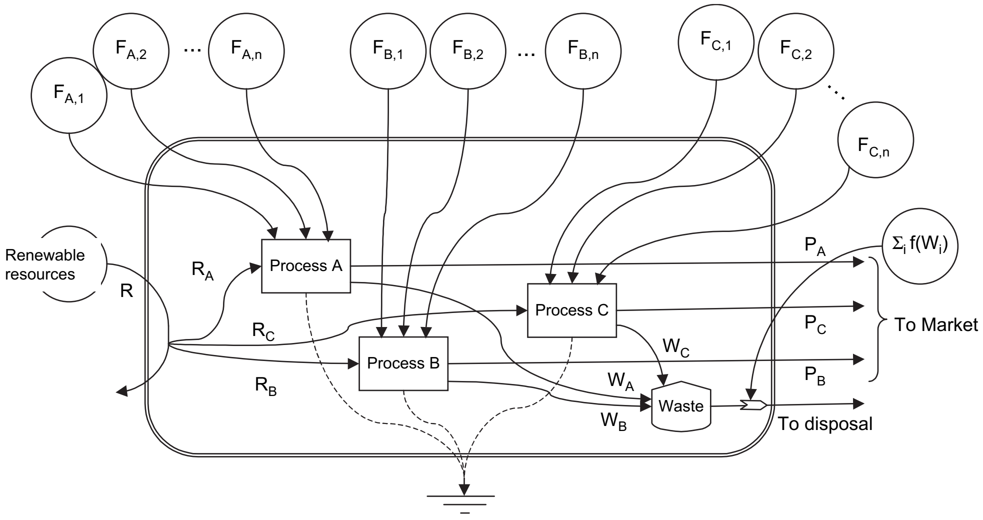

Fig. 3. Systems diagram of the traditional, linear pattern of industrial production. Resource inputs are processed and converted into the desired product(s) via independent production steps supported by outside resource inflows, each one releasing a given amount of unused waste. System's symbols from Fig. 1. Abbreviations used are as follows: P_i = mass of product(s) from the *i*th process; W_i = mass of waste(s) from the *i*th process; R_i = renewable e*m*ergy to the *i*th process; $F_{i,j}$ = non-renewable e*m*ergy of the *j*th input to the *i*th process; and $f(W_i)$ = e*m*ergy invested for disposal of waste from the *i*th process or for damage repair (i = A, B, C; $j = 1,\ldots,n$).

efficiency. When new information (innovative technologies, more trained labor, new patterns for use of residues and co-products, etc.) is added to the process, e*m*ergy-based efficiency offers a way to monitor the improvement of a system performance, towards a theoretical "maximum-power efficiency". The latter would be typical of an ideal process where optimum use of resources for maximum power is achieved, by means of appropriate emulation of natural sustainable cycles.

3.1. Modeling matter and emergy flows within a zero emission framework

Fig. 3 shows a local system composed of three independent production processes A, B, and C. After performing an inventory of all input and output flows, the e*m*ergy supporting a given process can be calculated by multiplying each renewable and non-renewable input flow of energy and matter by a suitable transformity value [3,24].

In so doing, the total e*m*ergy driving each process can be calculated (Table 1, first row) and then used to derive the transformity (unit e*m*ergy cost) of the final product (Table 1, last row). Input flows are supplied by the environment (all possible sources outside of the process) to each process. Each process in turn delivers a final product and a given amount of waste material (solid, liquid or airborne). Ulgiati et al. [32,33] suggested that an additional e*m*ergy input for safe disposal of waste materials or for repair of the damage generated by them should be assigned to the final product, thus increasing its transformity. In the same paper they provide quantitative equations for the assessment of the e*m*ergy cost of disposal and repair. This input is also included in the expressions of Table 1, as a function $f(W_i)$ of the amount of waste material released.[7] Processes A, B, and C in Fig. 3 do not exchange any resource flow, as also reported in Table 1.

Instead, Fig. 4 shows a significantly different situation, in which processes A, B, and C exchange some of their still usable waste resources, in addition to delivering their main products. The effect of this clustering is multifold. First of all, a lower amount of resources is required from the environment, which is indicated in Fig. 4 by the absence of flows $F_{i,n}$ replaced by the waste material exchanged between two processes. Second, a smaller e*m*ergy investment is needed for abatement, safe disposal, or damage repair, due to the smaller amount of waste released, $W_{i,r}$. Instead, additional e*m*ergy investments are needed, in order to make each process able to

