The Exergy Footprint and the resource cost of Externalities

Enrico Sciubba
Niccolò Cusano University, Roma
enrico.sciubba@unicusano.it

This paper provides a review of the concept of the Exergy Footprint, a novel Environmental Indicator formulated in a Thermo-Economic perspective. Every effort is made to present it as the latest -even if probably not the final- development of the brilliant intuition by Rant (formulated in 1955, almost 70 years ago) to use Thermodynamic principles to obtain a more rational cost allocation in multi-products lines. The ExF maintains that the real cost of a material or immaterial commodity is measured by the primary resource cumulatively consumed in its production, operation and disposal, i.e. in a life-cycle sense. Its novelty: it explicitly includes the externalities.

Starting from simple but rigorous examples, it is shown that if sufficient econometric data are available, a primary resource cost can be calculated for the Labour and Capital Externalities. It is then argued that the calculation of the Environmental Cost can be formulated in terms of an "extended exergy balance" in which the streams entering and leaving the system are either physical (material, energy) and "equivalent" (Labour, Capital). Once this step is completed, all three externalities are expressed by their equivalent primary exergy consumption.

For any technological chain it is then possible to calculate the actual amount of primary resource exergy "embodied" (in an extended sense) into a commodity. This amount is clearly a cost proper, and is called "Extended Exergy Cost" or, to better signify its importance, "Exergy Footprint", ExF.

For any human agglomerate it becomes then possible to derive an effective measure of its environmental impact, given by the weighted sum of the ExF of all of its "products". The Exergy Footprint can thus be also viewed as an Environmental Indicator and can be applied to every scale of a society, from the single production line to an entire city or region or nation.

Keywords: Environmental indicators; Non-equilibrium systems; Second Law; Sustainability; Exergy Footprint

1 – A NECESSARY HISTORICAL PRELUDE

Exergy definition by Bosniakovic [1961] & Rant [1955]: *The exergy of a system is the maximum useful work that can be extracted from a system by a process that brings it into equilibrium with a heat reservoir*.
And a more rigorous definition may add: "… (heat reservoir) *of infinite capacity, while the system interacts only with this heat reservoir* ".
I like also Szargut' definition: "*Exergy is the amount of work obtainable when some matter is brought to a state of thermodynamic equilibrium with the common components of the natural surroundings by means of reversible processes*" [Szargut 1988]

But important: *Exergy of a system in a state **x** is also the minimum reversible work that must be done on it to bring it from its equilibrium with the heat reservoir to state **x***.

Gibbs Available Energy "*The greatest amount of mechanical work that ideally can be obtained merely by proceeding from the given condition of the body to one on the surface of dissipated energy that has the same S and V*." [gaggioli 2002]. If we accept this definition, Exergy is NOT equal to Available Energy (but, see also [Keenan 1941])

(The word ''availability'' was introduced by Tait in 1868 and ''available energy'' by Maxwell ~1871. For over three decades, 1970-2008, "Availability" and "Exergy" were used to define the same thermodynamic function)

First mention of *economic value of exergy*, [Rant 1955]: "*Exergy is the part of energy having value. Energy without exergy is valueless*"

Exergists were criticized in Europe & Germany in the '60-'70s [Tuma 2016] (but they did not give up: in Germany Elsner [1965-1972], Fratzscher [1965-1977, Beyer [1972-1980] and many others; in Russia, Kalinina [1973-1978], Brodianskyi [1965], Nikul'shin [1980]; in Poland, Szargut [1957-1973]…

1962-1971: Tribus, Sama, Evans proposed a monetary cost balance based on exergy content of streams (=> there is a cost in destroyed exergy!) [1962-1981]

Exergists were criticized in Europe & US, 1980-1990, but Gaggioli founded the Second Law Group (1984) whose members did an impressive amount of scientific works and engineering applications that last until today.

