Article

A Critical Interpretation and Quantitative Extension of the Sama-Szargut Second Law Rules in an Extended Exergy Perspective [†]

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Abstract: Twenty-five years ago, Gaggioli, Sama and Qian published a series of 10 "second law guidelines" for design and process engineers, nicknamed at that time "the Gaggioli-Sama rules". These guidelines, some of them previously published by Sama between 1980 and 1983, are a compilation of "second law errors" to avoid in the design of energy conversion systems. The list was rearranged several times, until a revised version containing 21 rules was published by Sama and Szargut in 1995. Ever since, these guidelines came to be known as "the Sama-Szargut rules". The rules are a series of well-formulated and insightful suggestions that reflect a thermodynamicist's idea that the "best design" is the one that minimizes the overall irreversibility in a process or plant, under the prescribed technological constraints. Characteristically, the concept of "optimal system" is completely absent, the emphasis being on the extensive inclusion of second law reasoning into design decisions. A critical analysis of the rules would suggest that all of them be routinely implemented both in new designs and most important in retrofit projects. A survey of some of the current most common energy conversion installations shows that, quite on the contrary, most of the rules are disregarded in practical applications. This paper argues that the reason for this incongruency is the neglection in the engineering design decision of the real cost of installation, operation and decommissioning of a plant, and proposes a rephrasing of the rules in an extended exergy perspective: if the production cost, including the externalities, is measured in units of equivalent primary exergy, the Sama-Szargut rules can be directly interpreted in this sense, and abidance by the rules results in the reduction of the resource cost for any given objective.

1. Introduction

In 1989, expanding on previous works by Sama [1,2], Gaggioli, Sama and Qian published a series of 10 "second law guidelines" for design and process engineers, that came to be known as "the Gaggioli-Sama rules" [3]. These guidelines are a compilation of "second law errors" that must be avoided in the design of energy conversion systems. The list was rearranged several times [4,5], and its latest accepted version, containing 21 rules, was published by Sama and Szargut in 1995 [6]: ever since, they have been referred to as "the Sama-Szargut rules".

The rules reflect a thermodynamicist's idea that the "best design" is the one that minimizes the overall irreversibility in the process or plant under consideration. Significantly, the concept of "optimality" is completely absent from the rules, the insistence being on the extensive inclusion of second law reasoning into design decisions. In view of the evergrowing incentive to reduce resource use and to optimize the matching between primary sources and final uses, it should be expected that all of the rules be routinely implemented, both in new designs and in retrofit projects. It turns out, that the contrary is rather true: after some earlier public debates, which demonstrated that a careful application of the rules leads to superior (= better performing) energy conversion systems for a wide range of applications (heat exchanger networks [2], combined cycle plants [7]), most of the rules are actually disregarded in practice in the majority of the current energy conversion installations.

This paper contends that the reason for this apparently irrational behavior lies in the insistence of founding current engineering design decision on a distorted-purely monetary-view of the cost of installation, operation and decommissioning. It is argued that, if the production cost is assessed in terms of equivalent primary exergy use and a proper exergy accounting for the externalities is introduced, an Extended Exergy Accounting shows that the Sama-Szargut rules can be directly interpreted in their original sense, and their inclusion in the design process results in the reduction of the resource cost for any given objective.

2. A Commented Compilation of the Sama-Szargut 2nd Law Based Rules

Since the issue raised in this paper concerns process and plant design, it is convenient to classify the Sama-Szargut rules on the basis of their major perceived field of application. This classification is somewhat arbitrary, because some of the rules intrinsically pertain to more than one group. The classification presented here is the same proposed in [8].

2.1. General Process-Related Rules

1. *Do not use excessively large or excessively small thermodynamic driving forces in process operations.* This rule was originally formulated for heat exchangers, and prescribes that the temperature differences between the heating and heated fluid should not be too small (because the necessary heat transfer area will be too large) but also not too high (because the irreversibility in a heat transfer process grows with the T). The rule applies with obvious

modifications to chemical, electrical and fluid processes where the exergy decrement of one stream is the "fuel" Throughout this paper, the words "fuel" and "product" are used in the acception proposed by Tsatsaronis [9,10], *i.e.*, as "used exergy input" and "useful exergy output" respectively. used to increase the exergy content of another stream: the exergy destruction is proportional in all cases to the square of the driving force (ΔT, ΔG, ΔV, ΔH).

2. *Minimize the mixing of streams with differences in temperature, pressure or chemical composition.* The mixing of streams with different temperatures unavoidably leads to irreversible heat transfer in the temperature-equalization process. If the mixed streams have also a different composition (e.g., in the oxygen-enrichment of process air) a portion of the chemical exergy of the stream whose concentration is the farther from the reference one is destroyed. If the streams have different pressures or velocities the mixing results in a highly irreversible momentum transfer by viscous actions from one of the fluids to the other.

3. *Remember that in cyclic and pseudo-cyclic processes driven by chemical, nuclear or mechanical energy the rejection of heat to the environment in condensers of turbines, refrigerators, etc., is a reflection of the irreversibilities within the plant.* A decrease in heat rejected from condensers (which represents a discharge of exergy into the environment) can only be attained by a reduction of the irreversibility within the plant and it cannot be eliminated by the introduction of internal "improvements", like for example the recompression of vapour in evaporator systems. By adopting these measures, only the location of the rejection is changed (it appears some other section of the plant, possibly at a higher temperature).

