Entropy **2014**, *16*, 3903-3938; doi:10.3390/e16073903

OPEN ACCESS

entropy

ISSN 1099-4300

www.mdpi.com/journal/entropy

Review

Panel I: Connecting 2nd Law Analysis with Economics, Ecology and Energy Policy

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Received: 11 February 2014; in revised form: 4 June 2014 / Accepted: 10 June 2014 / Published: 16 July 2014

Abstract: The present paper is a review of several papers from the Proceedings of the Joint European Thermodynamics Conference, held in Brescia, Italy, 1–5 July 2013, namely papers introduced by their authors at Panel I of the conference. Panel I was devoted to applications of the Second Law of Thermodynamics to social issues—economics, ecology, sustainability, and energy policy. The concept called *Available Energy* which goes back to mid-nineteenth century work of Kelvin, Rankine, Maxwell and Gibbs, is relevant to all of the papers. Various names have been applied to the concept when interactions between the system of interest and an environment are involved. Today, the name *exergy* is generally accepted. The scope of the papers being reviewed is wide and they complement one another well.

Keywords: available energy; exergy; entropy; 2nd Law Analysis; resource utilization; sustainability; ecological impact; emergy; cost accounting

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1. Overview

This paper is a review of several papers from the Proceedings of the Joint European Thermodynamics Conference, held in Brescia, Italy, 1–5 July 2013. The following papers were introduced in Panel I:

Lazzaretto, A.	Fuel and Product Definition in Cost Accounting Evaluations: Is it a Solved Problem
Tsatsaronis, G.	Advanced Exergy Based Methods
Rosen, M.	Correlating Thermodynamics and Economic Investments for Energy Research
Verda, V.	Thermoeconomics as a Regulation Tool in Future District Heating Networks
Reini, M.	Emergy/Exergy Based Cost Accounting in Ecological-Technological Energy Systems
Sciubba, E.	Exergy Analysis of the Resource Intensity of Biological Systems and Human Societies
Valero, A.	Thermodynamic Accounting of the Global Depletion of the Mineral Capital On Earth
Gaggioli, R.	Relevance of the Dead State to Ecological and Economic Analyses

The full papers are available in the proceedings, available at [1].

2. Introduction

Energy, What is it? The word means different things to different people. In everyday circumstances, to the layperson "energy" means a resource, the key ingredient for "making things happen" physically —for impelling physical processes (such as lighting, heating, cooling, cooking, computing, vehicle propulsion, *etc.*). The layperson appreciates the value of "energy", finds it to be necessary, uses it, and pays for it. Moreover, it is clear to the layperson that, whatever this "marketplace energy" accomplishes, some is "used up"—consumed, annihilated—by the process.

On the other hand, in *science* the commodity called "energy" is never "used up". Rather, it is "conserved"; it cannot be created *nor* can it be annihilated. Clearly the layperson's concept and the scientist's concept of energy are different. Either (a) one concept or the other is wrong, or (b) two different concepts happen to use the same name.

Some interesting questions arise from this notion: (1) Is one concept wrong? (2) Is one concept a special case of the other? The answers are both "No". They are distinct. Then (3), can the two concepts be reconciled? Yes, but for scientific purposes, each should be given a unique name, in order to avoid confusion. Indeed, they have: *exergy* is the scientific name that has been given to marketplace energy.

3. Available Energy and Exergy

The underlying concept upon which all of the papers presented at this panel is *Available Energy*, a concept which goes back to mid-nineteenth century, comprising work (motivated by Carnot's) of eminent scholars such as William Thomson (Lord Kelvin), Rankine, Maxwell and Gibbs (numerous publications are referred to in [2]). It was Gibbs [3,4] who formulated it in the more general terms, eventually encompassing chemical as well as thermo-mechanical processes. As Gibbs made clear, the available energy content of a "body" (his terminology for any object, including combinations of many objects) is a consequence of the lack of equilibrium (whether apparent or latent) within the body. It is also evident from Gibbs work that the available energy of a body represents its potential capacity to influence other "bodies" in *any* manner, such as mechanically, thermally, chemically. And, in spite of the name "available *energy*" of a body, *while* the body employs some of its capacity to influence another *body*, the process could deliver energy *or* extract energy *or* not change the energy of the object and yet cause disequilibrium. Available energy is a measure of the system's potential to cause disequilibrium within other systems—recipients. When such potential is employed—whenever *any* process takes place—the increase in available energy of the recipient is inevitably less than that given up by the donor. When a system has given up all of its available energy, reaching equilibrium, it is said to be at a "dead state". Gibbs presents his definitions and results, complete in themselves, without equations. He illustrates them graphically. Further elaboration on his work is presented in [5].

The available energy of a body cannot be negative. Available energy is not "additive"; that is, for a body that consists of two or more subsystems the value is not identical to the sum of the individual available energies of the subsystems (which could each be zero).

As a *special* case, Gibbs considered the circumstance when the "overall body" consists of a composite of two subsystems, and one of the two is large, uniformly homogeneous and unchanging. He says, "These [preceding, basic developments] may be modified to make them approach more nearly the economical problems which actually present themselves, if we suppose the body to be surrounded by a [large, uniform, unchanging] medium, and let the body and medium together take the place of the body in the preceding [developments]." Gibbs illustrated this special case via reference to his earlier graphs, making verbal additions to it [6]. Among objects that exist within a medium, processes occur when, and only when, there is utilization of available energy to induce the process.

What Gibbs called the "available energy *of body and medium*" is today called "exergy", and it is attributed to the body. Exergy is additive: the sum of exergies, of individual bodies in a medium, is equal to the overall exergy (and available energy) of "bodies and medium" together. This additivity means that an "exergy balance equation" can be written for each subsystem, a fact that is invaluable to "exergy analysis" of processes and facilities [7].

One body's influence upon a second is proportional to the exergy delivered from the first to the second and, inevitably, there is exergy consumed (used up, annihilated, destroyed) by the process. When one body undergoes a spontaneous process (without interacting with others) there is exergy consumed within the body—a reduction in the body's potential to cause change (to cause disequilibrium in another body). The exergy content of a body within a medium can be called the body's value as a resource, within *that* surrounding medium.

Exergy provides a quantitative measure of a resource, and for measuring the overall and incremental expenditures thereof to accomplish a physical objective—a product—and a measure of the associated waste disposals. "Exergy Analysis" is the phrase commonly used for such tracking of resource use through a system (involving one or more processes). These analyses evaluate the transfers, conversions and consumptions (annihilations) of exergy, from the primary resource(s) [8] to that culminating in the product(s). An imaginary *ideal* process would deliver as much exergy into the product(s) as that supplied by the primary resource(s) [9]. In all real processes exergy is used up (annihilated) to impel the process(es).

Hence, compared to the ideal, the consumptions (destructions, annihilations) of exergy represent "costs", inefficiencies. Clearly, *some* cost is necessary—*some* resource must be used up, for driving a process, for making it happen. Keep in mind that, here, resources are defined to be "bodies" within a medium that are not in equilibrium with the medium itself.

"Natural Resources"—what are they? Objects that, together with "our environment", have available energy. *Insofar* as our environment is a surrounding medium, natural resources are those "bodies" that have exergy relative to it. However, "our environment" though large is neither uniform nor unchanging. Moreover, what is the scope of "our environment"? Clearly that scope is indefinable. To date, practical exergy analyses have invariably *assumed* a uniform, unchanging environment—a theoretical environment—as a hypothetical model of "our environment". That assumption is reasonable only insofar as, for the practical purposes at hand,

(i) The *assumed* scope of the environment is made clear and understood.
(ii) The *assumed* modes of interaction among subsystems and the theoretical environment is specified, clearly and understood.
(iii) The *assumed* modes of spontaneous change within any subsystem are clear and understood.

The total of the subsystem exergies calculated under these assumptions is (for the practical purposes at hand) close enough to the total available energy that the subsystems and the theoretical environment have, together, when limited to the specified modes. That total available energy depends upon and is limited by the limitations imposed by assumptions (i), (ii) and (iii), which limit the *dead state* the overall composite could reach. As will be discussed later, the implications of such limitations upon the conclusions reached should be well understood, especially when assessing the recommendations made.

3.1. Exergy Analysis

Undoubtedly, *energy* has proven useful for investigating and *modeling* processes. However, for *analyzing* processes—to locate and quantify inefficiencies—the use of energy is inappropriate, and it is often misleading. Ample evidence is available in the literature. Perhaps the simplest example is a home heating furnace (or "boiler"). Many are available today that are advertised and labeled to be over 95% efficient. That label, required by the government, is saying that 95% of the fuel energy is delivered to the home, and the only inefficiency is the 5% of the energy exhausted to the environment. That is true, but grossly misleading.

With few exceptions, the buyer, the seller, the manufacturer and the engineers believe that their 95% efficient furnace approaches the ideal; that it is within 5% of perfect use of the fuel. That 95% certainly is a commendable improvement over the 80% efficient furnaces of forty years ago. Fuel consumption has been reduced by 15%. That was achieved by the only conceivable means of saving fuel *energy*—*i.e.*, by squeezing more energy out of the exhaust gases.

In actuality, that 95% energy-efficient furnace is less than 15% efficient; *i.e.*, 85% *in*efficient (30% of the fuel exergy is annihilated in the uncontrolled conversion of chemical exergy to thermal exergy by the combustion process; 50% is wasted (annihilated) in the heat transfer from *very high* temperature combustion products to moderate temperature room air; 5% is lost in the exhaust gases leaving the furnace). If *truly* 90% efficient processes were available for utilizing the fuel to provide thermal comfort, the fuel consumption would be reduced more than 6-fold. Is that a ridiculous objective? How about striving to achieve 45% efficiency, using one-third of the fuel of today's 90% "energy-efficient" furnaces? Could today's furnace technology be employed? Could it be adapted and/or utilized as part of a more efficient system? Certainly, to answer these questions it is of critical importance to know the different causes that contribute to the 85% inefficiency, and the contribution of each to the 85%. The manufacturer and the engineer *should* know that: (i) the combustion process alone (which is virtually 100% "energy-efficient") is truly only 70% efficient, (ii) the heat transfer process from the combustion products to the home air (which appears to be 90% efficient) is only 35% efficient (0.5 × 0.7), and (iii) that overall inefficiency resulting from the exhaust is only 5%. By itself, exergy analysis cannot show how to cure a large inefficiency, but *only* exergy analysis can "uncover" sources of inefficiency, pinpoint them and quantify them.

The Ambit of Exergy Analysis

Exergy provides a measure of resources (natural, including "energy"), and of the utilization of resources. So it is useful for purposes of "everyday" research, development, and engineering, for ecological analyses including impact on the environment, and for planning of expenditures on equipment, on policy development and decisions (e.g., taxation), and on research and development. In principle, an exergy analysis can be applied to any kind of energy system, which can be synthetically described as a network of energy flows, connecting some nodes (named components, or sub-systems) where different kinds of irreversible, energy conversion processes may occur. This point of view is widely adopted for analyzing either natural, biological and ecological systems, or human-made, technological production systems, and it underlies all the lectures presented in Panel I of the JET Conference 2013.