Tsatsaronis (& Knoche) 1984/85 and Valero 1986 laid the basis for a) the exergy flowchart of a process; b) the TE assessment and optimization of a process.

Frangopoulos & von Spakovski: Environomics, ~1997: an attempt to explicitly include externalities in a TE formulation. Szargut had already proposed the inclusion of environmental effects in 1973, but his work did not obtain the due recognition until much later.

In fact, Gaggioli (& Petit, Reistad, Wepfer) had already presented an initial structuring of Exergy Economics between 1970-80:

Valero (& Valero-Delgado, Stanek) improved, completed and formalized Szargut's idea of Exergo-ecological cost [1995-2014]

Jørgenssen proposed a niche application under the name of Eco-exergy, ~2005.

Many other contributions, most of which are included in the Reference list, were published between 1990 and 2021. TE-based Diagnostics paradigms were formulated [Lazzaretto, Serra, Valero, Verda, 1994-2004], the loss structure was more accurately identified [Lazzaretto, Tsatsaronis, Valero, Verda, 1996-2002], applications to more complex systems and the links to the emerging "sustainability" concept was proposed [Wall, Whiting, Dai et al., Nowak, Sciubba, Stanek, Valero, Morosukk, Petrakopoulos, 1977-2014]

The first explicit inclusion of the Labour, Capital and Environmental costs into a non-monetary framework, called Extended Exergy, was proposed by Sciubba [1998]

One possible description (NOT a definition!): Thermoeconomics, TE, is a versatile concept that provides a general, systematic and integrated approach for the analysis of design systems. Being an exergy-aided costing method, TE offers additional insight on the cost formation of primary and secondary streams in energy conversion plants, as well as on the interactions among thermodynamics and economics and among the various plant components, all of which are important for improvement of energy system design.

2 – MONETARY THERMO-ECONOMICS

Every process admits of a **cost balance** equation:

$$C_P = C_F + Z_K \qquad \text{(in €/yr, neglecting profit)} \qquad (1)$$

Z_K [€/s] is the capital repayment cost flow (it may include scheduled maintenance, insurance & Labour).

Consider as a simple example the heating of a room: the Product is Q_{room}, the Fuel Q_{source}

$$c_{source} * Q_{source} + Z_K = c_{room} * Q_{room} \qquad (2)$$

Since we are interested in the cost of space heating, we can run an **energy cost balance** ("how many kWh it takes to generate the desired product?"):

$$c_{source} * Q_{source} + Z_K = c_{room} * Q_{room} \qquad (3)$$

…*c* in €/kWh, Q may be expressed as Δh, in kWh

$$c_{room} = \frac{c_{source} Q_{source} + Z_K}{Q_{room}} \qquad \text{in €/kWh} \qquad (4)$$

Rant [1955] argued that the real "value" of a commodity is its exergy content. The cost equation can be rephrased in terms of exergy:

https://doi.org/10.52202/069564-0004

$$c_{source} * E_{Qsource} + Z_K = c_{room} * E_{Qroom} \quad (5)$$

…c in €/kWh, E in kWh

E_{Qroom} is rather low because the room is almost at its dead state (p_0, T_0), $E_{Qsource}$ is much higher because there is indeed some work-generating capacity in the hot source … so:

$$c_{room} = \frac{c_{source} E_{Qsource} + Z_K}{E_{Qroom}} \quad \text{in €/kWh} \quad (6)$$

The same formula, very different meanings! In fact, $E_Q = Q - T_0 \Delta s$ is always lower than the enthalpy of an amount equal to the Gouy-Stodola irreversibly "lost work". As a consequence, the c_{room} given by eqtn. (6) is higher than its energy equivalent given by eqtn. (4).