4. *Fans or compressors should be designed to operate on the coolest streams that participate to the process.* The driving power of compressors and fans is proportional to the fluid density, and hence—for the same inlet pressure and the same pressure ratio—it decreases with the inlet temperature.

5. *Avoid the compression of a gaseous stream which has been previously expanded.* The exergy destruction affects twice the same stream in this case, and the unavoidable exergy destruction in the expansion causes the "recovered exergy" in the expander to be always less than the "used exergy" in the compressor, lowering—*ceteris paribus*—the efficiency of the process.

6. *Try to introduce cogeneration processes that simultaneously produce two or more useful effects.* A cogeneration process (e.g., joint production of heat and electricity, of desalinated water and power, of two different chemicals) brings about a shortening of the chain of processes and therefore ensures a reduction of the exergy destruction within the entire system (see rule 17). Furthermore, synergic effects in the process may lead to the generation of more units of "product" with the same amount of "fuel".

7. *Consider the influence of possible changes in the energy management of a part of a system on the exergy destructions in other links of the system.* Energy conversion systems are large, complex and non-linear systems, and a change in the type, quality or amount of energy stream(s) used as "fuel" in a component is very likely to affect some of the other components, be they up or downstream in the conversion chain. While a 1st Law analysis suggests that the

improvement in the conversion efficiency of one component is always an advantage, Thermo-economics (a 2nd Law-based analysis method) has convincingly shown that the separate optimization of one unit of an energy system does not necessarily lead to an increase in the exergy efficiency of the plant, due to the influence of the system connectivity (feedbacks, forward links, bifurcations, *etc*.). In an exergy analysis, a quantitative measure of the system connectivity on the relative values of the exergy destruction in different components is provided by the Beyer-Kotas coefficients [11,12].

8. *Some 2nd Law inefficiencies cannot be avoided, others can. Concentrate on those which can.* This is the basis of the novel Tsatsaronis' "avoidable costs" method [13], and represents a sort of Occam's razor for engineering decisions about seeking "local" improvements to a process. The idea is that once the type of component has been selected (for instance, a PV panel), its intrinsic technological limitations (in this case, the operating temperature of the PV-cells) pose some upper limit to its conversion efficiency, that cannot be removed unless one recurs to: (a) a different technology for the component (lower exergy destruction or loss); (b) a different component (lower exergy destruction or loss); or (c) the addition of a bottoming device that recovers some of the exergy loss (fluid cooling as implemented in hybrid PV panels).

2.2. Heat Exchange-Related Rules

9. *Do not discard heat at high temperature to the ambient or to cooling water, and do not heat refrigerated streams with hot streams or with cooling water.* High temperature waste heat has a relatively large exergy content, and it is better design practice to partially recover it by proper cascading processes. Symmetrically, in most cooling installations, the exergy of the discarded refrigerated streams can be partially recovered within the system boundary by heat exchangers where sub-ambient process streams need to be cooled.

10. *When choosing streams for heat exchange, try to match streams where the final temperature of one is close to the initial temperature of the other.* This reduces the logarithmic mean temperature difference (LMTD) of the process and maximizes the exergy recovery in the heat exchange process. The decision about how small the terminal temperature difference (TTD) must be taken in accordance with rule #1.

11. *The flow heat capacities ($C = c_p m$) of the streams exchanging heat should be similar. If large differences appear, consider partitioning the stream having a higher heat capacity between two or more heat exchangers heated (or cooled) by additional streams.* This is really a corollary of the previous rule. Large differences in heat capacity lead to a lower T in the large-C stream, increase the LMTD of the exchange and cause a non-uniform distribution of the exergy destruction within the heat exchanger.

12. *Any counter-current process is generally more thermodynamically efficient than its parallel equivalent.* Counter-flow heat exchangers and selective membranes display the smallest exergy destructions (see rule 1). Application of parallel current processes is acceptable only in the presence of case-specific design constraints.

2.3. Viscous Loss-Related Rules

13. *Exergy destructions due to hydraulic friction or irreversible heat transfer are the larger, the lower is the temperature in the process. Minimize these destructions especially below the ambient temperature.* The viscous exergy destruction is directly proportional to the fluid viscosity (that in most gases increases with decreasing T) and inversely proportional to T. The thermal exergy destruction is inversely proportional to the second power of T [14].

14. *Minimize the throttling of steam or other gases.* Throttling introduces a destruction of exergy which could be otherwise recovered, and is usually devoid of economic justification.

15. *Eliminate leaks in pipelines, valves and combustion chambers.* Even small leakages of compressed gases, of hot combustion gases or unplanned air injection into combustion gas ducts or combustion chambers lead to a large decrease of exergy efficiency of the total system (see rules 2, 5, 3, 14).