3.2. Exergetic Costing

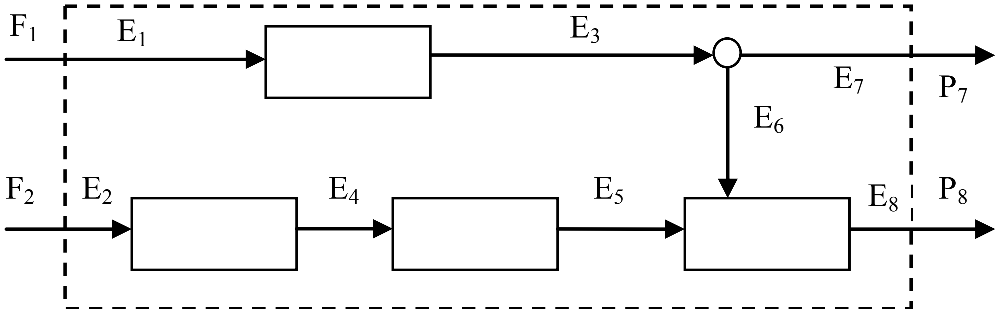
For any given "commodity" (such as energy, H atoms, money, exergy, …) supplied to a generic multi-component system, let's consider the basic issue of tracking the flow of the commodity through the system. Considering the commodity input to the system as a resource, how much of the resource is being used to maintain each flow within the system, from component to component and with the product flow(s) from the system? Figure 1 depicts an example showing a system network with flows among five components; four represent processing units and the fifth is merely a "splitter". The E_i represent flow rates of the commodity, with two "feeds" to the system (E_1 and E_2) and with two system "products" (E_7 and E_8).

If the flows making up the network are defined in order to properly describe the productive relations among components and with the outside of the system, each component (or process) can be regarded, at local level, as an autonomous production unit, having one, or more, output flows named Products or Functions and one or more input flows, named Fuels or internal resources. Thus, a local model of each component is isolated from the whole system model, whereas the overall network, defined in this manner, can be regarded as the so called Productive Structure (PS) of the system. If in addition, the system is similar to a linear chain (like the one in Figure 1) and it is operating in stationary (steady-state) conditions, the answer to the previous basic question can be easily inferred. In fact, flows E_1 and E_2 do correspond to the primary feeds F_1 and F_2, respectively; flow E_3 is maintained by F_1, so that its cost per unit of flow is defined as $k_3^* = F_1/E_3$, and a similar situation occurs for flows E_4 and E_5, too.

Let's think of the bifurcation of flow E_3 as a split, without any thermodynamic transformation or process, therefore flow E_7 is maintained by a fraction E_7/E_3 of flow F_1 and its unit cost is defined as $k_7^* = (E_7/E_3)\ (F_1/E_7) = k_3^*$. Flow E_8 is maintained by the remaining part of flow F_1 and by the entire flow F_2. Its unit cost is $k_8^* = k_3^*\ (E_6/E_8) + k_5^*\ (E_5/E_8)$.

Notice that although the choice of symbolism for the flows (E_i) could imply that the commodity being tracked is exergy, in principle the choice of the analytic formulation is free and is left to the analyst. Capital resources (as will be shown further), or simply energy, or other commodities could be used as well.

Figure 1. A simple linear system with a split.



If *exergy* flows are used to describe the productive relations inside the system, additional information can be obtained about losses inside each control volume and about distance from reversibility of each energy conversion process [10–13]. Nevertheless, the definition of a simple (e.g., linear) model can be sometimes simplified by using energy based descriptions of (at least some) productive relations (E_i) [14,15]. In any case, exergy based productive relations plays a crucial role in the cost allocation in case of multi-product components (which are not present in Figure 1) and have to be regarded as the option that generally applies [13,16–18].

Cost Allocation Rules

The origin of "exergetic costing"—application of exergy for monetary purposes—goes back, we believe, to the work of Keenan [19]. He addressed a problem presented to him by an electric power utility that was contemplating the co-generation of steam for distribution in a network to serve local enterprises. But the prospective price for steam that the company accountants had calculated was not low enough to attract customers. This did not make sense to a young company engineer who, somehow, realized that the cogenerated steam should be cheaper. Professor Keenan was consulted.

The following problem is an analogous though simplified one, comparable to that which led the utility to consult Keenan. Imagine a box representing the production facility, with one "fuel" stream (high-pressure steam) entering, and 2 products leaving, electricity and low pressure steam (say 4 bar).

The total cost of the two products per hour, C_{products}, would be constituted of (a) the portion attributed to the low-pressure steam ($C_{\text{LP steam}}$), plus (b) that attributed to the shaft power (C_{power}). This overall cost is a consequence of the expenditures (a) for "fuel" ($C_{\text{HP steam}}$), plus (b) the expenses of ownership, operation and maintenance of the turbine (Z):

$$C_{\text{LP steam}} + C_{\text{power}} = C_{\text{HP steam}} + Z$$

The *unit* cost of the "fuel" (c_{HP}) is known (0.15 cents/kg), so the expenditures for steam supplied to the turbine are $C_{\text{HP steam}} = c_{\text{HP}}F_{\text{HP}}$ where F_{HP} is the flow of HP steam into the equipment. For cost accounting purposes the utility desires to know proper, individual *unit* costs of the electricity and the LP steam, namely c_{Power} and c_{LP}:

$$C_{\text{LP}} = c_{\text{LP}}F_{\text{LP}} \text{ and } C_{\text{power}} = c_{\text{power}}F_{\text{power}}.$$

Thus, the former equation becomes:

$$c_{LP}F_{LP} + c_{power}F_{power} = c_{HP}F_{HP} + Z$$

While this "money balance" formula is applicable, it still doesn't satisfy the accountant's needs, because there are two remaining issues: (a) What do F_{LP} and F_{power} represent; flow of what? And (b) even when that is decided, the money balance is one equation with two unknowns, c_{LP} and c_{power}. So a second, "*auxiliary equation*" is needed, that involves c_{LP}. and/or c_{power}. To resolve these issues, the accountant seeks help from a mature company engineer: "What do F_{LP} and F_{power} represent?" Answer, "That's easy, energy!" Second question, "Look at the equation, there are two unknowns; how can that be resolved?" Answer, "That's easy, *the* primary purpose of the facility is to deliver power, so power should be charged for all of the owning costs (Z) and for all of the energy used ($F_{HP} - F_{LP}$) to produce the power." The answers appear to be reasonable, so the accountant adopts them. Hence,

$$c_{Power}F_{power} = c_{HP}\,[F_{HP} - F_{LP}] + Z$$

That is equivalent to *assuming* the second, auxiliary equation is $c_{LP} = c_{HP}$. With these two assumptions, the engineer finds the following results for the accountant [16]:

$$c_{fuel} = 0.15 \text{ cents/kg} = 0.81 \text{ cents/kWh-energy}$$

$$c_{LP} = 0.81 \text{ cents/kWh-energy} = 0.125 \text{ cents/kg}$$

$$c_{Power} = 0.9 \text{ cents/kWh-energy}$$

These results are proudly presented to the cost accountant, who expresses thanks, but then observes that the unit cost of power is much lower than expected, compared to power generated conventionally (*i.e.*, with no co-generated steam). Moreover it comes to light that steam at 0.125 cents/kg will not be compet-itive, so the immediate reaction is to scuttle the idea of co-generating. However, the accountant wonders, How can it be that small-scale boilers can generate steam more efficiently than our large scale facility, especially when we are costing the steam as if it were a "byproduct"? And again, "Why is the cogenerated power so cheap?" The accountant consults a younger engineer who ponders the issue, remembers something from Engineering Thermodynamics, called "exergy" by the professor, and suggests that the professor be consulted. Here are the professor's results (with F representing exergy flow, and with $c_{LP} = c_{HP}$):

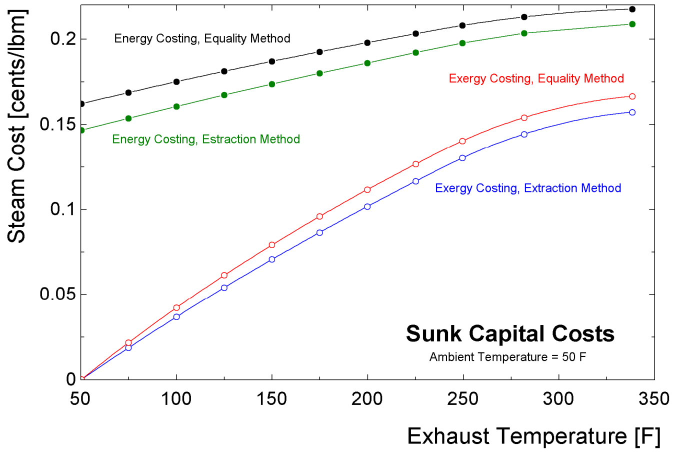
$$c_{fuel} = 0.15 \text{ cents/kg} = 1.96 \text{ cents/kWh-exergy}$$

$$c_{LP} = 1.96 \text{ cents/kWh-exergy} = 0.09 \text{ cents/kg}$$

$$c_{Power} = 2.4 \text{ cents/kWh-exergy} = 2.4 \text{ cents/kWh-energy}$$

The cost accountant is intrigued and pleased, because that unit power cost seems more consistent with what would be expected, and the reduced cost of steam means that it could be sold at a price that would be irresistible to prospective customers. But, having heard of energy before but not exergy, the accountant has a lingering concern. So there are more discussions with the young engineer and the professor. The professor ponders how the concern could be resolved and thinks, the results, if rational, should yield consistent conclusions no matter what the LP steam pressure is (and hence the steam's condensing temperature) [20]. The professor suggests, "Young engineer, use both 'energy costing' and 'exergy costing' in order to see how the unit costs from each behave, as functions of the LP steam pressure". The results are presented in Figure 2.

Figure 2. Example of variation of steam cost with temperature, employing different means of cost accounting, adapted from [16].



Consider first the green and blue curves (which are the results under the assumption at hand, that $c_{LP} = c_{fuel}$); green is for the case with F representing energy flows (energy costing) and blue is for exergy flows (exergy costing). Bear in mind that the LP steam's usefulness for heating is dependent upon the temperature; lower temperature means less usefulness. Moreover, as the temperature decreases toward ambient temperature, its value should drop to zero. Because, there would be no buyers, since that steam would have no practical use for heating. Energy costing makes the "value" of steam at ambient temperature significant, which makes no sense. Exergy costing obviously is more proper.

Upon seeing the results, the professor comments to the cost accountant, "The results are just as I expected. Do they convince you that exergy costing is appropriate and energy costing is not?" Answer, "Absolutely." The professor says, "By the way, in my opinion, the steam should be charged for some of the equipment expense. After all, it is benefitting from the high efficiency of the facility compared to conventional steam boilers. You might want to look at the cost breakdown between power and LP steam if they shared the equipment expense; that is with $c_{LP} = c_{power}$." The young engineer makes the calculations and the results are:

$$c_{fuel} = 0.15 \text{ cents/kg} = 1.96 \text{ cents/kWh-exergy}$$

$$c_{LP} = 2.15 \text{ cents/kWh-exergy} = 0.10 \text{ cents/kg}$$

$$c_{Power} = 2.15 \text{ cents/kWh-exergy} = 2.15 \text{ cents/kWh-energy}$$

which shows a modest increase in steam cost and a modest decrease in power cost. When the calculations are repeated at differing low-pressure steam condensing temperature, c_{LP} is shown by the red curve on Figure 2. (Again, when that curve is compared to the black curve, it corroborates the conclusion that energy costing is irrational.) Now, the cost accountant will need to *deliberate* (ponder, consult further), in order to choose between the two auxiliary equations (or find another, better alternative [21]).

4. Applications to Optimal Design and Operation of Engineered Systems

After Keenan's original work, most of the subsequent work on exergy costing has been devoted to the improvement of plant designs and operations; the improvements are directed toward an objective, an optimum (usually economic). Some of the work of the "Tribus school" (e.g., [22,23]) sought and achieved rigorous mathematical developments for finding, in theory, an economically optimal design of a system (when given the structure of the system—the flowsheet showing all of the component subsystems and their connections); see El-Sayed and Evans [24]. While the theoretical results of [24] have not (yet) proven to be practical, the two authors have since been important contributors to the theory, practice and elucidation of Thermoeconomics.

