Emergy, LCA, and Zero Emissions: The Search for Synergies

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ABSTRACT

Society uses environmental resources directly and indirectly from both renewable energy fluxes and storages of materials and energy that resulted from past biosphere production. The interaction and integration among a system’s components, the internal exchange of resources and services, the identification of matter and energy flows to, from, and within a system (Life Cycle Assessment), the demand for environmental support (emergy), 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. Mathematical expressions for total emergy demand; emergy savings from waste recycling; and emergy cost of technology and information needed for integration, waste disposal, and damage repair are provided and a quantitative criterion for the evaluation of benefits from zero-emission patterns is finally discussed.

INTRODUCTION

Human-dominated systems (e.g., whole economies, production sectors, technological processes) are all supported by primary energy and material flows through environmental services and ecosystem dynamics (Figure 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. It is imperative that insight be gained concerning the interplay of society and environment to help direct planning and policy for the third millennium. Emergy analysis and synthesis (Odum, 1996) provides a comprehensive tool for investigating and understanding the dynamics of resource flows between the biosphere and its sub-systems, with special focus on human-dominated processes and the need for sustainable use of resources and minimization of environmental impact.

Other evaluation tools (including Life Cycle Assessment [LCA], Material Flow Accounting [MFA], and Ecological Footprint [EF]) have been suggested and used for the evaluation of economic and technological systems. These tools, although significant and accepted worldwide by the scientific and policy-making communities, only partially address the need for a deeper insight into the quality and the sustainability of human-dominated processes on the larger time and spatial scale of the biosphere. Therefore, we suggest exploring the potential for synergies among different evaluation tools, in order to provide an assessment of processes at different hierarchical levels, at different spatial scales, and at different past and future time frames.

In this paper, a systems view of society and production processes is taken and a special focus is placed on the synergy between LCA and Emergy Synthesis methods. 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; the demand for environmental support; and,
Figure 1. Generic systems diagram (Ulgiati and Brown, 2002, modif.), showing renewable and nonrenewable 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. Systems symbols from Odum (1983, 1996).
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.

EMERGY 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 Emergy Synthesis, as a tool for evaluating the environmental support provided by nature to human societies, is summarized first. Environmental support, sometimes named “ecological footprint,” is very often disregarded in conventional economic analyses. How Emergy Synthesis can be synergistically 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 Lotka-Odum’s Maximum Power Principle (MPP). The concept of Zero Emission Technologies and Systems (ZETS) is presented and discussed and its links to MPP are highlighted. Finally, the concept of information (e.g., know-how and culture); 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 Emergy Life Cycle Assessment tool, which can be used for environmental policy development.

Emergy, 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. 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. H.T. Odum introduced the concept of *emergy* (spelled with an *m*) in the 1980s, in order to properly account for the quality of matter, energy, and information flows within systems, including their degradation due to second law losses (Odum, 1988). Emergy 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 (Odum, 1996; Brown and Ulgiati, 2004). By definition, emergy 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 emergy are solar emjoules (abbreviated seJ) to distinguish them from actual energy joules (abbreviated J). When the emergy 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 emergy joules per joule of output flow (seJ/J).

The total emergy 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 emergy 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.

\footnote{All energies can be converted to heat at 100 percent 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 cm³ of distilled water from 14.5 °C to 15.5 °C at the atmospheric pressure. A calorie is equal to 4.187 joules.}
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The emergy synthesis method is used in the remainder 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, emergy 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.

**Combining LCA and Emergy Synthesis**

LCAs conventionally account for all energy and matter flow to and from a chain of processes from raw material(s) to the final product(s) (Ayres 1995; ISO 1997, 1998). 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 that 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 (e.g., contribution to energy resource depletion, global warming potential, rain acidification potential), 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 (Szargut et al., 1988). 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, LCA, in general, only accounts for matter and energy flows occurring under human control. Instead, flows outside of market dynamics (such as environmental services) and flows that are not associated with significant matter and energy carriers (such as labor, culture, and information) are not generally included. When sustainability comes into play as a major concern, these flows become relevant and cannot be disregarded. Emergy Synthesis is the only way 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 emergy 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.