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[7] According to Ulgiati et al. [33], the function $f(W)$ is composed of at least two kinds of contribution: the investment needed for abatement or disposal, $f_d(W)$, and the investment needed for damage repair, $f_r(W)$. The direct e*m*ergy loss due to the generation of damages that cannot be repaired should also be accounted for, but its quantification is more difficult. The final expression is as follows:

$$f(W) = f_d(W) + f_r(W) = \sum_j c_j m_{wj} + \sum_k d_k N_k \qquad (1)$$

where c_i is the e*m*ergy investment needed (seJ/g) for safe disposal of one mass unit of the *i*th waste flow, m_{wj} (grams) and d_k is the e*m*ergy investment needed (seJ/unit) for repair of one unit of the *k*th damaged storage, N_k. A large number of possible damaged items can be accounted for as N_k. In the case of facades of buildings damaged by traffic emissions, N_k is m^2 of façade; in the case of forests damaged by acid rain, N_k could be hectares of forest ecosystems to be restored; if focus is on land degraded by mining activities, N_k is hectares of land to be reclaimed; finally, if human health damaged by pollution is of concern, a rough estimate for N_k could be the amount of additional health services (e.g. beds in the hospital, increased number of physicians) needed to face the increased pollution.

Table 1
E*m*ergy flows from and to the processes of a local economy and the surrounding environment, without e*m*ergy exchanges among processes

To / From	Environment	Process A	Process B	Process C
Environment (seJ)	0	$R_A + \sum_{j=1,\ldots,n} F_{A,j} + f(W_A)$	$R_B + \sum_{j=1,\ldots,n} F_{B,j} + f(W_B)$	$R_C + \sum_{j=1,\ldots,n} F_{C,j} + f(W_C)$
Process A (g)	$P_A + W_A$	0	0	0
Process B (g)	$P_B + W_B$	0	0	0
Process C (g)	$P_C + W_C$	0	0	0
Transformity of product (seJ/g)		$\left[R_A + \sum_{j=1,\ldots,n} F_{A,j} + f(W_A)\right]/P_A$	$\left[R_B + \sum_{j=1,\ldots,n} F_{B,j} + f(W_B)\right]/P_B$	$\left[R_C + \sum_{j=1,\ldots,n} F_{C,j} + f(W_C)\right]/P_C$

P_i = mass of product(s) from the *i*th process; W_i = mass of waste(s) from the *i*th process; R_i = renewable e*m*ergy to the *i*th process; $F_{i,j}$ = non-renewable e*m*ergy of the *j*th input to the *i*th process; $f(W_i)$ = e*m*ergy invested for disposal of waste from the *i*th process or for damage repair (i = A, B, C; $j = 1,\ldots,n$).

receive useful waste resources from a nearby process. This last input, $g(W_{i,u})$, includes transport, infrastructures and information[8] for reuse, recycling and re-designing. The new situation is quantified in Table 2.

Table 3 shows the total e*m*ergy supporting the three processes (A + B + C) with and without a resource exchange among processes. The difference between the situation without exchange and the situation with resource exchange is calculated as follows:

$$\begin{aligned}\Delta &= (\mathrm{A}+\mathrm{B}+\mathrm{C})_{\text{no-cluster}} - (\mathrm{A}+\mathrm{B}+\mathrm{C})_{\text{cluster}} \\ &= \sum_i F_{i,n} - \sum_i g(W_{i,u}) + \sum_i f(W_i) \\ &\quad - \sum_i f(W_{i,r}) \quad (i = \mathrm{A, B, C})\end{aligned} \tag{2}$$

Since $W_{i,r} < W_i$, then is$\sum_i f(W_i) - \sum_i f(W_{i,r}) > 0$. If also $\sum_i F_{i,n} - \sum_i g(W_{i,u}) > 0$ or, at least, not too negative, so that can be the whole expression $\Delta > 0$, the creation of links and exchange flows among components translates into a global advantage to the local system in terms of less e*m*ergy invested. The expression Δ includes the savings of e*m*ergy for process support and waste management, as well as the cost of knowledge and information that makes the cluster possible.[8] It should be underlined that decreasing the unused materials thanks to the cluster organization also pulls down the potential pollution at an e*m*ergy cost lower than without cluster, designing a trend towards zero emissions through process optimisation.

4. Maximum Empower and zero emissions in electricity generation: a case study

One of the most common cases of demand for decreased emissions is the reduction of climate affecting gases such as carbon dioxide and nitrogen oxides. It is shown later in this paper that (a) the increased efficiency obtained by increasing the number of active system components and (b) the maximum possible exploitation of available resources (as dictated by the Maximum Power Principle) lead to significant decreases of airborne emissions and at the same time are characterized by better e*m*ergy performance indicators.