2.4. Exergy Cost-Related Rules

16. *If you can reduce some exergy destruction, check whether you are increasing another exergy destruction or causing yet another to appear.* This is related to rule 7: the connectivity of a plant (its structure) ought to be taken into account, for instance by proper use of the Kotas coefficients of structural and external bond, σ and π. It is often the case that the elimination of the exergy destruction in one component causes a larger exergy destruction in a downstream unit: case in point is the intercooling in a multi-stage compressor in a gas turbine plant: the air stream that enters the combustion chamber is at lower temperature than without intercooling, and this causes a larger exergy destruction in the combustor, unless regeneration is implemented.

17. *Avoid to unduly extend the chain of thermodynamic processes for a certain product.* Every additional link in the chain is a real process and introduces new exergy destructions.

18. *Remember that the specific exergy cost increases "downstream" along the chain of processes.* This is again a contribution of Thermo-Economics: the specific cost of the fuel exergy in the *j*-th component of a process is smaller than the specific exergy cost of the product, and if this product is used downstream as a fuel in the $(j + 1)$th component, the specific exergy cost of the $(j + 1)$th products increases in turn. This applies to the cost formation of "residues" (by-products and waste flows) as well: the cost of a recycle from component *j* to $j + 1$ must be calculated from the cost-balance equation of the component it originates from, whatever the relative positions "*j*" and "$j + 1$" are in the process structure.

2.5. Monetary Cost-Related Rules

19. *When exchanging heat between two streams, minimize the use of intermediate heat transfer fluids.* The application of an intermediate fluid always increases the total heat transfer area. It may be justified only in specific cases, because of local constraints or when thermal energy must be transported across long distances.

20. *Accept an exergy destruction only if it is indispensable for the reduction of investment expenses. Exergy destructions devoid of an economic justification should be treated as the result of an engineer's error.* This is related again to Tsatsaronis' avoidable and unavoidable cost formulation: for instance, the exergy destruction due to irreversible heat transfer cannot be eliminated from a heat exchanger, because with vanishing temperature differences the heat transfer area would be infinitely large; the exergy destruction due to viscous effects in a compressor can be partially but not totally eliminated, *etc.*

21. *Try to reduce the exergy destructions in places where they are the greatest and in places where they are the most expensive.* The destruction of exergy in the final products is the most costly, because their exergy content is already charged with both the exergy and the capital cost of the upstream processes.

3. The Engineering Rationale for the Intentional Violations of the Rules

It was mentioned in the Introduction that the Sama-Szargut rules are often intentionally and improperly violated in engineering applications, where "improperly" means "without any plausible thermodynamic justification". As argued in [8], this apparent paradox is immediately resolved if one considers that design decisions are made by bringing another variable into consideration, namely the monetary production cost, that is influenced not only by thermodynamic factors (like efficiency or specific fuel consumption, source-end use matching *etc.*) but also-and predominantly-by the monetary cost of equipment purchase and installation, maintenance, labor, financial costs, *etc.*: all factors that reside outside of the realm of Thermodynamics. The cause for the neglection of the Sama-Szargut rules is thus to be found in the lack of congruency between the monetary cost and the resource cost: the latter can be measured in thermodynamic units, while the former cannot. A brief—albeit somewhat obvious—remark is in order at this point: the "best possible" design is such only at the time the design is completed, and only to the extent that all of the assumptions made throughout the design phase are reasonable then and remain so in operation. Technological developments, newly devised processes, changes in equipment and system configurations, prevailing legislation, taxation, a change in the boundary conditions, *etc.* are all factors that exert a strong influence on the real convenience of any production process.

A partial list of the most blatant violations of the Sama-Szargut rules detected in current energy-conversion plants and processes, that includes electrical heaters, combustion engines, desalination, gas turbine blades cooling by compressor's air, separate heating and cooling systems in the residential and commercial sector, steam throttling in steam powerplants and in refrigerating machines, is reported and briefly discussed in [8]. In all cases examined, the reason for the neglection of one or more of the Sama-Szargut rules is that the "minimum monetary production cost" had been selected as the major design constraint (better yet, as the design objective). In the following of this paper, we shall show that an alternative costing paradigm, called Extended Exergy Accounting, EEA [15] and based on the equivalent primary exergy of the material and immaterial fluxes that participate to the production process (including the externalities) resolves the paradox, reconciliating the production cost goal with the thermodynamic constraints set by the Sama-Szargut rules. A brief recapitulation of the basics of this costing paradigm are presented in Section 4, and two quantitative applications are discussed in Section 5.

4. Extended Exergy Accounting, EEA

What is the driving potential that sustains the operation of a biological entity? In a global system perspective, the rather obvious answer is "exergy" not "energy", because an energy balance cannot properly describe the dissipative dynamics of living beings; not entropy, because without an energy "level" and "intensity" to be associated with, an entropy analysis is only qualitative [16], because all living systems are known to absorb it from the surroundings and to destroy a large portion of this input to perform their biological tasks. Lotka [17,18] was the first to explicitly posit that living beings can operate inasmuch, and as long as, they can avail themselves of a sufficient flux of what he called "available energy". Odum [19] applied Lotka's intuition to human societies, and proposed to measure immaterial products like Labour and Capital using a physical numeraire, a path-dependent space, and time integral of solar energy that he named emergy: his choice of "energy scales", and "energy concentration" as the relevant parameters in the energy hierarchy turned out though to be unfortunate because it precludes the possibility of performing a rigorous comparison between different dissipative process chains. In [8], in an attempt to combine Lotka's and Odum's ideas, the extended exergy (EE), defined as the amount of equivalent primary exergy needed to generate a product, was proposed. EE is a quantity expressed in J (its flux in W and its specific counterpart ee in J/unit, J/J *etc.*) that measures the primary resource consumption by means of a proper thermodynamic procedure, and succeeds in quantifying the so-called externalities (Labour, Capital and Environmental remediation cost) in a systematic and reproducible way. A system analysis based on EE results in an costing method called Extended Exergy Accounting (EEA) The word "accounting" is used as a reminder that exergy in not conserved in real processes, and therefore—in rigorous terms—no "exergy balance equation" exists. whose details are described in [8,20–22]. What is of interest for the purpose of the present discussion is that the EE of a product includes (in a space and time integral sense):