**Lotka-Odum’s Maximum Empower Principle**

Designs are reinforced that maximize power output as much as possible from the resources available, as suggested by Lotka’s Maximum Power Principle (Lotka, 1922a and b). 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 (1983, 1996) restated Lotka’s principle via the emergy concept as Maximum Empower Principle. The revised statement is:

*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. 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 (Odum and Pinkerton, 1955). Societies deplete most of the known and accessible resource storages, on both the source side (reservoirs of nonrenewable resources such as oil, minerals, and 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 framework (ZETS, Schnitzer and Ulgiati, 2006).

**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 and 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.

Of course, zero-emission strategies are a trend, an ideal and desirable target and nobody should think

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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 and 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 and nutrients). 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 one percent 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.
that “zero” can be achieved in real systems. Yet, we can proceed towards decreasing emissions, but the extent to which it can be done is not the “end-of-pipe” approach, but instead the exchange of resources in order to make more with less.

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 (Pauli, 1998). 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 maximize power and, therefore, be successful in medium and long-term competition, when resources become more scarce.

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. 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 [Gravitis and Suzuki, 1999]). 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. (ZEF, 1999).

A significant experience in this regard is the so-called Industrial Symbiosis in the Danish town of Kalundborg, (Evans, 1995; Ehrenfeld and Gertler, 1997; 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 m³/yr), fuel oil (20,000 t/yr), and decreased SO₂ 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; sulphur, fertilizers, enzymes, and recycled materials are also extracted in large amounts and marketed. It is important to note that the Kalundborg Eco-Industrial Park was not initially designed as such, but gradually 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 (1996), Heeres et al. (2004), and Desrochers (2004).

The Information Cycle

The importance of knowledge and information as key factors for zero emission strategies were underlined in the previous section. 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 or to the way information is generated in natural and economic systems. Information is no doubt one of the concepts that H.T. Odum investigated deeply. 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. Living organisms reproduce, copy, repair, revise, and reapply their information (Odum, 1996).

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, testing them for survival, and discontinuing those copies that do not work (Figure 2).

In Odum’s words:

...a closed circle of information processing is necessary to maintaining one unit of information. It takes energy to support the whole cycle: very little energy to make copies, more energy to extract information in a form that can be disseminated (e.g.: spores, seeds, CDs), even more energy to sustain shared information (i.e. maintaining information by maintaining the whole population where this information is duplicated, selected and reproduced6). Finally, it may take even much more energy to develop new, useful information from its precursor (i.e. the energy 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 energy needed to copy, disperse, use, test and select the existing information as well as to generate new information units. (Odum, 1996).

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 energy flows. The information carried by books, software, money, and expertise is also generated and supported by direct and indirect energy 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 consensus on information measures, especially when complex systems (ecosystems, societies, culture) are involved (Shannon, 1948; Brillouin, 1962; Tribus and McIrvine, 1971). 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 energy terms. For example, Odum (1989) explored the energy 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 energy intensities per hour or joule of applied educated labor.

Several energy analysts calculated the total energy driving national economies for the generation of their Gross National Products (Huang and Shih, 1992; Cialani et al., 2005; Hagström and Nilsson, 2005; Sweeney et al., 2006; Cohen et al., 2006; Lomas et al., 2006; among others). Their data can be used to assess the energy intensity of one unit of GDP generated (energy 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 energy intensities of currency and labor can be used to convert hours of educated labor, money of earner income, and financial investments into information-related

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

6 For example, 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).
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Figure 2. The main features of an information maintenance circle, including depreciation, extracting, copying, operating, testing, and selection (Odum, 1996).

Emergy inputs to a process. Moreover, since labor and know-how cannot be applied without using additional technological devices, we should also recognize the emergy cost of the latter as part of the cost of providing and using information. For example, the emergy cost of material infrastructure for heat exchange between two firms adds up to the emergy supporting labor and services for design, construction, and operation of such an infrastructure. Both of them are emergy investments required to increase the interaction among different parts of a system, 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 emergy 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.