A traditional, cogeneration, natural gas power plant in Torino, Northern Italy, consisting of a 136 MW steam power group (ST), a 35-MW gas turbine (GT) and three integrative boilers (IB) supplying 47 thermal MW each (previously investigated by the author and his colleagues, Giannantoni et al. [11]), is chosen as a reference case study (hereafter STGT) and then it is compared to a more modern Combined Cycle Gas Turbine plant (CCGT), in order to show how the evaluation method can be applied. The choice of a cogeneration system was made because of the wide design options usually existing for thermal energy recovery.[9] Fig. 5 shows the systems diagram of the plant, with main components and flows to and from each component. The complexity of this traditional STGT plant is not significant, since its design is based on three parallel systems (steam turbine, gas turbine, boilers), which are completely independent from each other, in a similar way as processes A, B, and C in Fig. 3. The main matter and energy flows to, as well as the airborne emissions from the system (the latter calculated by also accounting for emissions from extraction and manufacturing of components and fuel) have been quantified in a previous evaluation for the Italian ENEA ([31] and update) and are summarized in Table 4. The first column refers to one unit of electricity and the second column refers to one unit of total exergy (available energy in electricity and heat) delivered.

The second power plant belongs to the new generation of multi-step, Combined Cycle Gas Turbine plants (CCGT,

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[8] As stated in Section 2.5, information in human-dominated processes can be roughly estimated as know-how, labor and financial investments. These in turn translate into the e*m*ergy needed to generate know-how as the result of education and research as well as the e*m*ergy required to drive economic activities which support labor and generate GDP. The fraction of this e*m*ergy which can be assigned to the investigated process is a proxy for the information supplied.

[9] Annual electricity generation is about 1000 GWh, heat being supplied as hot water at 120 °C/16 bar to a district heating grid; a low pressure extraction from the steam turbine is used in a hot condenser to supply 162 thermal MW (maximum heat generation), while the exhaust flue gases from the gas turbine feed a recuperator and supply 63 thermal MW. Most of the sulphur content was preliminarily removed from the natural gas, before feeding it to the plant.

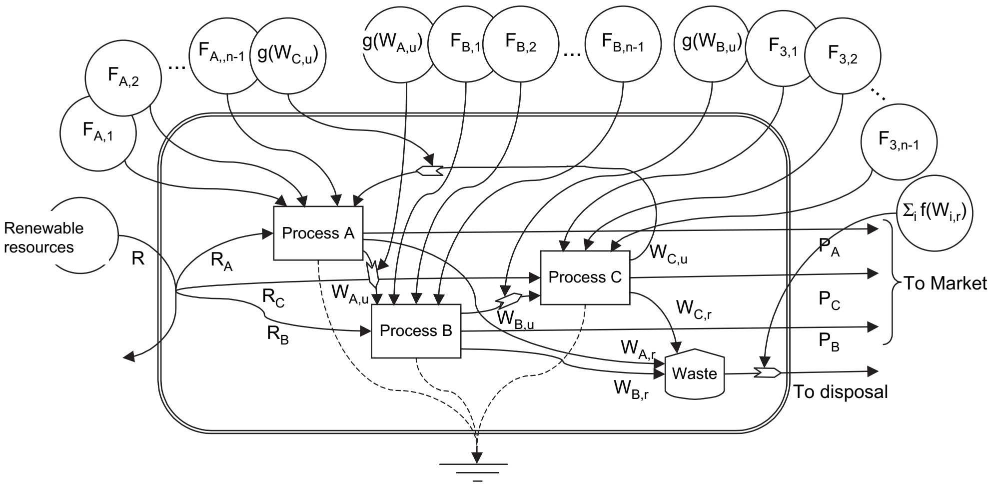

Fig. 4. Systems diagram of an integrated production system, in which the waste released by one process is at least partially used as raw resource by another process. In so doing, decrease of pollution and power output maximization are achieved. Information (technology, design, interaction among components, knowledge) becomes an important factor for such a production pattern, in addition to traditional input of resources, labor, and capital. Systems symbols from Fig. 1. Abbreviations used are as follows: P_i = mass of product(s) from the *i*th process; $W_{i,r}$ = residual mass of unused waste(s) from the *i*th process; $W_{i,u}$ = mass of waste(s) usefully transferred from the *i*th process; R_i = renewable e*m*ergy to the *i*th process; $F_{i,j}$ = non-renewable e*m*ergy of the *j*th input to the *i*th process; $g(W_{i,u})$ = e*m*ergy invested to transfer still usable waste materials from the *i*th process to any other process; and $f(W_{i,r})$ = e*m*ergy invested for disposal of residual waste $W_{i,r}$ from the *i*th process or for repair of the related damage (i = A, B, C; $j = 1,\ldots,n-1$).