4.1. Auxiliary Equations in Exergetic Costing

The issue of Auxiliary Equations (or of equivalent information) to be used in complex, multi-component systems, is not completely solved by Thermoeconomics. As can be easily inferred by the foregoing example, auxiliary equations are strictly related with Fuel and Product definition, but also this step is not generally formalized, whatever the kind of system. Some guidelines can be inferred from the whole body of literature: (i) a Product is an exergy flow, made available by the component, and utilized elsewhere in the system, or outside of it; (ii) a Fuel is an exergy flow, made available by other components, or from outside the system, that is used by the component in hand, in order to attain its Product(s).

Nevertheless, some authors argue that, regardless of a component's role in a particular system, the Product of a component is *ruled* by its *usual* "technological purpose". For example, turbines are designed for the *usual* purpose of generating shaft power, so those authors hold that in *any* application (usual or not), turbine power output shall be assigned as Product, and the Fuel is the difference between the exergy input and exergy output of the stream flowing through the turbine. Thus, in the foregoing example, if the facility were simply a steam turbine, then it is argued that the only correct auxiliary equation is $c_{LP} = c_{HP}$ (corresponding to so-called the "Extraction" hypothesis or method). The contention of those authors notwithstanding, there are turbine applications where its purpose is not strictly "usual"; e.g., the so-called "Equality" ($c_{LP} = c_{power}$) hypothesis may apply more properly (also, see [21]).

An elegant Exergy Cost Theory [11] by Valero and co-authors of the mid-80s can be regarded as an algebraic reformulation of previous Thermoeconomics of average costs (based on elementary costing principles outlined above) and on the axiomatic assumption of some postulates. The role of those postulates is to allow the definition of the auxiliary equations that have to be solved jointly with the exergy cost balance of all components, in order of identifying the exergy cost for those components with more than one output flow. Finally, they can be regarded as incorporating, into the algebraic formulation of the Exergy Cost Theory, the extraction and equality methods, as well as the option of an external cost assignment for the possible secondary output of some components.

In the early 90s Valero and co-authors presented the Structural Theory [25,26], where the auxiliary equations do not appear explicitly. Nevertheless, earlier auxiliary equation concepts are still present inside the Structural Theory, because it requires re-definition of the exergy interactions among components. Concisely, the physical flows inside the system have to be replaced by the Fuels and Products of each component. To do this, some fictitious junction and branches have to be introduced too, so that the cost balances of the latter take the place of auxiliary equations.

But this is not enough, because some components with more than one Product can still be present! (Notice that such an eventuality has not been considered for the simple system in Figure 1). The problem is solved in the Structural Theory by introducing a different approach, that may be considered as a generalization of the previous formulation of average costs: the new general formulation of average costs can be summarized by stating that they do correspond to the *shadow costs* [27] of the internal exergy flows (fuels and products), calculated at constant specific consumption (or efficiency) for all components. In this way, costs consistent with the cost conservation can be assigned also to the products of multi-product components, while the usual *average costs* are assigned to the products of all single-product components. The key point is the hypothesis of expressing each fuel (F) of a multi-product component as: $F = k_1 P_1 + k_2 P_2$ (where k_1 and k_2 are the specific consumptions of F for obtaining the two Products P_1 and P_2, *respectively*). Furthermore, the Structural Theory is perfectly consistent with the concepts of by-product (e.g., heat recovered from an energy conversion process) and residue (a useless product, which require consumption of resources in order to be properly discharged), cases in which the unit cost of one of the two products of the same component is defined externally of the component itself [28,29].

4.1.1. SPECO

A significant effort for obtaining a general and unambiguous "process based" criterion to define the Fuel and Product of each component has been made by Lazzaretto and Tsatsaronis, leading to the development of the Specific Exergy Costing (SPECO) method [30]. A summary of the main points of this method and some examples of applications have been presented at the JETC2013 by Lazzaretto. The following paragraphs paraphrase the presentation.

The SPECO method is based on the record of all exergy additions to and removals from the mass and energy streams of the real energy system. This criterion leads to a "productive structure" of the total system consistent with its physical structure, and allows one to directly extract the exact number of auxiliary equations that are needed to evaluate costs, when using the so called Fuel and Product rules. Lazzaretto claims, "However, among the possible definitions [of fuel and product], those given in agreement with the strict application of the SPECO criterion appear to be the most meaningful ones to evaluate correctly the costs (both exergetic and monetary) associated with mass and energy streams."

The SPECO criterion for Fuel and Product definition basically consists in:

(i) Calculating of the exergy differences between outlet and inlet of the component along each mass and energy stream crossing the component boundaries,
(ii) Checking the sign of these differences (positive and negative differences correspond to exergy additions and removals, respectively);
(iii) Including in the Product only the *desired* exergy additions, and leaving exergy removals and *undesired* exergy additions on the Fuel side.

Only in some cases in which chemical transformations are involved (e.g., in a gasification reactor in which a solid fuel is transformed into a gas) it may be meaningful to consider input exergies on the Fuel side and output exergies on the Product side.

Notice that, in spite of the claim of completely basing the SPECO method on thermodynamics, the concept of *desired* Product, still plays a role in the previous definitions, even if it appears only in the background, with respect to the record of all exergy additions and removals. Once the Fuels and Products have been defined, the F and P rule can be applied:

> F RULE: exergy is removed from each exergy stream belonging to the Fuel at the same unit cost at which it was supplied in the upstream components,
> P RULE: all exergy units belonging to the Product of the same component have the same unit cost.

4.1.2. SPECO *vs.* "Double Purpose" Approach

With the objective of proving standard applicability of the SPECO method, Lazzaretto presented three examples: a cogenerating steam turbine, a heat exchanger, and a mixing chamber. Equipment costs have not been included. In each case results deduced from SPECO and the "Double Purpose" approach were compared.

For the cogenerating turbine, the basic monetary balances (along with exergetic efficiencies) are presented for the two cases of SPECO and "Double Purpose" approach (DP, *i.e.*, considering both power and low pressure steam as main products of the component). For the turbine, SPECO declares that since the *usual* purpose of a turbine is to deliver power (W_T), the exergy delivered therewith should be a sole product, and so the Fuel is the exergy given up by the entering steam. In the DP method, the exergies delivered from the turbine by power and by LP steam are charged for expenditures equally.

So, respectively, the exergetic efficiency, the auxiliary equation, *and* the relationship between product costs and efficiency are:

$\varepsilon_{SPECO} = W_T/(E_{HP}-E_{LP})$; $c_{LP} = c_{HP}$ $c_W = c_{HP}/\varepsilon_{SPECO}$ (the previous "Extraction" method)

$\varepsilon_{DP} = (W_T + E_{LP})/E_{HP}$; $c_W = c_{LP}$ $c_W = c_{LP} = c_{HP}/\varepsilon_{DP}$ (the previous "Equality" method)

Note that product costs are inversely proportional to exergetic efficiency.

To argue the differences between the two costing approaches, Lazzaretto presented plots of the exergetic efficiency and the unit cost of the product *versus* the isentropic efficiency of the turbine (for three different turbine exhaust pressures), represented by Figure 3.

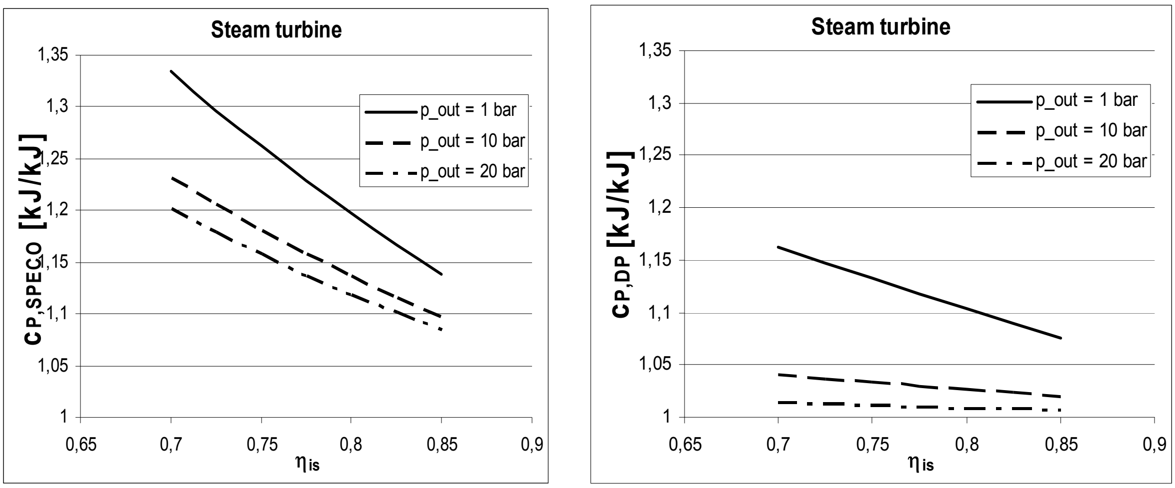
Figure 3 shows only the unit cost curves (since efficiency is simply reciprocally related thereto). In turn, he claims that "an improvement in the behavior of the component is expected to result in increasing the exergetic efficiency and decreasing the unit cost of the product".

Then, from the figures Lazzaretto *inferred* that:

(a) The DP method leads to constant or slightly variable values of the exergetic efficiency and of the unit cost of Product. This implies that improvements in the component design might not be "detected" by the DP exergetic efficiency and cost of product, which may therefore become *useless performance parameters* in a design improvement procedure,

(b) This is because the definitions of these parameters given by the DP approach places the "desired performance" of the component (that are stated according to the requirement of the users) before *the real thermodynamic behavior* of the component itself; so, different forms of exergy that undergo different processes within the component may be considered, in principle, as being generated in the same way and having the same value, but this is not consistent with *the real component behavior*.

Figure 3. Unit product cost *vs.* isentropic efficiency of a turbine, applying SPECO and DP approach.



(**a**) (**b**)

Even if these examples and remarks clearly show the *aim* of SPECO, some comments are relevant. First of all: (i) a strong correlation between SPECO's exergetic efficiency and isentropic efficiency is to be expected [31], and (ii) note again that the cost and efficiency curves contain equivalent information, not complementary information.

More importantly, the author *presumes* that the *behavior* of the equipment is measured by the SPECO *choice* for measuring *behavior*. For example, it is assumed that the "behavior" of a turbine is *always* measured by the efficiency with which it delivers shaft power, because presumably that is *always* the purpose of a turbine. There may be several other purposes that a turbine (or heat exchanger or mixing chamber) could serve [32]. These purposes (*i.e.*, what happen to the flows exiting the turbine *outside* that component) have to be taken into account when defining the Productive Structure, including for instance the option of regarding the LP steam as a sub-product of the cogeneration turbine [28,29]. But such options are not contemplated by SPECO Fuel and Product definition.

In some plants, the purpose of the cogeneration turbine could be simply to produce LP steam more efficiently, rather than use the common practice of throttling HP steam to produce needed LP. With SPECO accounting, the entire burden of exergy destruction costs and equipment costs is placed upon the shaft power. The LP steam is not debited for any of that; yet, with SPECO, the LP steam is the principal beneficiary of the turbine installation, because it is relieved of the cost of exergy destroyed by throttling, which is much greater than the destruction by the turbine.

Indeed it could be argued that, when the purpose of the turbine is to reduce the steam pressure more efficiently, then it is the LP steam (not the power) that should be charged for the cost of turbine exergy destruction (and equipment cost), and that the power is merely a by-product. It could still be profitable to install a turbine; then, the installation would be justified if, upon having the auxiliary equation simply assign to c_W the unit cost of purchased utility power, the resultant cost of LP steam exergy were nevertheless lower than it would be as a result of throttling from HP steam to LP.