STRATEGIES FOR ZERO EMISSION PATTERNS

Zero Emission strategies clearly indicate the direction for Maximum Empower to be achieved in human dominated systems, by suggesting that they emulate nature by increasing the complexity of relations between components. If the number of components and exchange links increases as a consequence of the availability of still usable resources, empower is maximized, even if the efficiency of individual processes cannot. Natural processes do not differ from all other human-dominated processes if considered individually. All of them release unused resource flows. However, natural selection rewards those systems (networks) that co-evolved with others by exchanging resource flows and using resources effectively. Therefore, Zero Emissions are impossible for any individual process, but become possible (or relatively possible) for a system as a whole. 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 as follows.
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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. Since they are potentially able to drive undesired processes within the surrounding environment, smaller environmental loads are generated and 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.

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 energy used and the amount of products generated (energy, goods, and services) over the whole chain of processes offers a way to calculate their global scale efficiency. When new information (e.g., innovative technologies, more trained labor, and new patterns for use of residues and co-products) is added to the process, energy-based efficiency offers a way to monitor the improvement of 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.

Modeling Matter and Energy Flows within a Zero Emission Framework

Figure 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 energy supporting a given process can be calculated by multiplying each renewable and nonrenewable input flow of energy and matter by a suitable transformity value (Odum, 1996; Brown and Ulgiati, 2004). In so doing, the total energy driving each process can be calculated (Table 1, first row) and then used to derive the transformity (unit energy 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. (1995) and Ulgiati et al. (2004) suggested that an additional energy 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 energy cost of disposal and repair. This input is also included in the expressions of Table 1, as a function f(W) of the amount of waste material released. Processes A, B, and C in Figure 3 do not exchange any resource flow, as also reported in Table 1.

Instead, Figure 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 reduction in the amount of resources is required from

According to Ulgiati et al. (1995), the function f(W) is composed with at least two kinds of contribution: the investment needed for abatement or disposal, Fd(W), and the investment needed for damage repair, Fr(W). The direct energy 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:

\[ f(W) = Fd(W) + Fr(W) = \sum c_i m_{wi} + \sum d_k N_k \]  

Eqn. (1)

where \( c_i \) is the energy investment needed (kJ/g) for safe disposal of one mass unit of the \( i \)th waste flow, \( m_{wi} \) (grams) and \( d_k \) is the energy investment needed (kJ/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.
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**Figure 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. Systems symbols from Figure 1. Abbreviations used: \( P_i \) = mass of product(s) from the \( i^{th} \) process; \( W_i \) = mass of waste(s) from the \( i^{th} \) process; \( R_i \) = renewable energy to the \( i^{th} \) process; \( F_{i,j} \) = non-renewable energy of the \( j^{th} \) input to the \( i^{th} \) process; \( f(W_i) \) = energy invested for disposal of waste from the \( i^{th} \) process or for damage repair. (\( i = A, B, C; j = 1, \ldots, n \)).

**Figure 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 Figure 1. Abbreviations used: \( P_i \) = mass of product(s) from the \( i^{th} \) process; \( W_{ir} \) = residual mass of unused waste(s) from the \( i^{th} \) process; \( W_{iu} \) = mass of waste(s) usefully transferred from the \( i^{th} \) process; \( R_i \) = renewable energy to the \( i^{th} \) process; \( F_{i,j} \) = non-renewable energy of the \( j^{th} \) input to the \( i^{th} \) process; \( g(W_{iu}) \) = energy invested to transfer still usable waste materials from the \( i^{th} \) process to any other process; \( f(W_{ir}) \) = energy invested for disposal of residual waste \( W_{ir} \) from the \( i^{th} \) process or for repair of the related damage. (\( i = A, B, C; j = 1, \ldots, n-1 \)).
Table 1. Energy flows from and to the processes of a local economy and the surrounding environment, without energy exchanges among processes.