Fig. 6) installed in Italy in the last years.[10] The increase of plant complexity (interaction among components, improved design and management options, similarly to the cluster system in Fig. 4) coupled with optimum use of waste heat, allows a better exploitation of the fuel exergy and decreases the amount of unused heat and chemicals that are released per unit of product. The fuel Q provided to the CCGT plant in Fig. 6 is firstly converted into electricity and hot combustion gases within a modern gas turbine. Heat carried by combustion gases is converted into steam to power a steam turbine for further electricity production. Residual heat is released to a heat exchanger as usable, low-temperature heat to meet the heat demand from nearby users (district heating, firms, etc.). Table 5 shows exergy flows and efficiency for each step of the system and for the system as a whole. Assuming a combustion temperature around 1500 K in the gas turbine and a heat release to the steam turbine around 900 K, a Carnot efficiency $\eta_{GT,F} = (1500-900)/1500\text{ K} = 40.0\%$ is calculated for the gas turbine, which means that 40.0% of total fuel energy Q is converted to electricity within the gas turbine. The residual $(1-0.4)$Q is transferred as heat to the downstream steam turbine. An amount of about 10%Q is assumed to be lost through the chimney, while a further, roughly estimated 5%Q must be subtracted due to several sources of irreversibility existing in both turbines, such as heat losses for conduction and friction, totalling a loss of about 15%Q. Assuming that the steam turbine input temperature is 900 K and the output temperature 600 K, its Carnot efficiency is calculated as $\eta_{ST} = (900-600)/900\text{ K} = 33.3\%$, which means that the steam turbine generates an amount of electricity equal to the 33.3% of the heat received from the upstream gas turbine, translating into about 16.6%Q. A residual heat is then passed to a heat exchanger at a temperature of about 600 K. The Carnot efficiency of the heat exchanger alone, assuming that some heat is in turn released unused at 350 K, is $\eta_{HE} = (600-350)/600\text{ K} = 41.7\%$, which means that in principle a useful exergy of about 11.8%Q can be delivered by the heat generator. Finally, it is as follows:

Exergy output as electricity from the gas turbine = 0.4Q joule
Exergy output as electricity from the steam turbine = 0.166Q joule
Exergy output as low-temperature heat from the heat exchanger = 0.118Q joule.

The total electric exergy efficiency is therefore, in principle, around 56.6% in good agreement with actual operation data of Italian CCGTs. The total (exergy) efficiency grows to 68.1% if the exergy of heat delivered is also accounted for as a usable product. Slightly smaller efficiencies may be obtained in real CCGT plants, due to other sources of irreversibility, not accounted for here. Table 6 shows fuel consumption as well as emissions of the main combustion products per unit of electricity delivered (first column) and per unit of total exergy (electricity + heat) delivered.

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[10] The main components of the plant are two power groups that are identical and supply a total net electrical power of about 735 MW. Auxiliary equipments that serve the power groups directly are also considered. Each group consists of a gas turbine, a heat recovery steam generator (HRSG), a steam turbine (ST) and a steam condenser that extracts the residual heat to be used for district heating. The basic flow of each group is described in Fig. 6. The HRSG, not shown in the figure, uses heat from GT to generate sub-critical steam which in turn is delivered to the steam turbine ST to provide further mechanical power. Both GT and ST are mechanically connected to the generator that supplies the electric power. The steam exhausted from the turbine is condensed in a heat exchanger, which allows further heat exploitation for district heating or other low temperature uses.

Table 2
E*m*ergy flows among the processes of a local economy and the surrounding environment, with e*m*ergy exchanges among processes

To ⇨ From ⇩	Environment	Process A	Process B	Process C
Environment (seJ)	0	$R_{\rm A} + \sum_{j=1,\dots,n-1} F_{{\rm A},j} + g(W_{\rm Cu}) + f(W_{\rm Ar})$	$R_{\rm B} + \sum_{j=1,\dots,n-1} F_{{\rm B},j} + g(W_{\rm Au}) + f(W_{\rm Br})$	$R_{\rm C} + \sum_{j=1,\dots,n-1} F_{{\rm C},j} + g(W_{\rm Bu}) + f(W_{\rm Cr})$
Process A (g)	$P_{\rm A} + W_{\rm Ar}$	0	$W_{\rm Au}$	0
Process B (g)	$P_{\rm B} + W_{\rm Br}$	0	0	$W_{\rm Bu}$
Process C (g)	$P_{\rm C} + W_{\rm Cr}$	$W_{\rm Cu}$	0	0
Transformity of product (seJ/g)		$\left[R_{\rm A} + \sum_{j=1,\dots,n-1} F_{{\rm A},j} + g(W_{\rm Cu}) + f(W_{\rm Ar})\right]/P_{\rm A}$	$\left[R_{\rm B} + \sum_{j=1,\dots,n-1} F_{{\rm B},j} + g(W_{\rm Au}) + f(W_{\rm Br})\right]/P_{\rm B}$	$\left[R_{\rm C} + \sum_{j=1,\dots,n-1} F_{{\rm C},j} + g(W_{\rm Bu}) + f(W_{\rm Cr})\right]/P_{\rm C}$

P_i = mass of product(s) from the *i*th process; $W_{i,r}$ = residual mass of unused waste(s) from the *i*th process; $W_{i,u}$ = mass of waste(s) usefully transferred from the *i*th process; R_i = renewable e*m*ergy to the *i*th process; $F_{i,j}$ = non-renewable e*m*ergy of the *j*th input to the *i*th process; $g(W_{i,u})$ = e*m*ergy invested to transfer still usable waste materials from the *i*th process to any other process; $f(W_{i,r})$ = e*m*ergy invested for disposal of residual waste $W_{i,r}$ from the *i*th process or for repair of the related damage (i = A, B, C; $j = 1,\dots,n-1$).