Again vis-à-vis the inferences referred to above, it is *inevitable* that DP costing will be less dependent upon turbine isentropic efficiency than SPECO—not because it is inferior to SPECO but *because of* fundamental thermodynamics: Consider that for both methods, $c_{product}/c_{HP} = 1/\varepsilon = 1 +$

$E_{destroyed}/E_{product}$. Now, at any operating condition (isentropic efficiency and "back-pressure" p_{out}) the exergy destruction is fixed, and much smaller than $E_{product}$, So $c_{product}/c_{HP}$ is not much greater than 1 (see Figure 3). *Moreover*, $E_{product}]_{DP}$ is significantly greater than $E_{product}]_{SPECO}$ so, with DP, $c_{product}/c_{HP}$ inevitably will exceed 1 by significantly less. Furthermore, as p_{out} is increased $E_{destroyed}$ (and SPECO product) decrease while DP product increases: then, $c_{product}/c_{HP}$ hardly exceeds 1 with DP. The relative constancy of DP unit costs cannot be regarded as a consequence of a misconstrued *supposition* about "real thermodynamic behavior" of equipment. Rather, the constancy is consistent with and a consequence of "real thermodynamics".

That is, an "improvement in a component's design" depends not on a supposed *conventional* application of the component but on the *specific* application. That relative constancy of $c_p]_{DP}$, does not imply a failure of DP to account for exergy *destruction*—which in any case can be charged for at the cost(s) of the input exergy. It is the exergy destruction costs and the equipment costs that are most relevant. In particular, for each component of a plant, what is relevant are: (i) the total of the input-exergy and equipment costs, as well as (ii) their percentages of the total. And for each component's relevance to the overall plant: (iii) the ratio of each component's total to the sum of all component totals. Conventional component performance parameters, such as isentropic efficiency, should not be taken to be a proxy for trade-off between equipment costs and exergy destruction costs. Obviously, depending upon the application, there are instances when lowering the efficiency and turbine costs would improve the overall plant!

In conclusion, the writers believe that, while there are instances when DP accounting should obviously be avoided, the conclusion that it should generally be avoided (and implicitly that SPECO should be used) is an overstatement.

The writers believe that the foregoing comments, directed at Points a and b, provide ample evidence that the ad hoc criterion presented by the author is not universally justifiable. It "begs the question"—*i.e.*, tries to justify a hypothesis using the conclusions drawn from it. If the need for cost accounting decision-making is a problem, then the problem is not resolved and, probably it cannot be solved looking (even in depth) at the thermodynamic behavior of isolated components, disregarding what happens in the specific overall system where each component is actually operating.

To its *credit*, SPECO does avoid the need to ponder alternative auxiliary equations. But to hold it to be *rigorous* in circumstances where *no* rule could be rigorous is claiming too much [33].

4.2. Engineering Optimization

Before delving into some details of current methodologies for applying exergy analysis and costing, let us review the end objectives. Invariably, an end objective is to pursue an *optimum* of resource usage. How can the objectives be expressed in mathematical terms?

In the cases of applications to engineered systems, the desired optimum is commonly expressed in monetary terms. *Whatever* the objective is, let us express it by the symbol *\$*; for examples the optimization may seek to maximize "return on investment", or minimize expenditures of resources (monetary, natural, …). Consider a system that involves *n* (*i* = 1, …, *n*) processes, and say that each is carried out in its own equipment. The system consists of a layout (flowsheet, structure) of the *n* items of equipment, linked with each other by connecting "streams". The system is designed or operated by modeling it (implicitly if not explicitly) mathematically. The model includes numerous equations that account for the performance of each item of equipment, and for the constraints upon interactions among the items. A correct model leads to a *workable design* (or a workable control of operation) [34].

For each item of equipment its performance is expressed by functions and variables that portray the equipment behavior, accounting for the processes occurring therein and the materials being processed. Each of the n items has m associated variables; for item i, ($j_i = 1, \ldots, m_i$): namely $\{x_{i1}, \ldots, x_{i,mi}\} \equiv \{\boldsymbol{x}_i\}$. So the number of equipment performance variables $M = \Sigma_i m_i$. Furthermore, there are numerous constraint equations imposed upon: (a) each i by its connections to other equipment and the environment, and (b) upon the system by either the "loads" (specified, constant [35] rates of delivery of some if not all of the system's products), or by the "feeds" (supplied to the system). Suppose there are $\boldsymbol{\ell}$ constraint equations. Finally then, in general the number of variables that can be varied independently will be $N = M - \boldsymbol{\ell}$. A *workable design*, one that will meet the loads (or utilize the feeds), is achieved by selecting a value for each of N independent variables $\{x_1, \ldots, x_N\}$, chosen (though not arbitrarily) from the M performance variables. Once the N variables are specified, that determines a value of $\$$ (but only by happenstance an optimal value). Modification of the design (or operation) can be achieved by varying one or more of the *N system parameters* (controlled by the system designer, or by the operator); thereby a new value of $\$$ would be found. So, fundamentally, the objective could be expressed as a function of *N independent* modeling variables: $\$ = f(x_1, \ldots, x_N)$. To construct the function f would require systematic variations of the independent variables—systematic redesigns.

From *any* workable design as a point of departure, with its particular values of $\{x_i\}$, an optimal design would be pursued by following the "differential" $\Delta\$ = f_1\, \Delta x_1 + \ldots. + f_N\, \Delta x_N$ (where the f_i are partial derivatives of f or increment approximations). While the optimum could be reached with improvements made with "trial and error" variations of the x_j, a systematic method would certainly be desirable. Preferably, Δf's would proceed continually in the direction of steepest ascent (or descent).

In any case, one important point of the foregoing discussion is that (at least in theory) the optimum design could be found from a mathematical model that employs an energy balance on each process, without any application of exergy.

Although exergy is not needed for *modeling* a system, a contention of its proponents is that of exergy *analysis* is invaluable for improving system design or operation [36]. Exergy analysis could, in theory (if the function f were continuous in all x's) lead directly to the optimum; e.g., that approach was proposed in [24]. In practice to date, the role of exergy analysis, in design applied to a specific system structure, has been to determine effective Δx_j for pursuing the objective. Moreover, it does so without explicitly constructing the function f. A creditable method of such exergy analysis and costing is presented in the next section.

While the mathematical discussion of objectives presented here have been in the language of "energy systems engineering", they are applicable across the whole ambit of exergy analysis. Paricularly for analysis of natural resource utilization and environmental impact.

Exergoeconomic and Exergoenvironmental Analysis

This terminology has been adopted for his work by Professor George Tsatsaronis of the Technical University of Berlin, a long term contributor to the development of exergy applications. His presentation at JETC 2013 includes the following additional points, with respect to the previous discussion about the Fuel and Product definition. The following paragraphs, in quotation marks, though not literal, are a summary that paraphrases the authors extended abstract and JETC presentation closely.

An exergetic analysis forms the basis for the exergoeconomic [37] and exergoenvironmental [38] analyses. *Conventional* exergetic analysis does not consider the real potential for improving the system, in relation with the interactions among the components of a system. These effects can be estimated and the quality of the conclusions obtained from an exergetic evaluation is improved, when for each important system component, the value of the exergy destruction is split into endogenous/exogenous [39] and avoidable/unavoidable [40] parts. We call the analyses employing such a splitting *advanced exergetic analysis*. An exergoeconomic analysis consists of an exergetic analysis, an economic analysis, and an exergoeconomic evaluation.

Endogenous exergy destruction is defined as that part of exergy destruction within a component obtained when all other components operate ideally and only the component being considered operates with the same efficiency as in the real system. The *exogenous* part of the exergy destruction is the difference between the value of total exergy destruction within the component in the real system and the endogenous part.

The *unavoidable* exergy destruction cannot be further reduced in the foreseeable future due to technological limitations, whereas the difference between total and unavoidable exergy destruction for a component is the *avoidable* exergy destruction. Improvement efforts should focus only on *avoidable* exergy destructions, costs, and environmental impacts.

"In analogy to the advanced exergetic analysis, an exergoeconomic and an exergoenvironmental analysis can be conducted by considering separately the endogenous/exogenous and the avoidable/unavoidable costs and environmental impacts. In this way, a consistent evaluation of a system from the viewpoints of thermodynamics, economics, and environmental protection is expected to be obtained. Exergoeconomics is based on the exergy costing principle, which states that exergy is the only rational basis for assigning monetary values to energy streams and to the thermodynamic inefficiencies within the system. All evaluations are conducted using definitions for *exergy and cost of fuel and product* deduced from the SPECO approach [30], and consistent *environmental impact associated with the fuel and the product.*"

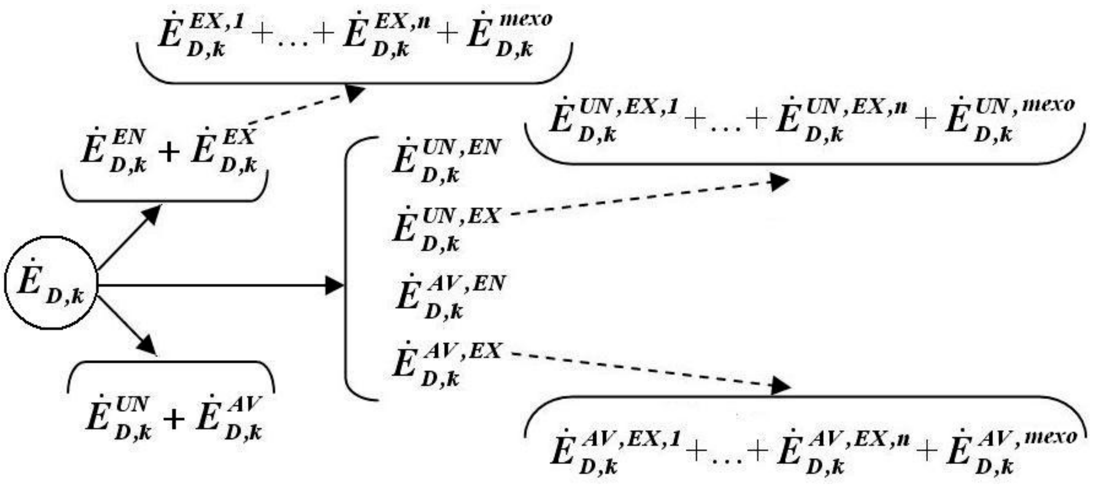
Reference [41] is a readable yet thorough summary of the basics underlying the author's presentation at JETC2013; it summarizes how advanced analyses, including exergetic, exergoeconomic, and exergo-environmental analyses, provide the user with information on the formation processes and the sources of thermodynamic inefficiencies, costs, and environmental impacts, and how they can enhance the creativity of engineers to develop ways for their minimization.

Keep in mind that the presented methodologies begin with a *workable design*. Then, by *analysis* of the design, highlighting interconnections among efficiency, investment cost and environmental impact, steps are proposed for iteratively improving it.

An exergy destruction represents in the design of a new energy conversion system not only a thermodynamic inefficiency but also an opportunity to reduce the investment cost and sometimes also the environmental impact associated with the component being considered and, thus, with the overall system. To take advantage of the opportunities, overall system improvement can be pursued by iteration of the system design parameters, guided by Advanced Exergy-Based Analyses.