a) The total exergy influx during operation;
b) The primary equivalent exergy that is required to produce, maintain and decommission the equipment;
c) The primary equivalent exergy required to sustain the labour force;
d) The primary equivalent exergy required to generate the necessary monetary capital;
e) The primary equivalent exergy needed for the environmental remediation actions.

EEA has been successfully applied to calculate the equivalent primary exergy consumption (called "exergy footprint" in [8]) of individual components, processes, societal sectors and entire complex systems.

4.1. The Basic Postulates

The EEA method is based on two fundamental postulates:

1st postulate: In any Society, the global influx of exergy resources E_{in} is primarily "used" to sustain the workers who generate Labour. In exergy terms:

$$\dot{E}_L = \alpha \dot{E}_{in} \qquad (1)$$

2nd postulate: The exergy flux needed to generate the monetary circulation M2 within a Society is proportional to the Labour exergy. In exergy terms:

$$\dot{E}_K = \beta \dot{E}_L \tag{2}$$

where both α and β are numerical factors that depend on the type of societal organization, the historical period, the technological level and the geographic location of the Society: they are, in other terms, time- and space dependent model parameters (for a pre-monetary society, α is high and β; for a modern strongly industrialized society, α is rather low and β is high, with β growing with the tertiarization of the society). Their value is not assigned by the theory, and must be calculated from econometric data [15].

4.2. The Specific Equivalent Exergy (a Resource Cost)

The equivalent primary exergy resource that goes into one work-hour is obtained by dividing the net total exergy flux that goes into Labour by the cumulative number of work-hours generated in a given period of time. It represents the cost of one workhour in terms of primary exergy:

$$ee_L = \frac{\alpha \dot{E}_{in,net}}{N_{wh}} \quad \text{[J/workhour]} \tag{3}$$

Similarly, to compute the equivalent primary exergy resource that goes into one monetary unit, we need to divide the total exergy flux that goes into Capital by the cumulative monetary circulation maintained for that period of time:

$$ee_K = \frac{\alpha \beta \dot{E}_{in,net}}{M_2} \quad \text{[J/€]} \tag{4}$$

Notice that:

a) Both α and β can be extracted with sufficient accuracy from econometric data: their calculation is clearly iterative, because it is necessary to calculate all the exergy fluxes that go into the generation of 1 work-hour and of 1 monetary unit;

b) Double accounting is excluded, because the model assumes that $\dot{E}_{in,net}$ is "used" solely to generate Labour;

c) Monetary circulation is a by-product of Labour. This allows to treat pre-monetary societies (by setting β = 0 in Equation (2)).

For the environmental externality, the EEA method adopts a remediation approach [15]: the equivalent primary exergy resource that goes into the elimination of the effects of some effluent X into the environment is equal to the EE of the (real or virtual) process needed to eliminate the "pollution" by manipulating X so that its thermal, chemical, mechanical… exergy is approximately equal to 0 at the discharge site.

The EE-cost of a product ***P*** is calculated using the same cost balance equations of the Thermo-Economic method [23–25]. Its specific counterpart, ee_p, represents the total amount of primary equivalent exergy needed to generate one unit (J) of product exergy.
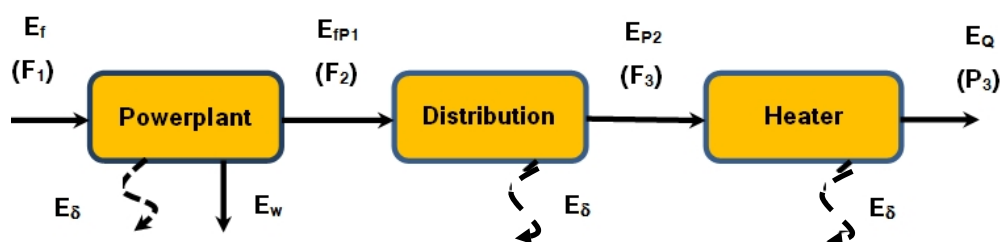
5. EEA and the Sama-Szargut Rules

Let us examine two cases of engineering applications in which the Sama-Szargut rules are violated, reassess the process in an EEA perspective and compare the monetary and the extended exergy costs. Because in some cases the available data were not sufficiently disaggregated, the calculations presented here are based on several lumped assumptions on the process configuration (for what both its design- and structural parameters were concerned) and therefore the results are obviously not very accurate: but the degree of approximation is good enough to draw some convincing—albeit preliminary—conclusions.