A comparison between Table 4 and Table 6 clearly shows the large decreases of greenhouse gases and other emissions due to the more complex and innovative structure of the CCGT plant. The much lower consumption of fuel per kWh of electricity or per kWh of exergy delivered translates into a better environmental performance.

The total e*m*ergy supporting the investigated plants was also assessed. Natural, material and economic input items needed for each plant construction and operation were calculated on a yearly basis and multiplied by appropriate values of e*m*ergy intensities (seJ/J, seJ/g, seJ/yr, seJ/€), thus yielding the amount of e*m*ergy associated to each input item. The sum of all input e*m*ergies, divided by exergy joules of produced electricity and heat, yields the e*m*ergy intensity (transformity) of each product. Further calculations generate e*m*ergy-based performance and sustainability indices as well as help identify the relative weight of input item categories (renewables, fuels, goods and machinery, labor and services) for proper assessment of plant performance and understanding of the role of each category. In so doing, it is possible to evaluate the environmental support to both power plants, in order to understand the global cost of the two alternatives and prevent any doubts about the existence of hidden costs afforded to increase the CCGT plant performance. The heat from steam and gas turbines was considered as a co-product of electricity generation: input and output flows were assigned to both products according to the e*m*ergy algebra [3]. The same rationale applies to the heat transferred from step to step in the CCGT process. Instead, the heat production from the integrative boilers of the STGT plant clearly represents a split of the input fuel, distinct from electricity production, and therefore, only the inputs for the boiler structure, fuel supplied and related services were assigned. Selected results from e*m*ergy accounting are presented in Table 7.

5. Discussion of results

Flows in the first column of Tables 4 and 6 are related to one unit of electricity generated, while in the second column the product is one unit of exergy (also including the exergy of co-generated hot water). Indicators for the latter case are generally much better, as expected, due to the optimum use of waste heat. However, the results still show a large potential for improvement. Tables 5 and 6 show the much better performance of a CCGT plant, where more useful output is generated per unit of fuel, and less chemicals are released per unit of product.

Table 3
Environmental support to the local system of production processes A, B, and C, with and without cluster-type organization (from Tables 1 and 2)

System	E*m*ergy supplied (seJ)
$({\rm A}+{\rm B}+{\rm C})_{\text{no-cluster}}$	$\sum_i R_i + \sum_i \sum_{j=1,\dots,n} F_{i,j} + \sum_i f(W_i)$
$({\rm A}+{\rm B}+{\rm C})_{\text{cluster}}$	$\sum_i R_i + \sum_i \sum_{j=1,\dots,n-1} F_{i,j} + \sum_i g(W_{i,u}) + \sum_i f(W_{i,r})$
Difference (no-cluster−cluster)	$\sum_i F_{i,n} - \sum_i g(W_{i,u}) + \sum_i f(W_i) - \sum_i f(W_{i,r})$

$W_{i,r}$ = residual mass of unused waste(s) from the *i*th process; $W_{i,u}$ = mass of waste(s) usefully transferred from the *i*th process; R_i = renewable e*m*ergy to the *i*th process; $F_{i,j}$ = non-renewable e*m*ergy of the *j*th input to the *i*th process; $g(W_{i,u})$ = e*m*ergy invested to transfer still usable waste materials from the *i*th process to any other process; $f(W_i)$ = e*m*ergy invested for disposal of total waste from the *i*th process or for repair of the related damage; and $f(W_{i,r})$ = e*m*ergy invested for disposal of residual waste $W_{i,r}$ from the *i*th process or for repair of the related damage. (i = A, B, C).