The following diagram (Figure 4) illustrates schematically the author's work, included within Advanced Exergy-Based Analyses. The far left circle encompasses the rate of exergy destruction within the *k*-th component of the system. Moving to the right and up, the breakdown into (a) endogenous and exogenous contributions is shown. Continuing upward is (b) a breakdown and summation of the exogenous part into the *k*-th component's *direct* influence on *each* of the other components, plus a "mexogenous" term (which reflects higher order interactions involving *k* and *all* of the other components). Moving down and to the right is (c) a further breakdown, similar to the preceding but summing the *unavoidable exogenous* parts of each contribution. It is this sum, plus the *unavoidable endogenous* contribution that are relevant to improvement efforts.

Figure 4. Schematic diagram illustrating advanced exergy-based analyses.



Another summation, associated with component *k* was presented at JETC2013, namely the sum of avoidable exergy destruction caused by the component *k*:

$$\dot{E}_{D,k}^{AV,\Sigma} = \dot{E}_{D,k}^{AV,EN} + \sum_{\substack{r=1 \\ r\neq k}}^{n} \dot{E}_{D,r}^{AV,EX,k}$$

This relation is elaborated upon by T. Morosuk in "Strengths and Limitations of Advanced Exergy Analysis" [42]. There it is stated, "To identify the real importance of components based on information obtained from an advanced exergy-based analysis, [this new summation] is introduced. This sum is "the avoidable endogenous exergy destruction within the *k*-th componenet and the avoidable exergy destruction within the remaining components caused by the the *k*-th, …, [and] is the best variable for demonstrating the importance of the *k*-th component within the system from the thermodynamic point of view. It is clear in [42] that the task of calculating the overall sum is laborious: Using three case studies (drawn from earlier papers), [42] is very informative regarding "strengths and limitations". The paper surveys (a) calculation procedures for making the various endogenous-exogenous and avoidable-unavoidable breakdowns, and (b) the types of reasoning that is employed to draw conclusions from calculated values. Practical results achieved by applying the conclusions would be very helpful and might well be presented in a sequel paper.

In the presentation at JETC2013, as well as in reference [41], the proponents state that in addition to an exergy analysis, the concepts of avoidable or unavoidable as well endogenous or exogenous exergy destruction can be applied to the investment and fuel costs in exergoeconomics. Thus the exergoeconomic analysis can be based on (i) avoidable endogenous costs, and (ii) avoidable exogenous costs.

To improve the performance of an energy-conversion system from an environmental (ecological) point of view, it is very helpful to understand the formation of environmental impact at the component level. A so-called exergoenvironmental analysis rests on the notion that exergy is the only rational basis for assigning also environmental impact values to the transports of energy and to the inefficiencies within a system. The first step is the usual exergetic analysis of the system. The second step is a life-cycle assessment of (a) each relevant system component, and (b) all of the relevant input streams to the system. In the last step, the environmental impact obtained from the LCA is assigned to the streams in the system: *exergoenvironmental variables* are calculated and an *evaluation* is conducted.

With the aid of an exergoenvironmental analysis, the most important components with the highest environmental impact should be identified. The methodology parallels that of exergetic, monetary costing; unit environmental impact costs are associated with exergy streams (in analogy with unit monetary costs), and component related environmental impact is quantified (in analogy to the component capital and operating costs, Z's, of monetary costing).

It should be mentioned that one of the other schools of Thermoeconomics is that of Valero, where analogous breakdowns (under the ambit of the "Structural Theory") include the definitions of "dysfunction" and "induced malfunction", whose summation is analogous to the *exogenous* exergy destruction, distinct from the "intrinsic malfunction" that is analogous to the *endogenous* exergy destruction [43].

4.3. Applications of Thermoeconomics to District Heating Product Costing

In principle, the exergy based costing methods can be applied to any kind of energy system, including the District Heating Networks (DHNs). Verda, Caccin and Kona presented such an application at JETC2013. The objective is to provide costs of system products (deliveries of "heat" to users) to regulators who would determine the pricing. A hypothetical case study is presented, which takes into consideration the possibility of a second "heat supplier" (as a "third party") to the network.

The costing methods employed are "standard exergy costing". However, since regulators and customers consider that it is "heat" that is transacted, after the cost of each product is determined per unit of exergy, the results are converted to "per unit of energy" values (simply by applying the thermodynamic ratio of calculated exergy to calculated energy of the product). It is important to make the basic calculations on the basis of exergy, because final users (customers) that require the same amount of "heat" may require it at different temperatures. This issue, along with others, is taken into account by Verda, Caccin and Kona, as well as in previous publications [44–46]:

(a) By applying the exergy based costing methods at component level, taking account of each thermal energy producer, each single pipe in the network, each pumping system as well as of the capital cost and exergy destruction of each of them;
(b) By costing the energy supplied to the user at the end of the production chain on heat basis, therefore by comparing different technological and operating option on the basis of unit cost of heat.

This approach leads to a different unit cost for the various users. This cost depends on the characteristics of the user, particularly its heat demand, its minimum temperature requirement, and the position of the user with respect to the other users and the thermal energy suppliers. Its position affects the irreversibilities and the investment cost of the portion of network required to reach the user itself. This concept is the basis for using thermoeconomics in optimal planning of district heating networks.

The definition of a proper cost of heat for each final user and establishing objective relations among these costs and the physical structure and the operating condition of the DHN is of great importance, in particular when Third Party Access (*i.e.*, separation between generation and retailing of district heating) is considered in order to open up the network to more competitors, to improve the efficiency of the market.

An additional aspect that should be considered refers to the use of thermal storage devices, which operation (charge and discharge) may be decided on the basis of the cost of heat, total heat demand, supply temperature requirement of the network. All these aspects can be included in the costing analysis when a method based on the exergy evaluation of "heat" flows is considered; thus thermoeconomics is a suitable tool to manage third-party access to the district heating network.

Finally, a proper costing methodology is crucial when the final users have the option of modifying their demand profile and/or temperature requirements in a way that positively affects the operation of the DHN, or of the heat suppliers. This happens, for instance, when the final users may adopt low temperature heating systems, such as radiant floor, or when energy savings initiatives (e.g., wall, roof or window insulation) are introduced. This kind of initiative has positive impact on the efficiency of district heating systems since network can be operated at lower temperatures and because the existing heating system becomes oversized, so that additional users could be connected. The main advantage in the reduction of the operating temperatures consists in the larger plant efficiency. An additional advantage that is obtained by lowering the return temperature consists in the reduction of the mass flow rate flowing in the district heating network, which allows one to reduce the pumping cost. Final users that take this kind of initiatives should obtain a lower price of heat, with respect to other users, in order of not de-incentivize any energy saving action at building level.

Verda's paper is a good example of the use of exergy for costing products, particularly taking into account various operating parameter, some controllable.

5. Applicability of Exergy to Energy Policy and Research Funding

Besides applications to "systems engineering", another place where exergy analysis is of importance is for allocation of funding for research and development, whether the funding is corporate, entrepreneurial or governmental, as well as for establishing policies. That brings us to another paper presented at JETC 2013, by Marc A. Rosen.

The energy utilization of a country or region is conventionally analyzed by examining the flows of energy through various sectors of the economy. But energy analysis can be misleading and such analyses sometimes indicate the main inefficiencies to be in the wrong sectors and tend to state a technological efficiency higher than actually exists. It can be asserted that in order to properly assess how well a country or region utilizes its resources, an examination of the flows of exergy, rather than energy, through the sectors is required.

As shown in the previous presentations and comments, many researchers observe that exergy, but not energy, is a consistent measure of economic value, and that accounting and pricing are better performed when based on exergy rather than energy. One outcome of that research has suggested that financial investments in energy research should be related to or guided by exergy rather than energy measures. The paper presented at JETC 2013 by Rosen expands upon that suggestion.

Specifically, energy and exergy losses are compared with energy research-and-development spending, demonstrating that the latter correlates with energy inefficiencies, even though it would be more sensible to allocate R&D funding in line with exergy inefficiencies, as they represent the actual deviation from the ideal. The methodology is outlined and illustrated with two case studies in North America.

Consistent with the diagram shown in Figure 5, the author presents two detailed versions, one showing energy and one for exergy flows through the economy of the province of Ontario, Canada (circa 1990; see [47]). The diagrams follow the format of Reistad [48], which analyzed the U.S. economy. The detailed diagrams can be found in the full paper, on the JETC2013 website. The results will be summarized forthwith. First, some definitions:

Inefficiencies:

Sector j perceived inefficiency = $1 - \eta_j$ = (Sector j energy loss)/(Sector j energy input).

Sector j actual inefficiencies = $1 - \psi_j$ = (Sector j exergy loss)/(Sector j exergy input).

where η_j denotes the energy efficiency and ψ_j the exergy efficiency of sector j.

Inefficiency Breakdown:

Fraction of perceived inefficiency for sector j = (Sector j energy loss)/(Total energy loss).

Fraction of actual inefficiency for sector j = (Sector j exergy loss)/(Total exergy loss).

Figure 5. Model of a region, country or the world, showing flows of resources, like energy.

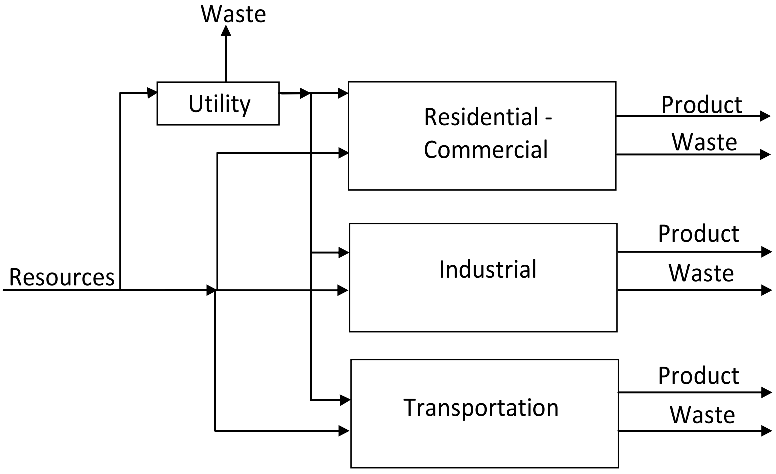


Table 1 summarizes the efficiency of each sector, from an energy viewpoint and from an exergy viewpoing. In each column there is a double entry, one for Ontario and a second one for the USA (deduced from the work of Reistad [48]). The last column represents funding appropriated to the various sectors by government agencies; Ensearch in Ontario, and the U.S. Department of Energy (circa 1983). Funding will be elaborated upon in a subsequent table; of primary interest in Table 1 are the major differences between energy and exergy efficiencies. Note that the overall energy efficiencies are about 50%, while those for exergy are in the low 20's. The principal factors are the differences associated with the Industrial and the Residential-Commercial sectors. The discrepancy is especially high in R&C, where "energy" is used largely for comfort purposes. It could be argued the largest fraction of R&D funding should be devoted to this sector, inasmuch as it provides the greatest opportunity for improvement. Whereas, from an energy standpoint it would appear to deserve the least. (Why is there such a discrepancy? Because much of the energy deployed for comfort is used with equipment like the furnaces referred to earlier.)

Table 1. Summary of Sector Efficiencies and Funding.

SECTOR	Energy Efficiency	Exergy Efficiency	Percent of Funding
Industrial	70%/78%	40%/36%	54/18
Residential-Commercial	70%/80%	12%/14%	9/20
Transportation	15%/20%	15%/21%	15/34
Utility	36%/32%	36%/36%	22/28
Overall	48%/50%	23%/21%	100

The preceding table, however, does not show the fraction of the overall economy's inefficiency that is attributable to each sector. That perspective is provided by Table 2.

Table 2. Comparison of Funding to Energy and Exergy Inefficiency, by Sector.