<table>
<thead>
<tr>
<th>To</th>
<th>Environment</th>
<th>Process A</th>
<th>Process B</th>
<th>Process C</th>
</tr>
</thead>
<tbody>
<tr>
<td>From</td>
<td>(seJ)</td>
<td>R_A + Σ_{j=1,\ldots,n} F_A,j + f(W_A)/P_A</td>
<td>R_B + Σ_{j=1,\ldots,n} F_B,j + f(W_B)/P_B</td>
<td>R_C + Σ_{j=1,\ldots,n} F_C,j + f(W_C)/P_C</td>
</tr>
<tr>
<td>Environment</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Process A (g)</td>
<td>P_A + W_A</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Process B (g)</td>
<td>P_B + W_B</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Process C (g)</td>
<td>P_C + W_C</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Transformity of product (seJ/g) = \frac{[R_A + Σ_{j=1,\ldots,n} F_A,j]}{P_A} + \frac{f(W_A)}{P_A}.

Abbreviations used:
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 energy to the i^{th} process; F_{i,j} = non-renewable energy of the j^{th} input to the i^{th} process; f(W_i) = energy invested for disposal of waste from the i^{th} process or for damage repair. (i= A, B, C; j= 1,...,n).

Table 1 shows the total energy 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:

\[ \Delta = \text{Emergy} (A+B+C)_{\text{no-cluster}} - \text{Emergy} (A+B+C)_{\text{cluster}} = \]

\[ = \sum_i R_i + \sum_{j=1,\ldots,n} F_{i,j} + \sum_i f(W_i) - \left[ \sum_i R_i + \sum_{j=1,\ldots,n} F_{i,j} + \sum_i g(W_i) + \sum_i f(W_i) \right] = \]

\[ = \sum_i F_{i,in} - \sum_i g(W_i) + \sum_i f(W_i) \quad (i= A, B, C) \quad \text{Eqn. (2)} \]

Since \( W_{i,\text{in}} < W_{i,\text{ir}} \), then \( \sum_i f(W_i) - \sum_i f(W_i) > 0 \). If \( \sum_i F_{i,in} - \sum_i g(W_i) > 0 \) or, at least, not too negative, the whole expression \( \Delta > 0 \), and the creation of links and exchange flows among components translates into a global advantage to the local system in terms of less energy invested. The expression \( \Delta \) includes the lower energy demand for process support and waste management, as well as the additional cost of knowledge and information that makes the cluster possible. It should be underlined that decreasing the unused materials thanks to the cluster organization also pulls down the potential pollution at an energy cost lower than without cluster, designing a trend towards zero emissions through process optimization.

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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 energy needed to generate know-how as the result of education and research as well as the energy required to drive economic activities which support labor and generate GDP. The fraction of this energy which can be assigned to the investigated process is a proxy for the information supplied.

9 The term \( g(W_{i,\text{ir}}) \) might also include some energy carried by the flow transferred from a process to another. If a waste flow \( W_{i,\text{ir}} \) is re-used within or re-directed to process 2 of the cluster is a split from process 1, it should carry its share of energy driving process 1, according to the energy algebra. Instead, if it is a co-product, it should in principle carry the total energy driving the process. We assume here that co-product flows that go outside the boundary of the cluster do deliver additional energy to an outside process, while instead co-product flows that are used within the boundaries of the investigated cluster as a whole do not, as they are considered recycled flows at the more aggregated level of the cluster and the energy algebra is applied accordingly.
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Table 2. Emergy flows among the processes of a local economy and the surrounding environment, with emergy exchanges among processes.