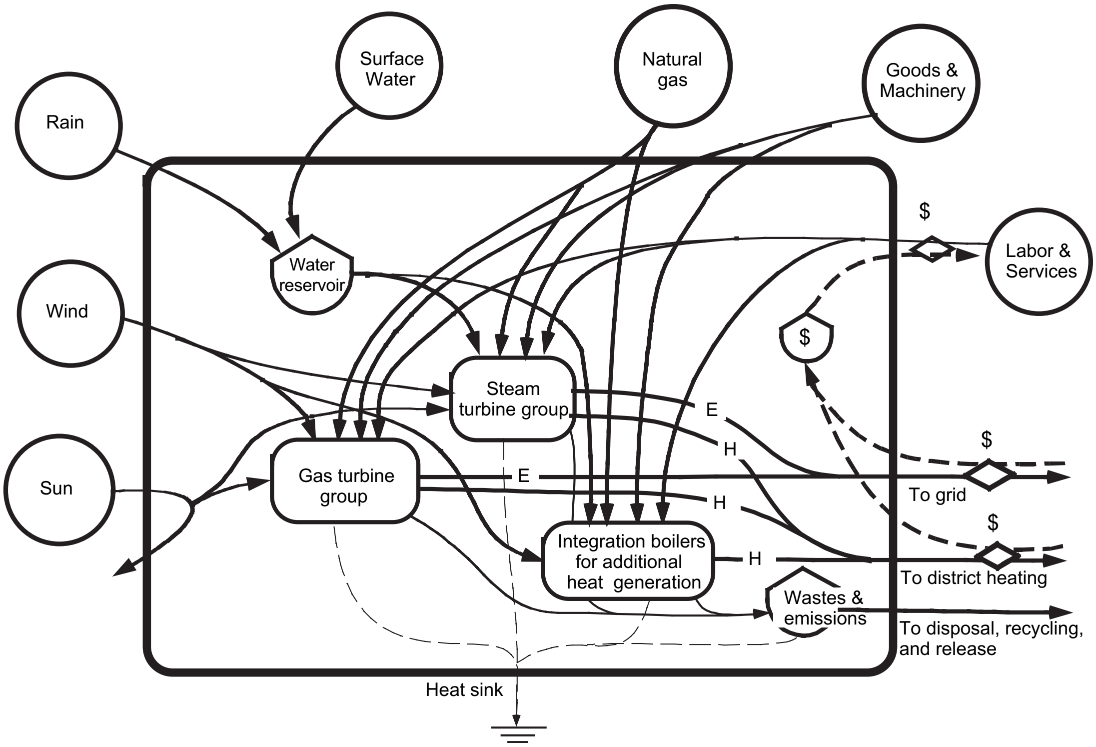

Fig. 5. Systems diagram of a Steam Turbine/Gas Turbine cogeneration plant, with additional boilers for hot water production. The three thermal systems (Steam Turbine, Gas Turbine and Integration Boilers are independent to each other: they convert fuel into electricity and heat without interacting. Three distinct heat flows (H) converge to district heating, while two electricity flows (E) converge to the grid. System's symbols from Fig. 1. Thin dotted lines represent waste heat to sink and thick dotted lines represent money flows.

LCA results highlight a system's performance on the local (or process) scale, i.e. they focus on the interactions between the process and the directly surrounding environment. The local performance could, however, differ from an assessment based on larger time and spatial frames, due to the different environmental dynamics of each matter and energy flow on both source and sink sides. Something may appear environmentally friendly on the local scale, but may be very energy intensive or highly polluting on the large scale and therefore, require a larger amount of environmental services for support and dilution. Again, this means that, when the complexity of the larger system surrounding and supporting the process is accounted for, LCA results do not fully describe the interplay of the system and the environment. Sustainability assessment requires this dynamics to be clearly identified, which is not very often the case in published case studies. Table 7 shows a comparison between the two kinds of plants based on e*m*ergy results. Transformities, a measure of the global scale efficiency of a process, indicate the direct and indirect environmental support to the investigated system(s). Previous investigations of different power plants in Italy [3] provided transformities in the range 1.10E+05−3.54E+05 seJ/J, the lower figure referring to electricity from a wind turbine and the higher one to electricity from a more traditional oil fueled steam power plant. The transformity for STGT electricity (3.15E+05 seJ/J) falls very close to the higher end of the range, as expected, while instead CCGT electricity requires a much lower environmental support per unit of product (1.90E+05 seJ/J). The transformity of total, co-generated heat and electricity (both measured in exergy units) drops significantly by about 50% in the case of the STGT plant, as a consequence of the large amount of resource available in the generated heat. This makes the plant best suited to provide heat for district heating, in spite of its

Table 4
LCA efficiency and mass flows in the steam turbine/Gas Turbine (STGT) plant

	G/(kWh$_{el}$yr)	g/(kWh$_{(el+q)}$yr)
Main mass flows to the STGT process		
Concrete	0.464	0.558
Iron and steel	0.369	0.444
Copper	0.005	0.006
Diesel, cooling oil, lube oil	0.141	0.170
Natural gas	283.077	154.599
Main airborne emissions from the STGT process		
CO_2	739.336	403.779
CO	0.381	0.208
CH_4	0.014	0.008
VOC and HC	0.007	0.004
NO_x	1.036	0.566
N_2O	0.007	0.004
Particulate matter	0.017	0.010
Plant efficiency		
η_{el}	24.65%	
$\eta_{(el+q)}$	45.14%	

q = Thermal exergy of co-generated heat.