SECTOR	% of Total Energy Inefficiency	% of Total Exergy Inefficiency	Percent of Funding
Industrial	21%/14%	24%/27%	54/18
Residential-Commercial	12%/10%	25%/27%	9/20
Transportation	27%/41%	20%/27%	15/34
Utility	40%/35%	31%/19%	22/28
Overall	100%	100%	100

Notice that the US research funding correlates strongly with the sector's contribution to energy inefficiency, with significantly higher funding to the Transportation and Utility sectors than to R&C and Industrial. Whereas, from an exergetic viewpoint, apportionment should be more or less equal to the three end-use sectors, and significantly lower to utilities. Again, R&C has the lowest exergetic efficiency and therefore the largest opportunity for improvement.

Except for the high proportion of funding going to the Industrial sector, in Ontario the funding also follows the energy inefficiency. The inordinate amount dedicated to "Industrial" is very likely a consequence of a policy of Ensearch that requires grant recipient to cover two-thirds of project costs, and it is likely that industry is more likely to cover those expenses. Aside from this anomaly the comments made regarding the US apply to Ontario as well.

Conclusions of the Outlined Methodology

In comparing energy research budget allocations with thermodynamic losses, it appears that, of all factors affecting energy R&D budget allocations to the sectors of the economy, the perceived inefficiency (which is based on energy) is significant and the actual inefficiency (which is based on exergy) is of less importance or is overlooked completely. If actual inefficiencies were considered in research budget allocations, one would probably see more funding for the residential, commercial, and utility sectors, because these are the sectors with a large room for improvement.

The results are expected to be of use to government and public authorities that administer research and development funding and resources and should help improve the effectiveness of such investments. The comparison made in the case studies between energy research spending for the economic sectors of societies with energy and exergy inefficiencies in those sectors reinforces these conclusions.

6. Some Applications to Ecology, Human Society and Resources Accounting

The idea of applying the Cost Accounting in terms of primary energy resources consumption also to ecological and social systems has led to the definition of procedures for the evaluation of the so-called "embodied energy" [15]. Among these, the better documented and most successful is certainly Emergy Analysis (EMA, see, for instance [49]). As considered later in this paper, Exergy Cost Theory (ECT, see, for instance [11]) can also be applied to this kind of system.

6.1. Cost Accounting in Ecological-Technological Energy Systems

In spite of being based on the same Elementary Costing Principles, two differences between EMA and ECT methodologies appear immediately:

- The boundaries of the system are not the same. In fact ECT is typically applied to power plants (or other energy conversion systems), having a fossil fuel as the main input and electric and/or thermal power as the output. The EMA control volume includes also the portion of the biosphere that generates the goods and services directly or indirectly required for operating the system.
- EMA measures energy flows by their energy content and mass flows by their eMergy ("embodied energy) content, while ECT measures energy and material flows alike by their exergy content, evaluated with respect of a proper set of ambient conditions.

The first point is not a real problem. In fact, the system limits usually defined by the ECT could be extended, up to coincide with those of EMA. In this matter, the large experience of EMA could be of help to extend the application of the exergy based cost accounting methodology.

The difference in the second point has been vanishing in recent years. In fact the idea of measuring energy flows through their exergy content is now widely accepted and practiced in the field of EMA [49–51]. In addition, it could be noted that energy and exergy based cost accounting actually provide different results only if some flow splits (like flow 3 in Figure 1).

Otherwise, in spite of the unit costs being different, the total cost flows are the same; as Reini highlighted at the JETC 2013, if we disregard the different nature of the subjects (biological ecosystems *vs.* technological industrial systems) and we leave aside the issue about the proper definition of Emergy as "Embodied energy" rather than "Embodied exergy" [51], but we focus on the cost allocation rules, it is apparent that the Emergy and the Exergy Cost are analogous concepts and that they are obtained applying the same cost allocation rules, at least in case of simple systems, like that in Figure 1. In the same way the "Transformity" and the "unit exergy cost" do correspond to one another.

The real differences arise when multi-product components (or bifurcating flows) have to be taken into account, because in this case the problem of average cost allocation cannot be solved on the basis of the cost balances alone. Therefore, a generalization of average costs has been introduced in both methodologies, but the two generalizations turn out to be different: When emergy algebra introduces the co-product bifurcations, the principle of cost conservation is violated (whereas in exergetic costing it is not, thanks to the generalization of the average costs introduced with the Structural Theory, as previously mentioned). In the former approach the total energy cost of all input (that is named the input Emergy) is allocated on each one of the products, so that additional rules have to be introduced, in order to avoid "double counting" of cost downstream from the co-product bifurcation, or in case of recycling one of the co-products.

Thus, the different hypotheses, formulated to deal with bifurcation and recycling of flows, have to be regarded as the main obstacle towards a unified formulation of the two methodologies. Notice that similar differences are found when comparing EMA with the Embodied energy Analysis by Herendeen [15].

In recent years, the effort to re-think the fundamental background of EMA and the aim to enlarge its application field, are bringing inside the EMA some new contributions that could bring the two methodologies closer [52–54]. Yang *et al.* [52] proposed a new EMA method for waste treatment, reuse and recycle that is very similar to the sub-product and residue concepts defined in the ambit of ECT. Reini and Valero [28,29] have suggested how an additional cost allocation criterion, very similar to the case of co-product in the EMA, can be formulated within the ECT frame: in all cases in which there are two (or more) products, but only one degree of freedom is available for the multi-product component, this new allocation criterion goes as follows. One product is correlated with the degree of freedom, so that it can be modified in accordance with the requirements of the downstream production chain, while the second one is considered a necessary flow, which cannot be varied independently from the previous one.

If the PS does not allow the second product to be identified as a by-product, or a residue, the average unit costs can still be calculated by applying their definition of shadow costs at constant specific consumption; the result is a unit cost equal to zero for the second product, as if it were a wasted output or a residue devoid of disposal cost. To obtain the not-null value of its transformity, a complication has to be accepted: The roles of the dependent/independent flow have to be exchanged and the average cost calculation has to be performed a second time. This two-step procedure yields a pair of unit costs, usable within the framework of EMA, in substitution of the co-product cost allocation rule. (Notice that the simultaneous production of two flows of different nature, has always been accounted for in the emergy literature, but with its co-product concept having a peculiar, not-conservative, cost allocation rule. When co-products occur in living energy systems, it is generally not possible to distinguish between byproduct and residue. In technological energy conversion systems, the distinction is generally feasible.)

To address the problem of recycling flows, Tilley and Brown [53,54] have developed an approach to deal with those processes in which the recycle of material is present inside the system. This kind of approach (named Dynamic Emergy Accounting, DEA) provides for explicitly taking into account the dynamic characteristic of the components inside the system, including a transient period before steady-state conditions are reached.

In this way, the emergy of the recycled flow (which has to be stored in a buffer, before of being used in the up-stream production chain) can be regarded as an actual productive factor in spite of being the output of a bifurcating node, where the recycled material is separated from the principal product. This is different from what traditionally happens in the EMA, in which the not-double-counting rule applies to all recycling flows, without distinguishing whether they come from splits or co-products. In the DEA approach the transformity of the recycled material flow does coincide with that of the material inside the buffer: therefore, because the buffer cannot be completely empty at the beginning of the transient period, this transformity becomes an input datum that must be specified by the analyst. Consequently, with the DEA approach the transformities of the recycled flows can be fixed by the analyst, and they affect the emergy accounting in the up-stream production chain, so that the emergy of some flows in that chain may be greater than the total emergy input of the system. Notice that this may happen in the ECT, when some flow is recycled backward in its own production chain, but it had been explicitly excluded by the orthodox emergists, before the definition of the DEA approach.

By combining the generalized methods of ECT, where the co-product, split and by-product concepts have been introduced, as recently suggested in [28,29], with a quite natural generalization of the results of the DEA, where the transformities of all the recycled flows (except the dependent co-products) affect the emergy accounting in the up-stream production chain, a new general cost accounting method could be outlined. In this integrated approach, the cost allocation rules of classical EMA and ECT apply to a set of particular cases, so that it is expected to enlarge the options the analyst can use in the PS definition and to allow the correct use of the results of both methodologies.

6.2. Tracking Resource Utilization by Biological Systems and Human Societies

Another approach that is explicitly aimed at extending exergy analysis to very large systems, including biological systems, ecosystems and human societies, has been suggested by Sciubba and followers [55–61] starting in 1995, with the name of Extended Exergy Accounting.

In order to highlight the distinctive aspects of the EEA, let us consider how to assign a unit exergy cost to each energy and material product inside a system of the previous kind.

In order to define a consistent set of costs, all products have to be regarded as obtained by using the same set of primary exergy resources. If technological components and biological resources have to be taken simultaneously into account, the exact evaluation of all of the actual primary exergy resources “used” by the process would lead, exactly like in the Emergy method, to system boundaries very remote from the process, and encompassing a relevant portion of the ecological and (external) industrial system. A practical alternative to such an unwieldy practice is to stop the backward search at a certain level and, akin to Szargut's CEC ("Cumulative Exergy Content") approach [62], assign to each reasonably proximate input an exergy cost.

In this perspective, it is natural for EEA to transmute the set of costs per exergy unit, adopted in Thermoeconomics, as the "exergy equivalents" of the input fuels. Whenever possible, though, like in Emergy Analysis, an (approximate) backtracking of all energy streams down to their "raw resource" exergy content is performed. Also in a procedure similar to the Emergy approach, monetary costs and labour are accounted for in "exergy equivalent" units of the respective primary resources [49]. Thus, a completely "exergy-budget" for any production chain is implemented.

Given a generic system, provided that (a) exergy values can be defined also for the fuel and products of biological systems, ecosystems and human societies and (b) that the conversion chain from the "raw materials" are known, then (as in standard thermoeconomic approach) the fuel/product ratio can be defined. Thereby, a measure of the exergy cost of each product is obtained—determining how many "units" of primary exergy are embodied in every exergy unit of Product.

Since it is unlikely that all Fuels reach the boundary of A directly from the environment, without any previous treatment, it is necessary to backtrack the production process of each one of them, to compute its own exergy cost: this backtracking comes to a halt when all inputs have been assigned a valid equivalent primary exergy value. This procedure is in line with that proposed by Szargut [62] for calculating the CEC of a product, as a rational measure of the load placed by A on the environment at any instant, for obtaining its Products.

But in EEA the picture is not yet complete because the mode of operation of system A may imply the production of residues; these are effluents which are discharged by A in a physical state different than their respective "environmental conditions" (for example, they may consist of a material discharge at T different than the ambient, T_0). This poses an additional "load" on the environment, which must now use a portion of the primary exergy it can avail itself of (for example, solar radiation) to exert some buffering action and reduce each discharge to its environmental state. The amount of exergy necessary for the buffering can be calculated if we know (or assume) the processes involved, so that an additional consumption of exergy resources can be reallocated on the Products of system A. (Notice that this procedure is very similar to the way in which residues can be taken into account by the Structural Theory [28,29].)

Since the cost here obtained represents the primary equivalent exergy embodied in the product and already includes a proper internalization of the so-called environmental externalities, is it possible to devise a similar treatment for the remaining externalities, namely labour and capital? The EEA suggests an affirmative answer. In fact, it computes the primary exergy equivalents of labour (ee_L, in kJ/workhour) and capital (ee_K, in kJ/€) on the basis of two econometric coefficients: the first (α) is derived from the pro-capite exergy consumption in the society within which the technical process A is operating, and the second (β) from the society capital intensity, measured by a monetary circulation indicator, usually M2 (also called "money plus quasi-money").