It is interesting to quote [Rant 1955]: "*A system, let us say a heated room, requires a given quantity of heat (Q_{room}) at temperature T_{room} (Sl. 2). This heat is represented in the s-T diagram by the area of rectangle 1-2-3-4. The heat is available at temperature T_{source} (e.g. the average temperature of flue gases in a furnace) and the environment temperature is T_0. The simplest method of heating involves direct removal of heat from the heat source and its transfer to the user. In this way, the amount of thermal energy Q_{source} removed from the source at temperature T_{source} equals the amount of heat supplied to the heated system:*

$$Q_{source} = Q_{room} \quad (7)$$

In Sl.2, Q_{source} is represented by the area 7-8-9-10, which is obviously equal to the area 1-2-3-4. There are no losses as far as energy is concerned.

What about the exergies? The exergy of heat Q_{room} is $E_{room} = Q_{room} (T_{room} - T_0)/T_{room}$, equal to area 1-2-5-6; the exergy of the thermal energy Q_{source} used for heating is $E_{source} = Q_{source}(T_{source} - T_0)/T_{source}$,; E_{source}=7-8-11-12; considering $Q_{room} = Q_{source}$ and $T_{room} < T_{source}$, we can also establish that $E_{room} < E_{source}$. The exergy has been reduced in this process. The cause for the loss of exergy is the irreversible transfer of heat from the source to the system at a limited and, usually, quite large temperature differences $T_{source} - T_{room}$. Wherever irreversibilities are present, things are not in order energetically, even if it seems otherwise. The method of heating can be improved significantly as follows (Sl. 3):

Only as much heat Q'_s is removed from the source at temperature T_{source}, so that its exergy E'_s equals the exergy E_{room} of thermal energy Q_{room} used for heating. We get:

$$Q'_S = Q_{source} \frac{T_{room} - T_0}{T_{room}} \frac{T_{source}}{T_{source} - T_0} \quad (8)$$

The exergy E'_s coming from the source of removed heat Q'_s is converted to work using a power cycle, and this work is then used to drive a reversed Carnot cycle 1-6-5-2. Valueless heat 6-5-3-4 is removed from the environment in this process (this heat has zero exergy). The heated system is provided with heat Q_{room} =1-2-3-4 having the necessary exergy E_{room} = 1-2-5-6. This method of heating removes less energy from the heat source than that required for heating; but the exergy removed from the heat source equals the spent exergy. This is the operating principle of a Heat Pump." And in the conclusions: … "*The existing method for energy pricing (accounting) in combined plants on the basis of used enthalpies is fundamentally wrong. It has to be replaced with pricing (accounting) on the basis of used exergies, which is the only proper way.*"

(text slightly adapted by this author)

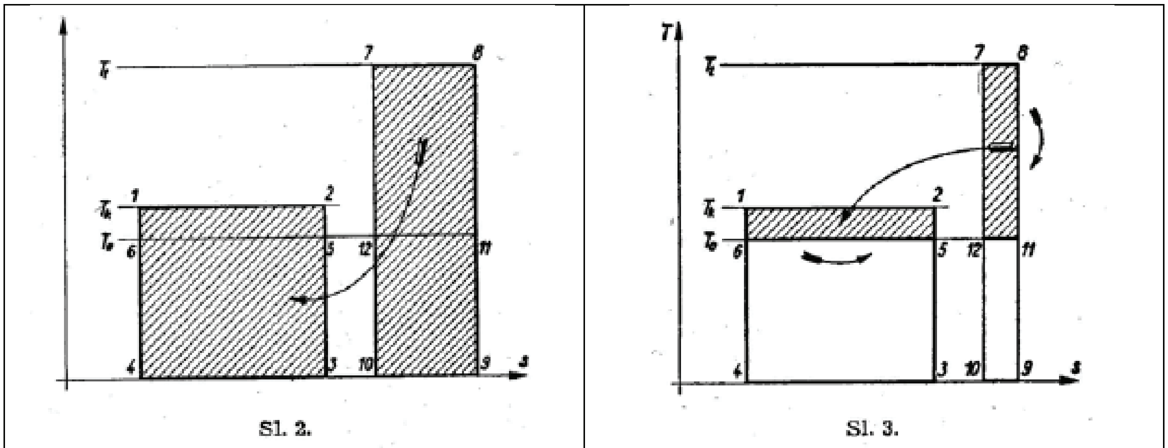


Figure 1 – Rant's [1955] original explanation of the "e" vs "h" evaluation of a heating device