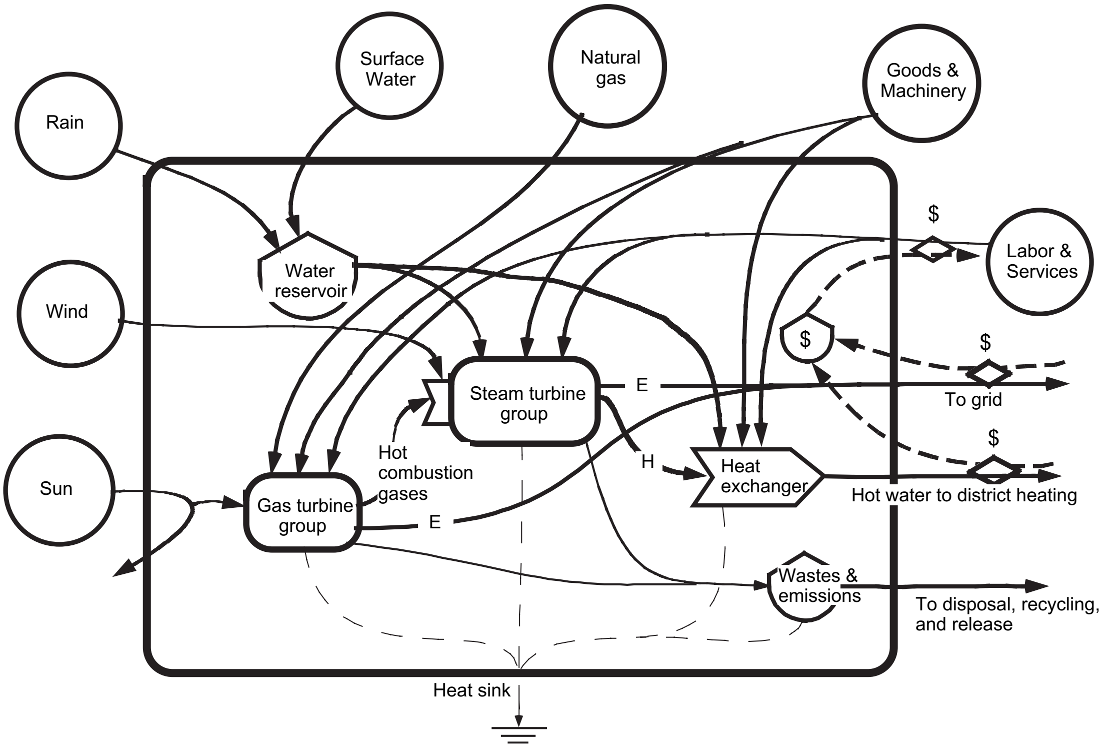

Fig. 6. Systems diagram of a typical Combined Cycle Gas Turbine, with cascade utilization of fuel exergy, for maximum power output. Combustion gases from Gas Turbine deliver heat to the Steam Turbine, where further electricity is generated. Finally, residual heat is delivered to district heating, via a heat exchanger and related infrastructure. Heat flow (H) is delivered to district heating, while two electricity flows (E) converge to the grid. Systems symbols from Fig. 1. Thin dotted lines represent waste heat to sink and thick dotted lines represent money flows.

low efficiency. Instead, when the exergy of co-generated heat is also accounted for, a smaller improvement is calculated for the CCGT, since this plant is designed to achieve the maximization of electricity production at the expenses of a lower residual exergy in waste heat. Anyway, the transformity of the total exergy delivered by the CCGT plant (1.56E+05 seJ/J) is very close to the lower end of the range (the renewable sources) and indicates a conversion process where direct and indirect environmental inputs are converted very efficiently.

Table 5
Thermodynamic performance of a CCGT − Combined Cycle Gas Turbine plant

Index of performance	Gas turbine	Steam turbine	Heat exchanger	Flows delivered to final user or environment
Type of product flow delivered	Electricity	Electricity	High temperature water	−
Temperature of input heat (K)	1500	900	600	−
Temperature of output heat (K)	900	600	350	−
Carnot efficiency, η	40.0%	33.3%	41.7%	−
Exergy input	Q	0.5Q[a]	0.284Q[b]	−
Heat loss at chimney	0.1Q	−	−	−
Additional heat loss due to irreversibility	−	0.05Q	−	−
Heat delivered to the next step at lower temperature	0.5Q[a]	0.284Q[b]	0.165Q[c]	−
Waste heat step by step and total	0.1Q	0.05Q	0.165Q	0.315Q[d]
Useful exergy delivered, step by step and total	0.4Q	0.166Q[e]	0.118Q[f]	0.684Q[g]
Cumulative exergy efficiency	40.0%	56.6%[h]	68.4%[i]	−

[a] (1−0.4−0.1)Q.