As previously discussed, labour and capital also could be taken into account, in principle, via their exergy cost. But tracking back all direct and indirect inputs would require the inclusion in the control volume of a substantial portion of the ecological and industrial system of planet earth (think, for instance, of imports of intermediate goods). To avoid this (practically impossible) task, all of the labour and capital inputs, for which a production chain cannot be explicitly evaluated in exergy terms, are taken to possess an exergy content respectively equal to their man-hours of work, multiplied by the primary exergy equivalents of labour, and their market monetary cost multiplied by the primary exergy equivalents of capital.

It must be remarked that the procedure adopted in EEA to calculate the primary equivalents of labour and capital has been subjected to some criticism as to its consistency with the real state of affairs in real societies, and, at present, it must be regarded as a premise of the procedure.

Thanks to α and β coefficients both labour and capital expenses can be expressed in primary exergy units and included in the exergy flow diagrams as Fuels: the final result is that an extended exergy cost can be assigned to any product, including the amount of primary exergy "embodied" in the product, as well as a proper internalization of the externalities due to the discharging of residues in the environment, the usage of human labour and capital. The "extended exergy cost" can therefore be regarded as the exergy footprint of a product, a rigorous ecological indicator measured in kJ/kJ and rooted both in system analysis and thermodynamic principles.

Several applications of the EEA method have been published in the archival literature. All applications suggest that the EEA results provide additional insight into the thermodynamic intensity of the internal flows in a process (or in a society) and result in useful information about possible improvements that may be obtained by reducing the primary exergy consumption for a prescribed output.

6.3. Accounting of the Mineral Capital of the Earth and its Depletion

Antonio Valero presented at the JETC 2013 a contribution following the idea that Thermodynamics could be used as tool for accounting scarcity, unavailability and dispersion of minerals. Since a "mine" (highly concentrated mineral) is a very improbable occurrence in the Earth's Crust, exergy and its related concept of replacement exergy cost, can be used to make a systematic accounting of the loss of Mineral Capital on earth.

In 2010 and 2011, Antonio and Alicia Valero-D proposed a model of the Planet Earth they called Thanatia. This model represents a planet totally exhausted of concentrated minerals in the crust and completely devoid of life in its atmosphere and hydrosphere [63–66]. Thanatia is a thermodynamic model for a dead earth where all fossil fuels have been burned and converted into CO_2 and all mineral deposits have been uniformly dispersed. The resulting degraded atmosphere has a carbon dioxide content of 683 ppm and a mean surface temperature of 17 ºC; the degraded hydrosphere is assumed to have the current chemical composition of seawater at 17 ºC. For the upper continental crust, the authors proposed a model which includes composition and concentration of the 294 most abundant minerals currently found on earth as bare rocks. In this sense Thanatia represents, in the viewpoint of the Valeros, a coherent baseline for the assessment of mineral resources in exergy terms. Note that Thanatia itself has non-negative exergy, with respect to other "conventional" reference environments, like those of Szargut [67] and Ahrendts [68].

Since Thanatia contains virtually every mineral found in the crust, the chemical exergy of the minerals from that reference is zero (as they do not need to be constructed). As opposed to chemical exergy, *concentration exergy* expresses the minimum exergy required to concentrate the given mineral from the depleted state in Thanatia to the conditions found in the mineral deposits, with the specific ore grade. This concentration exergy can be calculated, at least for ideal mixtures, such as solids where there is no chemical cohesion among the substances. But cohesion exergy is always present in any mineral. Cohesion forces are sufficiently strong to require physical comminution processes like crushing, grinding, or milling. Therefore, a factor is missing in the characterization, namely the comminution exergy, *i.e.*, the minimum exergy required to bind the solids from the dispersed state conditions of Thanatia to those in the mineral deposits. Nevertheless, in [69], the authors demonstrated that comminution is a very exergy intensive process when it comes to fine grinding and milling operations, but it is not so relevant in crushing operations, and becomes negligible when evaluating the mineral loss of capital on earth. This is why the concentration exergy term only is taken into account, when assessing the Mineral Capital on Earth.

It should be noted that, if the assessing is limited to the foregoing methodology, the numbers obtained are unexpectedly far from those expected, because exergy is assessed assuming reversible processes. Hence, it is necessary to replace exergy with the actual exergy costs (kJ), which represent the sum of *all* actual exergy resources that would be required to replace a mineral from Thanatia (or grave) to the conditions actually found in nature (or cradle). To make this calculation the authors *assume* that the same "backup" technologies are applied in the imaginary process from Thanatia to the mine (grave to cradle stage) those used in the real mining and preparation processes (mine to industry gate). Therefore, a Life Cycle Assessments of mining-to-industry processes become essential for assessing costs.

All proposed concepts, Thanatia, exergy resource and exergy replacement cost are solidly based on the Second Law. The exergy and exergy replacement costs provide a measure for quantifying this degradation, which is systematically being ignored in conventional accounting systems. The authors propose that the United Nations System of Environmental-Economic Accounting (SEEA) and its global framework would be the best world infrastructure to convert the replacement cost accounts into a Global System of Environmental-Thermo-economic Accounts (SETEA). In such a way, "Thermodynamic accounting of mineral resources" may play an important role in the global management of the natural resources of the Planet.

7. Implications of the "Dead State" upon Exergy Analyses

The concept of "dead state" is important to engineering applications of exergy, and to ecological and economic applications. The following discussion emanated from the doctoral dissertation of W. J. Wepfer [70]. The portion of that work dedicated to the "dead state" appears in [71]. What is called "state *f*" in [70] is "dead state" here; "system available energy" there is "available energy (of Gibbs)" here; "subsystem available energy" there is "exergy" here [72].

The ideas of "subject" and "dead state" (as described below) are of importance to the application of the exergy concept (a) to engineering, and (b) to ecological and sustainability applications. Reference [71] is devoted primarily to (a), and [73] primarily to (b). Both are based on Gibbs' concept of Available Energy.

7.1. The Basic Concepts: Available Energy, "Subject", "Dead State" and "Constraints"

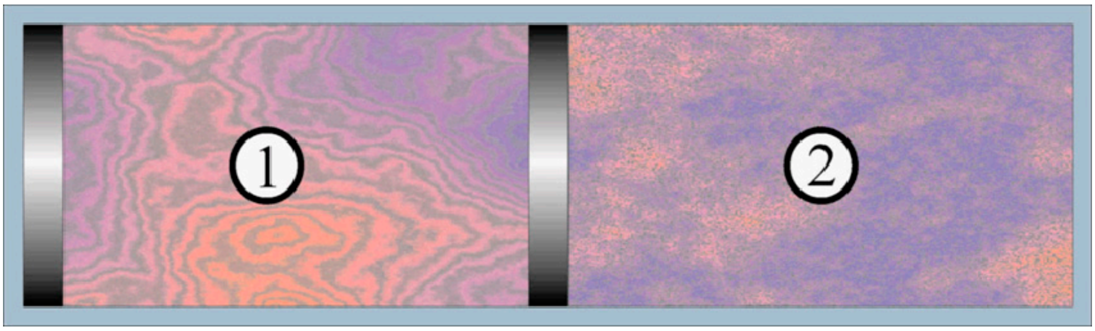
The following is an elaboration of the JETC presentation by Gaggioli and of [73].

The Gibbs' Available Energy of a Body—of a "Subject"—can be illustrated starting from the simple example in Figure 6. At any instant *t*, disequilibrium within the subject indicates potential to influence other objects; that means that there is Available Energy, A(t). It is the amount of energy deliverable from the *subject* to any *object*, upon reaching the subject's *dead state.* The dead state is the equilibrium state reached, subject to *constraints*, such as total entropy (S), total volume (V), *etc.* Then,

$$A(t) = E(t) - E_{min}(S,V, \ldots)$$

where E_{min} is the energy at the equilibrium, dead state, under the *constraints* S(t), V(t), ….

Figure 6. Example of a "subject" (① and ② together) at an instant t.



If (S, V) *alone* are the *constraints*, the net *transfers* of entropy and volume to or from the subject are to be equal to zero, *while* transfers of entropy and volume only are allowed between subsystems 1 and 2, then:

$$A(t) = E(t) - E_{min}(S,V)$$

If another constraint is imposed, such as V_1 (and hence V_2) the available energy would be less, because $E_{min}(S, V, V_1) \geq E_{min}(S, V)$. The dead state for (S, V, V_1) differs from that for (S, V), generally.

From the previous remarks, it can be inferred that the *contro*l of internal constraints can improve the *utilization* of available energy. For *example*, by controlling V_1 more available energy can be delivered, practically. One more example of internal constraints would be the amounts of chemical constituents, n_i.

Three special cases from [73] were presented at the JETC by Gaggioli, illustrating that:

(a) Available energy can be wasted by not applying and controlling variable constraints.
(b) Available energy can go undiscovered by not recognizing a metastable or quasi-stable constraint, and by not controlling the removal of such constraints.

By applying *prospective* constraints and controlling them, more available energy can be delivered, practically.

The basic principles underlying the foregoing have important relevance, to engineering practice (see [71]) and to future developments.

7.2. Relevance to Ecological and Economic Analyses: The "Constraints" and the "Subject"

The implications and limitations of the *subject* (the "isolated system") encompassed by an analysis are often unstated, and then overlooked by the reader.

What is (implicitly or explicitly) included in the subject? The *dead state* depends upon its scope. When, as usual, a *reference environment* ("medium") is included within the subject, the question arises: what limitations does it impose?

An exergy analysis can be misleading if *constraint* assumptions are wrong (or not understood). What is the scope of the underlying *science* being employed to model the processes, by selection of constraints? Generally, the processes have been limited to "classical" chemical reactions. Available Energy (of resources) depends upon *Available Science*. Utilization of available energy depends upon *Technology*, which depends upon Available Science.

In proposals for applying exergy analyses, especially to matters of ecology and sustainability, keep in mind that prognostications require *assumptions*, namely: (a) *The Subject*—its "extent" (Neighborhood? …, Earth? …, Universe?) and its subsystems. And (b) Available Constraints; *i.e.*, *Science*, and (c) Available control of constraints; *i.e.*, *Technology.*

In some recent and ongoing applications of exergy there is implicit if not explicit projection of the future implications of present and forthcoming government "energy policies". It is often suggested that exergy analysis is "the" key to well-informed policy decisions. It is certainly agreed, here, that exergy is "a" key. However, it is vital to recognize that the calculated exergies are *limited* by the underlying suppositions (the subject and constraints assumed by the model; the status of science and technology).

8. Some Comments and Viewpoints

8.1. Regarding Applications of Exergetic Analysis and Costing to Design and Operation

We proponents of exergy often ask ourselves and one another, "After all these years of showing the importance of exergy and its usefulness, why hasn't it become a standard tool of practicing engineers?" A common answer from those who reject it is, "I don't need it" that is, it is not necessary for carrying out design work and oversight of process operations.

Even though exergy analysis is not necessary, that response is trite. The problem is "cultural". When shown results of exergy analyses, a practicing engineer may find it interesting but rarely is there enough interest to overcome the problem of "time".

In the culture of the marketplace, time is of the essence. From the viewpoint of the engineer's client, the principal "design guideline" to be followed is "with today's readily available technology, find the least expensive system for meeting the loads economically". Of course, there is a contradiction in terms there. But generally the client's No. 1 priority is "the least expensive system". The engineer may be welcomed to propose a better system, but additional capital expense will need to be justified by a financial analysis showing significant payback from operational savings *over a short time period*.