5.1. Electric Heaters

The procedure that leads to the calculation of the exergy efficiency of an electric heater is quite simple [26]: the production chain for the final exergy flux (the product) is shown in Figure 1: the efficiency of the powerplant is multiplied by that of the distribution net and by that of the final user.

Figure 1. The chain of generation of a fossil fuelled electrical heating Q.

The values assumed here for the exergy efficiencies are reported in Table 1. It is useful to reason though in terms of cost instead of efficiency, the "exergy cost" being the amount of used exergy (the fuel) divided by the exergy dispatched to the final user (the product). In the assumption of a linear conversion chain in which each component j has only 1 fuel and 1 product, $c_j = F_j/P_j$, $F_{j+1} = P_j$ and thence $c_{j+1} = P_j/P_{j+1}$. We obtain:

$$c_Q = \frac{F1}{P3} = \frac{F1}{P1}\frac{F2}{P2}\frac{F3}{P3} = \frac{F1}{P1}\frac{P1}{P2}\frac{P2}{P3} = 2 \times 1.075 \times 6.86 = 14.75 e_{F1} \tag{5}$$

Using for $e_{\text{fuel oil}}$ the value $1.1 \times e_{\text{chem,oil}}$ [27] we find that each Joule of delivered product has a cost of $16.22 \times e_{\text{chem,oil}}$ J of primary exergy. Monetary and environmental costs are not included: this is the procedure introduced by Szargut [28] and known under the name of "cumulative exergy content" (CEC).
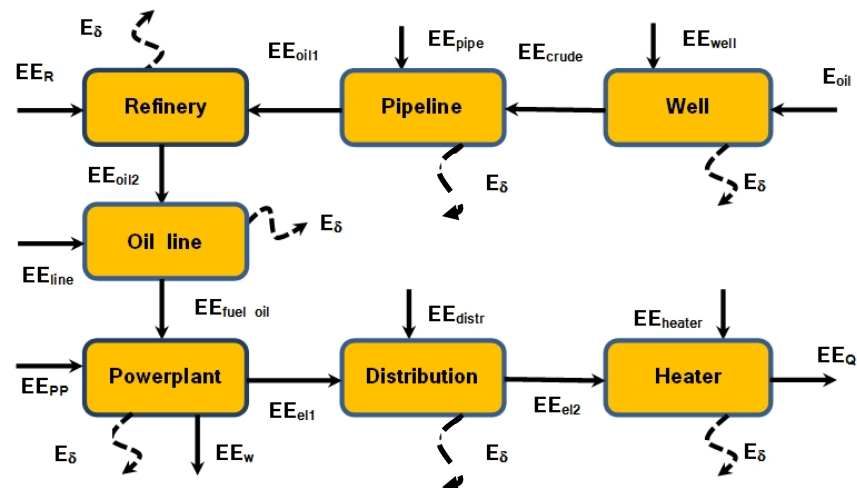
Table 1. Conversion chain for an electric heater.

Power Plant		Electrical Transformation & Distribution System		Electric Heater	
$\eta_{ex} = 0.5$	$c_{ex} = 2$	$\eta_{ex} = 0.93$	$c_{ex} = 1.075$	$\eta_{ex}=1 - \frac{T_0}{T} = 1 - \frac{293}{343} = 0.145$	$c_{ex,Q} = 6.86$

In an EEA perspective, the system's boundary is enlarged to encompass all of the upstream processes that lead to the production of the fuel oil. In addition, the externalities are explicitly

included: Figure 2 reports the corresponding flow diagram. The cost calculation now is based on the exergy of the oil in the well, e_{cr} (assumed to be equal to e_{chem}) and becomes more involved because at each step it is necessary to include in the cost calculations the labour-, capital- and environmental remediation equivalent exergies "invested" in the process.

Figure 2. The EEA chain of a fossil fuelled electrical heating load Q.

For the present discussion, the ee-costs have been extracted from the results of several published results [29–34] and are shown in Table 2. We obtain:

$$ee_Q = c_{oil,1} \times c_{oil,2} \times c_{oil,3} \times c_{fuel\ oil} \times c_{el,1} \times c_{el,2} \times c_{ex,Q} = 27.04 \tag{6}$$

The higher value of the EEA cost w.r.t. the CEC cost indicates that if the externalities are neglected, the real consumption of primary exergy "embodied" in the product "electrical heating" is underestimated by 45%. The reason is apparent: the EEA budget includes at each step not only the exergy destruction (like the CEC), but also the primary exergy equivalent of labour, capital and environmental remediation "services".

Another interesting result is that the CEC of the fuel oil usually assumed in most exergy analyses to be given by the Szargut-Styrylska formula, amounts to approximately 46,955 kJ/kg, while the real primary exergy resource embodiment in 1 kg of fuel oil is, according to EEA, almost twice as high at 82,877 kJ. As a result, any commodity generated by a production line that uses an amount of X kJ/unit of fuel oil ought to be "charged" with an exergetic surtax of 82,877/46,955 = 1.76 for the corresponding portion of energy use.

Table 2. EEA conversion chain for an electric heater.