[b] [(1−0.333) × (1−0.4−0.1)−0.05]Q.

[c] (1−0.417) × [(1−0.333) × (1−0.4−0.1)−0.05]Q.

[d] (0.1 + 0.05 + 0.165)Q.

[e] 0.333 × (1−0.4−0.1)Q.

[f] 0.417[(1−0.333)(1−0.4−0.1)−0.05]Q.

[g] (0.4 + 0.166 + 0.118)Q.

[h] 40.0% + 16.6%.

[i] 40.0% + 16.6% + 11.8%.

Table 6
Fuel consumption and main emissions in a Combined Cycle Gas Turbine plant

	g/(kWh$_{el}$ yr)	g/(kWh$_{(el+q)}$ yr)
Fuel supplied to the CCGT process		
Natural gas	123.288	100.976
Main airborne emissions from CCGT process		
CO_2	339.042	277.685
CO	0.095	0.078
CH_4	0.002	0.002
VOC and HC	0.005	0.004
NO_x	0.324	0.266
N_2O	0.002	0.002
Particulate matter	0.037	0.030

q = Thermal exergy of co-generated heat.

5.1. Information cost

As suggested in Section 2.5 and footnote 8, a rough estimate of information input to a process or system can be obtained from converting labor and services into e*m*ergy units. Labor is human activity performed within the process, services are human activity performed outside of the process and before the process beginning. While we can measure hours of direct labor, it is much more difficult to measure the hours spent in the thousands of activities which support the process by providing fuels, know-how, and technology. What is information e*m*ergy in a power plant? It is the e*m*ergy it took to design the plant components, assemble them into a plant and keep it running properly. It also includes the e*m*ergy required to find, extract, refine and transport oil or natural gas to power the plant. It is important to note that this e*m*ergy is not the e*m*ergy content of the fuel (i.e. the e*m*ergy invested by nature to make fossil fuels in underground reservoirs), but it is instead the e*m*ergy invested in know-how, technology, and education needed to performs all of these tasks. It includes indirect inputs required for training workers and technicians, as well as all inputs required to support directly or indirectly the human labor involved in planning, designing and actually making parts and infrastructures.[11] In general labor can be measured in hours, years or money of income; services are always measured in money units, on the basis of the assumption that income reflects working role which in turn reflects previous training and education (which is not always the case, however). Both labor and services are then converted into e*m*ergy and provide a preliminary, gross estimate of the information supplied to the plant in the form of e*m*ergy supporting all kinds of human activities involved. We calculated this value for several power plants. In the case of a 1280-MW coal fired power plant in Italy, information e*m*ergy was 9.04E+04 seJ/J$_{el}$, equivalent to the 24% of total e*m*ergy input, while instead for the STGT 171 MW natural gas power plant we calculated about 3.03E+04 seJ/J, equivalent to 9.3% of total e*m*ergy input. Of course, information fraction is relatively small in power plants, where fuel e*m*ergy and construction materials dominate, while it becomes a major input in activities based on information processing in the service sectors of modern societies.

Table 7
Selected results from e*m*ergy analysis of STGT and CCGT processes

Transformity of	seJ/J
STGT process	
Electricity delivered	3.15E+05
Total exergy delivered (electricity + heat)	1.73E+05
CCGT process	
Electricity delivered	1.90E+05
Total exergy delivered (electricity + heat)	1.56E+05

6. Conclusion

A joint application of Life Cycle Assessment and E*m*ergy Synthesis, named E*m*ergy Life Cycle Assessment, is shown to provide information about input and output material flows as well as about the environmental support to the system, in order to facilitate choices and policy-making towards Zero Emission Strategies and Techniques. Results show that increasing the complexity of the system as well as the use of co-products helps to achieve a better performance and an optimum use of available resources. The case study is only based on the performance comparison of two power plants, which does not entail all the possible ways for complexity increase. In fact, if a plant (or any other production system) is really integrated within the local productive structure, it is no longer just a point source of electricity, hot water and released chemicals. Other cycles can be involved (water and wastewater, fuel from urban and biomass waste, use of sulphur from fuel purification, etc.), which could generate further non-negligible economic and environmental advantages. In order to do this, the input of information needed may take the form of landscape planning and alternative option exploration, and lead to the construction of infrastructures capable of linking all the possible partners involved in co-product/raw material exchange and use.

The new framework for the evaluation of production activities presented in this paper, the so-called Zero-Emission strategy, is found to be in very good agreement with Lotka–Odum's Maximum Power Principle in ecosystems. The two strategies/statements are, in principle, equivalent. Zero-emission technologies to guide the way human-dominated systems can achieve maximum power output in times of scarce resources, like natural ecosystems have already learned to do over their evolutionary trajectories.

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