<table>
<thead>
<tr>
<th>To From</th>
<th>Environment</th>
<th>Process A</th>
<th>Process B</th>
<th>Process C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environment</td>
<td>0</td>
<td>(R_A + \sum_{j=1}^{n-1} F_{A,j} + g(W_{Cu}) + f(W_{Ar}))</td>
<td>(R_B + \sum_{j=1}^{n-1} F_{B,j} + g(W_{Au}) + f(W_{Br}))</td>
<td>(R_C + \sum_{j=1}^{n-1} F_{C,j} + g(W_{Bu}) + f(W_{Cr}))</td>
</tr>
<tr>
<td>Process A (g)</td>
<td>(P_A + W_{Ar})</td>
<td>0</td>
<td>(W_{An})</td>
<td>0</td>
</tr>
<tr>
<td>Process B (g)</td>
<td>(P_B + W_{Br})</td>
<td>0</td>
<td>0</td>
<td>(W_{Bu})</td>
</tr>
<tr>
<td>Process C (g)</td>
<td>(P_C + W_{Cr})</td>
<td>(W_{Cu})</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Transformity of product (seJ/g)

\[
\text{Transformity} = \frac{[R_A + \sum_{j=1}^{n-1} F_{A,j} + g(W_{Cu}) + f(W_{Ar})]}{P_A} \quad \frac{[R_B + \sum_{j=1}^{n-1} F_{B,j} + g(W_{Au}) + f(W_{Br})]}{P_B} \quad \frac{[R_C + \sum_{j=1}^{n-1} F_{C,j} + g(W_{Bu}) + f(W_{Cr})]}{P_C}
\]

Abbreviations used:

- \(P_i\) = mass of product(s) from the \(i^{th}\) process;
- \(W_{ir}\) = residual mass of unused waste(s) from the \(i^{th}\) process;
- \(W_{iu}\) = mass of waste(s) usefully transferred from the \(i^{th}\) process;
- \(R_i\) = renewable energy to the \(i^{th}\) process;
- \(F_{ij}\) = non-renewable energy of the \(j^{th}\) input to the \(i^{th}\) process;
- \(g(W_{iu})\) = emergy invested to transfer still usable waste materials from the \(i^{th}\) process to any other process;
- \(f(W_{ir})\) = emergy invested for disposal of residual waste \(W_{ir}\) from the \(i^{th}\) process or for repair of the related damage.

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).

<table>
<thead>
<tr>
<th>System</th>
<th>Energy (seJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>((A+B+C)_{\text{no cluster}})</td>
<td>(\sum_i R_i + \sum_j F_{ij} + \sum_i f(W_{i}))</td>
</tr>
<tr>
<td>((A+B+C)_{\text{cluster}})</td>
<td>(\sum_i R_i + \sum_j F_{ij} + \sum_i g(W_{iu}) + \sum_i f(W_{ir}))</td>
</tr>
<tr>
<td>Difference (no cluster - cluster)</td>
<td>(\sum_i F_{ij} - \sum_i g(W_{iu}) + \sum_i f(W_{i}) - \sum_i f(W_{ir}))</td>
</tr>
</tbody>
</table>

Abbreviations used:

- \(W_{ir}\) = residual mass of unused waste(s) from the \(i^{th}\) process;
- \(W_{iu}\) = mass of waste(s) usefully transferred from the \(i^{th}\) process;
- \(R_i\) = renewable energy to the \(i^{th}\) process;
- \(F_{ij}\) = non-renewable energy of the \(j^{th}\) input to the \(i^{th}\) process;
- \(g(W_{iu})\) = emergy invested to transfer still usable waste materials from the \(i^{th}\) process to any other process;
- \(f(W_{ir})\) = emergy invested for disposal of total waste from the \(i^{th}\) process or for repair of the related damage.

MAXIMUM EMPOWER AND ZERO EMISSIONS IN ELECTRICITY GENERATION: A CASE STUDY

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,\(^\text{10}\) (previously investigated by the author and his colleagues, Giannantoni et al., 2005), is chosen as a reference case study (hereafter STGT) and 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 a wide variety of design options usually exist for thermal energy recovery.\(^\text{11}\)

---

\(^{10}\) Integrative boilers are only used to cover peak demand of heat in winter. Therefore, matter and energy input flows related to their operation are only charged in proportion to actual heat demand and use (see Table 4).