Extraction from well			Crude oil pipeline		
$ee_K + ee_L + ee_{Env} \approx 0.06\ e_{cr}$	$e_{extr} \approx 0.1\ e_{cr}$	$ee_{crude} = 1.16$	$ee_K + ee_L + ee_{Env} \approx 0.2\ e_{cr}$	$e_{pump} \approx 0.1\ e_{cr}$	$ee_{oil,1} = 1.3$
Crude oil refining			**Fuel oil distribution system**		
$ee_K + ee_L + ee_{Env} \approx 0.01\ e_{cr}$	$e_{en} \approx 0.02\ e_{cr}$	$ee_{oil,2} = 1.03$	$ee_K + ee_L + ee_{Env} \approx 0.15\ e_{cr}$	$e_{pump} \approx 0.1\ e_{cr}$	$ee_{f.oil} = 1.25$
Power plant			**Electrical transformation & distribution system**		
$ee_K + ee_L + ee_{Env} \approx 0.101\ e_{cr}$	$\eta_{ex} = 0.5$	$ee_{el,1} = 1.351$	$ee_K + ee_L + ee_{Env} \approx 0.05\ e_{cr}$	$\eta_{ex} = 0.93$	$ee_{el,2} = 1.502$
Electric heater					
$ee_K + ee_L + ee_{Env} \approx 0$	$\eta_{ex} = 0.145$	$ee_{ex,Q} = 6.86$			

One of the reviewers observed that other methods, and specifically the monetary-based costing methods like TE and standard economic cost, also account for extraction, refining, *etc.* costs. This is absolutely correct, but the emphasis here is on the fact that EEA is the only method to date that offers a reproducible (and falsifiable) procedure for calculating the Capital, Labour and Environmental externalities homogeneously, in terms of primary resource use (in J/J).

The above calculation can be repeated for other heating systems, if a consistent and sufficiently disaggregated database of labour, operating and capital costs for each subunit were available: with very few exceptions, such data do not exist. But approximate comparisons can also be instructive: consider an alternative configuration in which the heating unit consists of a solar hybrid PV panel coupled with floor panels (Figure 3).

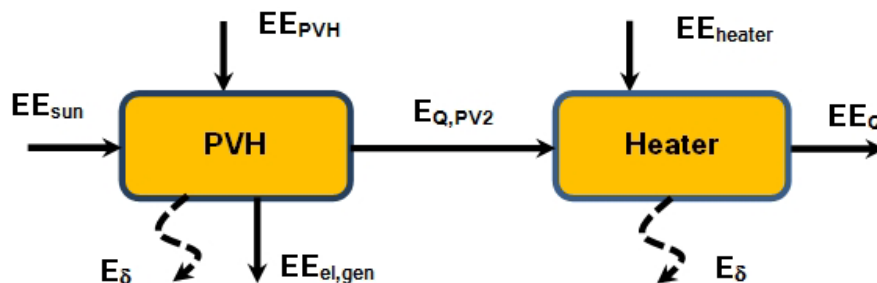**Figure 3.** The chain of the generation of a heating load Q by hybrid PV and floor panels.

Table 3. Conversion chain for floor panels heating fed by a PV-hybrid panel.

PV-panel		Floor heating panel	
$\eta_{ex} = 0.5$	$ee_K + ee_L + ee_{Env} \approx 0.245\ e_{sun}$	$\eta_{ex} = 0.37$	$ee_K + ee_L + ee_{Env} \approx 0.005\ e_{sun}$

Assuming a PV-panel efficiency of 12%, and with the values for the exergy efficiencies and equivalent environmental remediation costs reported in Table 3, the cost factors become the data upon which the cost estimates for the solar PV hybrid panel are based have been extracted from [31]:

$$ee_{el} = \frac{ee_{Pel}}{e_{sun}} = 6.01;\ ee_Q = \frac{ee_Q}{e_{sun}} = 17.31 \tag{7}$$

The above result indicates that a simple comparative EROI of different heating devices does not tell the whole story: what matters is the total equivalent primary exergy embodied in a product (in the case in point, the heat flux Q). If a reduction of the degree of unsustainability is sought after, the system boundary must necessarily be the biosphere and the time window must be the entire life-cycle of the "product", in a well-to-grave approach. In such a perspective, the Sama-Szargut rules recover their role as mandatory design guidelines: for space heating, the PV/FP system configuration abides by rules 1, 9, 17 and 21, while the electrical heater explicitly contradicts the same rules. An EEA analysis quantifies the concept of "more rational resource use", making comparisons possible on a rational basis.