In order to use "state of the art" exergy methods (e.g., "Exergo-methods") one needs to become an expert. Even if practitioners can be introduced to the methods with short courses, it is unlikely that they will develop the needed expertise [74]. An answer for getting exergy methods accepted in everyday engineering would be the development of programs that can be used "robotically". Even though an interested engineer may find the concepts and theory understandable and interesting, the tedious work of making the necessary calculations—especially when the results aren't necessary and there is one deadline after another to be met—is onerous and distasteful. And experienced colleagues, mentors, are not at hand. Programs are needed that (a) will make the calculations, and hopefully (b) will provide direct guidance to design-variable changes. For example, such a program would be an invaluable adjunct to the methods of the Tsatsaronis School, especially if it led to the optimal design (or operation). Clearly, program development would be an arduous task, but would be important to implementation of exergy methods into "real world" engineering. Conceivably, a program could be incorporated into existing system simulation software (including the incorporation of exergy amounts onto a system flow sheet).

There is a seeming paradox. Exergy is *not necessary* for guidance to improve a workable design. An alternative is to use system simulation software to construct the function *f* and to use it to find "the" optimum (in the manner outlined earlier). However, *even if* that approach is used to improve a design, it *is* important to know the sources and extent of ineffective use of resources (fuels, feedstocks, minerals, …).

A worthwhile project, which might well be carried out cooperatively by different "schools" working together, would be to compare alternative computational design-optimization procedures—starting with small scale systems like the refrigeration system in Reference [41]. The various procedures could include:

(a) Exergo- and other Thermo-economic methods,
(b) Direct-modeling without exergy,
(c) Methods employing Lagrange multipliers, used directly to find optima, along the lines of [24], or
(d) Used as "pointers" directing step-wise evolution to the optimum (and this could be tried with exergy, or with "direct-modeling"), and
(e) A convergence of Thermoeconomic methods with emergy in the pursuit of an optimum, along the lines of the procedure advocated by Reini, in this panel.

Of course there may be other, important procedures that have not been mentioned here. The objective of such a project would not be to "compete" but to work together toward one or more practical methodologies (and incorporation of variable-load [or feed] spectra should be a goal) [75].

A key phrase, earlier in the statement by the engineer's client, is "readily available technology". That means system structures and, especially, components that have shown to be (or are being marketed to be) cost effective in the marketplace. One conceivable place where exergy methods could be promoted in the near-term is among component manufacturers; for (a) improvement of their components, (b) development of alternatives, (c) conception of new system structure for using them, and (d) for marketing—to engineers and/or their clients. One field that comes to mind is manufacturers of equipment for building comfort and utilities (including refrigeration).

8.2. Regarding Applications to Ecology and Sustainability

It can be easily recognized that, when the aim is to deal with systems (subjects) as big and as complex as the whole planet earth, a set of quite strong simplifying assumptions cannot be avoided, therefore the only possible way of proceeding is to explicitly state all assumptions and incorporate them into the methodology, as shown in the presentations by Valero and Sciubba.

It is essential for readers of such exergy studies to understand the importance of underlying assumptions that are taken for granted. Above all, what are the implications on underlying assumptions of the physical science that is employed? Is there other science at hand that could be the basis for finding or developing more available energy, not merely to serve as an "energy resource" but also for environmental control? Moreover, realize that today's science is far from definitive.

Future prospects:

(1) *The Subject*—depends upon exploration, prospecting, discovering, "mining" of resources, of disequilibrium (metastable, quasi-stable). There are: Unexplored lands on earth; the seas and their floors; space—one example, asteroids; Solar system; Universe—e.g., night sky at 2.5 K, far from equilibrium with our earth. Reducing E_{min}; Recuperation of generated entropy. New "elements" (subsystems)—exergetic; functional. Unexpected scientific discoveries resulting from "exploration".

(2) *Constraints/controls*—exploration, prospecting, discovering, "mining", ….

(3) *Science*—the amount of yet-undiscovered science is great; many mysteries remain. History provides evidence that science will advance and, in turn, technology—particularly when motivated by "necessity". As science marches ahead, technology follows.

(4) *Technology*—controlling constraints; unlocking and controlling metastable (and quasi-stable) constraints.

Let the resourcefulness of the young at heart—of today and of the future (near and distant): Discover, develop, resources, science and technology. Meanwhile: Let us proceed: carefully, but confidently.

8.3. Regarding Applications to Funding and Policy

Perhaps, today this is the most urgent and possibly most productive use of exergy analysis, for promoting more rational (a) investment of R&D funds, and (b) energy and environmental policies. Proponents might well apply even more effort, toward both the marketplace and government.

9. Conclusions

The foregoing review of the papers presented at Panel I of JETC 2013 illustrate, by examples, the direct applicability of the 2nd Law of Thermodynamics, quantitatively, to social issues. This article and the papers reviewed here provide an introduction to such 2nd Law applications. The publications referred to in the Reference section below are links to an extensive, relevant literature.

Author Contributions

Both authors contributed jointly to composing this paper and both of us, having approved the final manuscript, take responsibility for what has been said.

Conflicts of Interest

The authors declare no conflict of interest.

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6. Gibbs covers the basics of available energy on four (small) pages. The presentation is amplified in [5].
7. Some exergy (X) is "used up"—annihilated—in all real processes; so for any real process the change in exergy content of a subsystem over any time interval is represented by $\Delta X = \Delta X_\tau - \Delta X_\delta$ where ΔX_τ is the net amount of exergy transferred into and ΔX_δ is the amount of exergy destroyed within the subsystem. Such an equation *can* be, and commonly is, called an 'exergy balance' (over the objections of some who would reserve the word "balance" for conserved additive properties). The derivation of expressions for exergy content X, transports X_τ and destruction X_δ can be found in most textbooks on "Engineering Thermodynamics". Incidentally, when a system consists of two or more distinct subsystems, whether one is a "medium" or not it is in fact feasible to define exergy for each subsystem, an additive property, with balance equations [76].
8. A primary resource could be a crude "mineral" taken from the earth or elsewhere, or a fuel or a chemical feedstock that has been refined from the crude, or solar radiation, …, or any "source" that is not in equilibrium with the medium and hence has exergy.
9. Some processes can be *modeled* well enough by assuming that there is no exergy destruction *within* the system being modeled, accounting for any exergy consumption by interactions with the system's surroundings. (A couple of examples are (a) classical mechanics models, when it is assumed that frictional effects at the boundary have negligible effect upon the thermostatic state *within* the body; (b) lumped-parameter modeling of free thermal convection to or from an object, when gradients of temperature *within* the body are assumed to be negligible.
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20. The purpose of the low-pressure steam is for heating of chemical processes to expedite the rates of reaction. Different processes call for different temperature steam, which depends upon the steam pressure. Steam is delivered to processes at two pressures, HP and LP; further control of the temperature is achieved by throttling steam at the point of use.
21. Consider the following case, which is just *one* example of when yet another alternative would be called for. Suppose that the cost of purchased power from the local public utility were 2.10 cents/kWh. Then it would be inappropriate (and impractical) to charge in-plant users of power 2.15 cents/kWh. An appropriate auxiliary equation would simply be to *assign* $c_{\text{Power}} = 2.10$ cents/kWhr. The resultant cost of LP steam would be 2.2 cents/kWh, which is significantly less than the 4.5 cents/kWhr (2 cents/kg) cost when obtained by throttling the HP steam. (With a 10,000 kW turbine using 360,000 kg/h of steam, the *earnings* from the turbine investment is $8000/h. Calculations were made using data circa 1980 [16].)
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27. In a few words, the shadow cost associated with a resource (Fuel or Product) tells how much more *total* fuel consumption you would get by increasing the amount of that resource by one unit, for external consumption. It can be proved (reminiscent of [24]) that the shadow costs correspond to the Lagrange Multipliers of a LP problem, having the total fuel consumption as objective function and

the Fuel—Product relations (of all components, junctions and branches) as linear constraints [10,12]. The point of the generalization of average costs is not stressed inside the papers [25,26], probably because the idea of the authors was to present the Structural Theory as based on the physical model of the system, instead of on some mathematic abstractions.

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31. The numerator of both of these two efficiencies is the same. In the case of exergetic efficiency the denominator *excess* over the numerator is an amount equal to the exergy destruction by the real turbine, which is the product of the reference (ambient) temperature times the entropy production by the turbine: $T_0[s_{out} - s_{in}]$. For isentropic efficiency the excess is again proportional to the entropy production, in this case multiplied by a mean temperature T_m between the actual outlet T and the outlet T for the hypothetical perfect turbine: $T_m[s_{out} - s_{in}]$. For reasonably efficient turbines the two efficiencies are relatively close in value, because the denominators exceed the numerators by only five to 20%, *and* the values of T_m are, roughly, only 30% above T_0. (As shown by the plot, lowering turbine exhaust pressure reduces T_m, toward T_0.)
32. The foregoing remarks are also relevant to Lazzaretto's Point b), where he refers to "*real thermodynamic behavior of the component itself*". Component "*real thermodynamic behavior*" is represented by (modeled by) balance equations, property and kinetic relations and imposed boundary/initial conditions, not by an arbitrarily defined "efficiency" (as a "performance *parameter*"). Every "efficiency" (or "figure of merit" or Eco-indicator) is arbitrarily defined, as a convenience. At times they are used in a mathematical model, but they are not necessary. They are a convenience, usually useful but not fundamental [71].
33. The reader should know that there has been a long-standing disagreement between the writers and the promoters of SPECO, regarding the selection of auxiliary equations. So far the dispute has been amicable and hopefully it will remain so. The promoters know that the writers have limitless respect for their work (which has received several well-deserved awards). At this point, the reader can be the judge, or withhold judgment until the promoters rebut. Meanwhile, interested readers can refer to several "case studies" (of a co-generating turbine invoking auxiary equations different from SPECO and DP) in the References of this paper.
34. For each of the *n* items, one of the equations related thereto is an energy balance (implicitly if not explicitly). Notably, an *exergy* balance is not *necessary* for the mathematical modeling.
35. Generally the actual loads on a system vary with time, in a response to demand for the product(s). Commonly "design loads" are the maximum outputs that are expected or sought from the system. Taking load variations into account while seeking an optimum design is certainly important. For simplicity, here cases where load variations are very small are considered, which is sufficient for the discussions that are immediately relevant to the papers of Panel I. Means for accounting for a

"schedule" of load variations (say for a spectrum showing "percent of full load' versus 'number of hours per year at that load") can be conceived. Likewise, variations of feed inputs and interactions with the environment are being neglected here.

36. Moreover, in so doing, exergy analysis uncovers needs (and hence opportunities) for the development of system-structure modifications and/or new technologies. Energy *analysis* is misleading and counter-productive. It is suggested here that, when energy is used appropriately (for modeling), when representing that role the phrase "energy analysis" should be avoided.
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72. (a) The terminology associated with the general concept of 'available energy' and definitions related thereto have been very erratic, and is somewhat unsettled yet. One factor causing confusion is that different investigators, not in communication with each other, specified a name for a particular concept, used at their "school". The name exergy has become well 'standardized' for the concept called "subsystem available energy" in [71] and which had commonly been called "available energy" or 'availability' in the USA. (b) There is a significant typographical error in Equation (14) of [71]. The second line should read, $= E_A + p_f V_A - T_f S_A - \Sigma \mu_{if} N_{iA}$. (c) Some of the developments in [19] have been streamlined since; e.g., in [76] and [73].
73. Gaggioli, R.A. The Dead State. *Int. J. Thermodyn.* **2012**, *15*, 191–199.
74. An exception would be an individual who developed the expertise in order to become a consultant, specializing in its use. Likely, finding clients—marketing—would be difficult.
75. An interesting possibility would be to replace the use of energy balances in modeling with exergy balances. This would not be as simple as one might hope. It would require the explicit incorporation of entropy balances in the model; however they are there now, implicitly, when efficiencies (or figures of merit) are included to represent the behavior of devices (or, in continuum models, when transport and kinetic coefficients are employed to represent material behavior). Explicit inclusion of entropy balances can simplify modeling [77].
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