\(^{11}\) 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...
Figure 5 shows the systems diagram of the STGT 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 Figure 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 (National Agency for New Technologies, Energy and the Environment, www.enea.it, Ulgiati, 1996 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 investigated belongs to the new generation of multi-step, combined cycle gas turbine plants (CCGT, Figure 6) installed in Italy in recent years. The increase of plant complexity (interaction among components, improved design and management options, similar to the cluster system in Figure 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 Figure 6 is first 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).

A comparison between Table 4 and Table 5 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 better environmental performance.

The total energy supporting the investigated plants was finally 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 energy intensities (seJ/J, seJ/g, seJ/yr, seJ/€), thus yielding the amount of energy associated to each input item. The energy needed for uptake of pollutants by means of technological devices, as well as for dispersal and dilution of fractions released was also accounted for and assigned as an environmental cost to the product(s) electricity and heat.

The sum of all input energies, divided by exergy joules of produced electricity and heat, yields the energy intensity (transformity) of each product. Further calculations generate energy-based performance and sustainability indices, as well as help identify the relative weight of input item categories (e.g., renewables, fuels, goods and machinery, and 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 energy 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.

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 Figure 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.
Chapter 12. Emergy, LCA, and Zero Emissions: The Search for Synergies

**Figure 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. Systems symbols from Figure 1. Thin dotted lines are waste heat to sink, thick dotted lines are money flows.

**Table 4.** LCA efficiency and mass flows in the steam turbine/gas turbine (STGT) plant.

<table>
<thead>
<tr>
<th>Matter input and output flows</th>
<th>g/(kWh_{el}+yr)</th>
<th>g/(kWh_{el+q}+yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Main mass flows to the STGT process</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>0.464</td>
<td>0.558</td>
</tr>
<tr>
<td>Iron and steel</td>
<td>0.369</td>
<td>0.444</td>
</tr>
<tr>
<td>Copper</td>
<td>0.005</td>
<td>0.006</td>
</tr>
<tr>
<td>Diesel, cooling oil, lube oil</td>
<td>0.141</td>
<td>0.170</td>
</tr>
<tr>
<td>Natural gas</td>
<td>283.077</td>
<td>154.599</td>
</tr>
<tr>
<td><strong>Main airborne emissions from the STGT process</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>739.336</td>
<td>403.779</td>
</tr>
<tr>
<td>CO</td>
<td>0.381</td>
<td>0.208</td>
</tr>
<tr>
<td>CH₄</td>
<td>0.014</td>
<td>0.008</td>
</tr>
<tr>
<td>VOC and HC</td>
<td>0.007</td>
<td>0.004</td>
</tr>
<tr>
<td>NOₓ</td>
<td>1.036</td>
<td>0.566</td>
</tr>
<tr>
<td>N₂O</td>
<td>0.007</td>
<td>0.004</td>
</tr>
<tr>
<td>Particulate matter</td>
<td>0.017</td>
<td>0.010</td>
</tr>
<tr>
<td><strong>Plant efficiency</strong></td>
<td>( \eta_{el} )</td>
<td>( \eta_{el+q} )</td>
</tr>
<tr>
<td></td>
<td>24.65%</td>
<td>45.14%</td>
</tr>
</tbody>
</table>
algebra (Brown and Ulgiati, 2004). 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 emergy accounting are presented in Table 6, while further details about how to perform an emergy evaluation of power plants were published in Brown and Ulgiati, (2002), Ulgiati and Brown (2002) and Ulgiati et al. (2005).

Figure 6. Systems diagram of a typical combined cycle gas turbine, with cascade utilization of fuel exergy. 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 Figure 1. Thin dotted lines are waste heat to sink; thick dotted lines are money flows.

Table 5. Fuel consumption and main emissions in a combined cycle gas turbine plant.