5.2. Desalination by Reverse Osmosis

Consider two seawater desalination plants of the same capacity $m_D = 0.5$ kg/s, one based on the cogenerated MSF and the other on the RO technology. The size of the plants is neither too small for the MSF nor too large for the RO, so that the comparison is of realistic engineering significance. The simplified flow diagrams of both processes are shown in Figures 4 and 5: the most significant inputs are the seawater, the electricity and the externalities for the RO and the seawater, the fuel, some minor amount of electricity and the externalities for the MSF; the product is the desalinated water, assumed for simplicity to be of the same quality. In an EEA perspective, the cost of fuel delivered to the MSF plant is 1.94 e_{crude} (see Section 5.1), while that of electricity is 3.94 e_{crude}. Adapting the performance & cost data from [35–38], see Table 4, including as above the CO_2 tax (calculated here on the basis of the CO_2 emission trading costs 2013 [39]) in the ee of the generated or consumed electricity, and adopting for the specific exergy of the distillate the value $e_{dist} = 4000$ kJ/m^3, the final costs are:

$$ee_{MSF,cogen} = 14.71; ee_{RO} = 19.77 \tag{8}$$

Figure 4. EEA flow diagram for a cogenerated MSF desalination process.
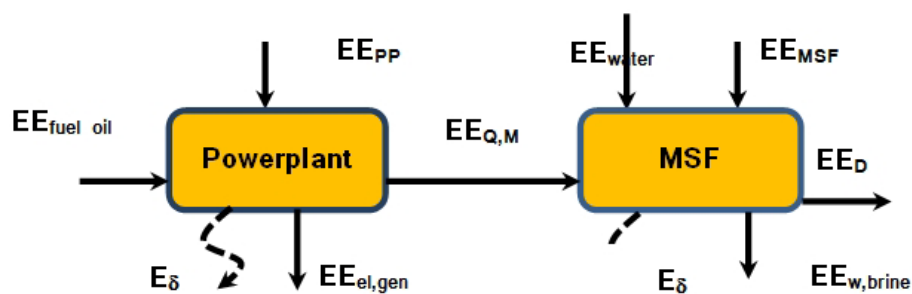

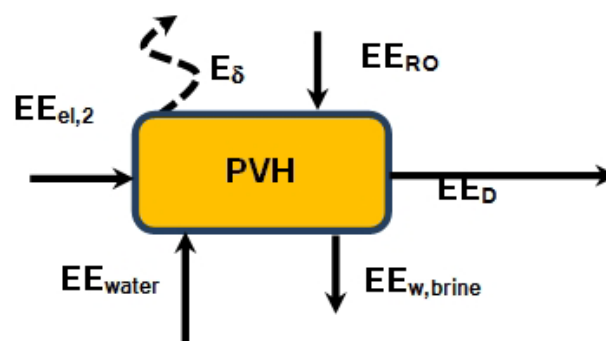**Figure 5.** EEA flow diagram for a RO desalination process.

Table 4. Comparative EEA conversion chain for MSF and RO desalination.

Cogenerated MSF			Reverse Osmosis		
Powerplant			**RO + energy recovery**		
$EE_K + EE_L + EE_{Env} \approx$ 0.563 MJ/s	$ee_{el} \approx 4.89$*	$ee_Q = 4.89$	$EE_K + EE_L + EE_{Env} \approx$ 2.05 MJ/s	$ee_{el,in} = 3.94$	$ee_D = 19.77$
Multi-stage flashing unit					
$EE_K + EE_L + EE_{ENV} \approx 0.384$ MJ/s	$ee_D = 14.71$				

* This value is higher than the one calculated in Table 2, because of the scale effects on the plant installation cost.

This indicates that exergy footprint of the cogenerated MSF, *i.e.*, its cumulative primary resource use, is lower than that of RO ($ee_{MSF,cogen}/ee_{RO} = 0.744$). Such a result is in contrast not only with the usual wisdom supported by energy and monetary analysis, but also with the conclusions of a standard exergy/thermo-economic analysis. The difference, once again, consists in the exergy-based internalization of the externalities. What is of interest for the thesis of the present paper is that the EEA analysis completely recovers the suggestions of the Sama-Szargut rules which, as discussed in Section 2.1, discourage the use of non-cogenerated MSF and are critical *vs.* the source/final use mismatch of an electrically-powered desalination process. Consider that a PV-powered RO facility or a solar-thermal MSF plant would be the solutions suggested by the rules. No sufficiently disaggregated data are though available to provide an EEA analysis here.

6. Conclusions

Engineering design is guided by the axiom of generating the specified output with the minimal expenditure. The EEA paradigm calculates this "expenditure" in terms of primary equivalent exergy resources, and thus privileges solutions that minimize the exergy footprint of the product. Since EEA is based on a systematic use of exergy budgets, its correct application automatically enforces the Sama-Szargut rules, provided they are consistently interpreted in a purely exergetic sense. Since on the other hand the current monetary cost calculation procedures are totally uncorrelated with thermodynamic principles, not only the numerical value, but the structure itself of the monetary cost is not necessarily congruent with the actual resource consumption. Therefore, we can conclude that:

a) Any product has two "price tags": one is the customary production cost $c_{\text{€}}$ expressed in €/unit, and the other one is the extended exergy cost *ee* expressed in J/unit. By means of the equivalent capital exergy ee_K it is possible to convert *ee* into $c_{\text{€}}$ and vice versa: but the values will in general not be the same (because a possible distortion of the monetary cost in any of the streams that participate to the process has an impact on the value of E_{in} and therefore on ee_K);

b) Moreover, a change in the production structure is reflected in disproportional variations in $c_{\text{€}}$ and *ee*, because their functional structure is intrinsically different, since the path of the buildup of the monetary cost is in general different from the physical structure of the production process;

c) An EEA analysis leads to the automatic enforcement of the Sama-Szargut rules. This is not a coincidence, of course, because the "value scale" of EEA is exactly the same of that of the rules, since the former converts all production cost factors—including externalities—into equivalent primary exergy flows, to which of course the Sama-Szargut rules coherently apply.

Nomenclature

c	cost
C, W/K	Heat capacity
c_p, J/(kgK)	Specific heat
E,e, J; J/unit	Exergy, specific exergy
EE,ee, J,J/unit	Extended exergy
F	"Fuel", used input

G, J	Gibbs energy
H, J	Enthalpy
K, €	Capital
L, workhours	Labour
m, kg/s	Mass flow rate
MSF	Multistage Flash desalination
M2, €/yr	Monetary circulation
N	Number of workhours
P	"Product", useful output
P, W	power
RO	Reverse Osmosis desalination
T, K	Temperature
TIT, K	Turbine Inlet T
V, m^3	Volume

Greek Symbols

α,β	EEA econometric coefficients
Δ	Gradient
π,σ	Beyer-Kotas coefficients

APPENDIX—Exergy and Extended Exergy Calculations

A.1. Fossil-Fuelled Electrical Heater (Figure 1)

Energy balance: $m_f LHV - E_{w,PP} - E_{w,distr} - E_{w,H} = Q + P_{el,1}$

Exergy budget: $m_f ex_f - Ex_{w,PP} - Ex_{\delta,PP} - Ex_{\delta,distr} - E_{\delta,H} = Ex_{el,1} Ex_Q$

Extended Exergy balance: $EE_f + EE_{PP} + EE_{distr} + EE_H = EE_{el,1} EE_Q$

$P_{el,1}/(m_f LHV) = 0.5$	$\eta_{distr} = 0.93$	TQ = 343 K	$\eta_{heater} = 1$
$f_{szargut,fuel} = 1.1$	$e_f = f_{sz}LHV$	LHV = 41,000 kJ/kg	

A.2. EE of Fuel Oil and Final Electricity (Figure 2)

Cumulative Exergy budget:

$$Ex_{oil} + Ex_{in,well} - Ex_{\delta,well} + Ex_{in,pipe} - Ex_{\delta,pipe} + Ex_{in,R} - Ex_{\delta,R} + Ex_{in,oil\,line} - Ex_{\delta,oil\,line}$$
$$= CExC_{fuel\,oil} Ex_{fuel\,oil}$$

Extended Exergy balance: $EE_f + EE_{PP} + EE_{distr} + EE_H = EE_{el,1} EE_Q$

$ex_{in,extr} = 0.11\ ex_{oil}$	$ex_{in,pipe} = 0.1\ ex_{oil}$	$ex_{in,ref} = 0.02\ ex_{crude}$	$ex_{oil} = ex_{chem} = 42,300$ J/kg

A.3. Hybrid Photovoltaic and Floor Heating Panel (Figure 3)

Exergy budget: $Ex_{sun} - Ex_{\delta,PVH} - E_{\delta,FP} = Ex_{el,PVH} + Ex_Q$

Extended Exergy balance: $EE_{sun} + EE_{PVH} + EE_{FP} = EE_{el} + EE_Q$

$\eta_{PVH} = P_{el,PVH}/E_{sun} = 0.12$	$\varepsilon_{QPVH} = 0.7$	$\eta_{FP} = 0.98$	$T_{QPVH} = 353$ K	$T_Q = 313$ K
$Q_{PVH} = \varepsilon_{QPVH} \times E_{sun} \times (1 - \eta_{PVH})$	$Ex_{QPVH} = (1 - T_0/T_{QPVH}) \times Q_{PVH}$	$Ex_Q = (1 - T_0/T_Q) \times Q$	$T_0 = 293$ K	

A.4. Fossil-Fuelled Cogenerating MSF Desalination (Figure 4)

Exergy budget: $m_f ex_f - Ex_{w,PP} - Ex_{\delta,PP} - Ex_{\delta,MSF} + E_{water,in} = Ex_{el,1} + Ex_D$

Extended Exergy balance: $EE_{fuel\ oil} + EE_{PP} + EE_{MSF} + EE_{water,in} = EE_{el,1} + EE_D$

$ee_{fuel\ oil} = 1.94\ e_{chem}$	$\eta_{PP} = 0.4$	$\varepsilon_Q = 0.7$	$ex_{water,in} = 0$	$ex_{discharge} = 0$	$T_Q = 423$ K	$T_{brine} = 393$ K
$ex_{distillate} = 4000$ kJ/m^3	$Q = \varepsilon_Q * E_{fuel} * (1 - \eta_{PP})$		$Ex_Q = (1 - T_0/T_Q) * Q$		$T_0 = 293$ K	

A.5. RO Desalination Process (Figure 5)

Exergy budget: $m_f ex_f - Ex_{w,PP} - Ex_{\delta,PP} - Ex_{\delta,distr} - E_{\delta,H} = Ex_{el,1} Ex_Q$

Extended Exergy balance: $EE_f + EE_{PP} + EE_{distr} + EE_H = EE_{el,1} EE_Q$

$ee_{el,2} = 3.94 e_{chem}$	$ex_{water,in} = 0$	$ex_{distillate} = 4000$ kJ/m^3	$ex_{discharge} = 0$

Conflicts of Interest

The author declares no conflict of interest.

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