<table>
<thead>
<tr>
<th>Matter input and output flows</th>
<th>g/(kWh_{el}*yr)</th>
<th>g/(kWh_{el+q}*yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel supplied to the CCGT process</td>
<td>123.288</td>
<td>100.976</td>
</tr>
<tr>
<td>Natural gas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>339.042</td>
<td>277.685</td>
</tr>
<tr>
<td>CO</td>
<td>0.095</td>
<td>0.078</td>
</tr>
<tr>
<td>CH₄</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>VOC and HC</td>
<td>0.005</td>
<td>0.004</td>
</tr>
<tr>
<td>NOₓ</td>
<td>0.324</td>
<td>0.266</td>
</tr>
<tr>
<td>N₂O</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>Particulate matter</td>
<td>0.037</td>
<td>0.030</td>
</tr>
</tbody>
</table>
Table 6. Selected results from energy analysis of STGT and CCGT processes.

<table>
<thead>
<tr>
<th>Processes</th>
<th>Transformity seJ/J</th>
</tr>
</thead>
<tbody>
<tr>
<td>STGT process</td>
<td></td>
</tr>
<tr>
<td>Electricity delivered</td>
<td>3.15E+05</td>
</tr>
<tr>
<td>Total exergy delivered (electricity + heat)</td>
<td>1.73E+05</td>
</tr>
<tr>
<td>CCGT process</td>
<td></td>
</tr>
<tr>
<td>Electricity delivered</td>
<td>1.90E+05</td>
</tr>
<tr>
<td>Total exergy delivered (electricity + heat)</td>
<td>1.56E+05</td>
</tr>
</tbody>
</table>

DISCUSSION

Flows in the first column of Tables 4 and 5 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. Table 5 shows the much better performance of a CCGT plant, where more useful output is generated per unit of fuel and fewer chemicals are released per unit of product.

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). However, the local performance could 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 dynamic to be clearly identified, which is not very often the case in published case studies. Table 6 shows a comparison between the two kinds of plants based on energy 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 (Brown and Ulgiati, 2004) provided transformities in the range 1.10E+5 to 3.54E+5 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 CCGT electricity requires a much lower environmental support per unit of product (1.90E+05 seJ/J).

The transformity of the total co-generated heat and electricity (both measured in exergy units) drops significantly by about 50 percent in the case of the STGT plant as a consequence of the large amount of resources available in the generated heat. This makes the plant best suited to provide heat for district heating, in spite of its 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.

Information Cost

As suggested above and in footnote eight, a rough estimate of information input to a process or system can be obtained from converting labor and services into energy units. Labor is human
activity performed within the process, service is human activity performed outside of the process and before the process begins. While we can measure hours of direct labor, it is much more difficult to measure the hours spent in the thousands of activities that support the process by providing fuels, know-how, and technology. What is information emergy in a power plant? It is the emergy it took to design the plant components, assemble them into a plant, and keep it running properly. It also includes the emergy required to find, extract, refine, and transport oil or natural gas to power the plant. It is important to note that this emergy is not the emergy content of the fuel (i.e., the emergy invested by nature to make fossil fuels in underground reservoirs), but is instead the emergy invested in know-how, technology, and education needed to perform 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. In general, labor can be measured in hours, years, or money; services are always measured in money units, based on the assumption that income reflects labor hierarchy, which in turn reflects previous training and education (which is not always the case). Both labor and services are then converted into emergy and provide a preliminary, gross estimate of the information supplied to the plant in the form of emergy supporting all the 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 emergy was 9.04E+04 seJ/Jel, equivalent to the 24 percent of total emergy input, while for the STGT 171 MW natural gas power plant we calculated it as 3.03E+04 seJ/Jel, equivalent to 9.3 percent of total emergy input. Of course, information fraction is relatively small in power plants, where fuel emergy and construction materials dominate, while it becomes a major input in activities based on information processing in the service sectors of modern societies.

**CONCLUSION**

A joint application of Life Cycle Assessment and Emergy Synthesis, named Emergy 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 Technologies and Systems. Results show that increasing the complexity of the system, as well as the use of co-products helps to achieve better performance and an optimum use of available resources. The case study is only based on the performance comparison of two power plants and does not include all the possible ways for complexity to 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.) that 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 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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13 The emergy supporting information created by nature (DNA, landscape) are in principle included in the values calculated for all input items (fuels, materials) other than labor and services. It is much more difficult to calculate as a separate item.
REFERENCES


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