Since realistic processes are much more complex, some "cost rules" must be introduced to maintain rigor and abide to common engineering sense. This was done by Gaggioli & coworkers, Lazzaretto, Tsatsaronis-Cziesla, Morozyuk, Reini [2021-2023],Valero.

In real processes, there are inevitably some material or immaterial discharges. The corresponding term C_D must be included in the cost balance, eqtn. (1), as well.

$$C_P = C_F + Z_K + Z_{ENV} + C_D \tag{9}$$

There are additional prescriptions on how to handle the C_D term, but they are not essential to our scope here.

Let us provide a simplified outline of the procedure proposed by Tsatsaronis & Valero: (the following treatment is simplified for conciseness & clarity and is not completely rigorous!).

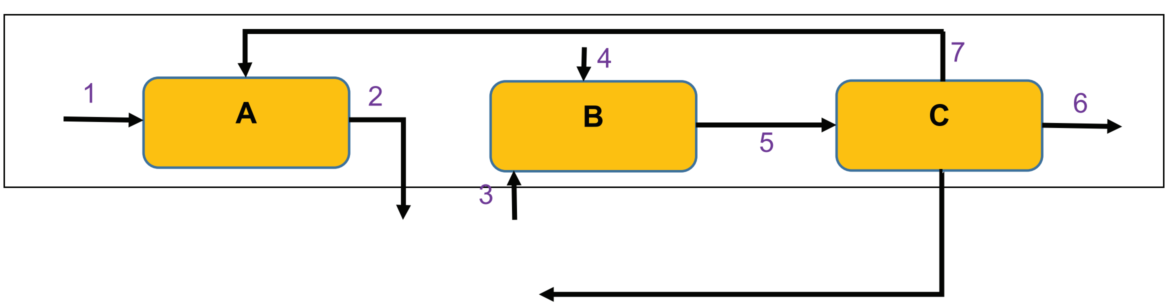
Let us write the cost equations for each individual component in figure 2:

$$\begin{aligned} c_1\dot{E}_1 - c_2\dot{E}_2 + c_7\dot{E}_7 + Z_A &= 0 \\ c_3\dot{E}_3 + c_4\dot{E}_4 - c_5\dot{E}_5 + Z_B &= 0 \\ c_5\dot{E}_5 - c_6\dot{E}_6 - c_7\dot{E}_7 - c_8\dot{E}_8 + Z_C &= 0 \\ c_2\dot{E}_2 - c_3\dot{E}_3 + c_8\dot{E}_8 - c_9\dot{E}_9 + Z_D &= 0 \end{aligned} \tag{10}$$

Where $C_j = c_j\dot{E}_j = c_j\dot{m}_j e_j$ for material streams and $C_j = c_j P_j$ for immaterial ones (*P* being the power). Assuming the Z_j are known, system (10) has 4 eqtns. (the cost balances, 1 for each component) and 9 unknowns (the c_i). A possible set of 5 auxiliary equations needed to make its coefficient matrix square is:

$$\begin{aligned} c_1 &= \xi \\ c_4 &= \psi \\ c_6 - c_7 &= 0 \\ c_6 - c_8 &= 0 \\ c_9 &= \varphi \end{aligned} \tag{11}$$

If the system (10+11) has a $Det(M_{coeff}) \neq 0$, the system admits of a solution.
The auxiliary equations are derived on the basis of a proper set of general rules on the *function* of a stream in the component's operation.



https://doi.org/10.52202/069564-0004

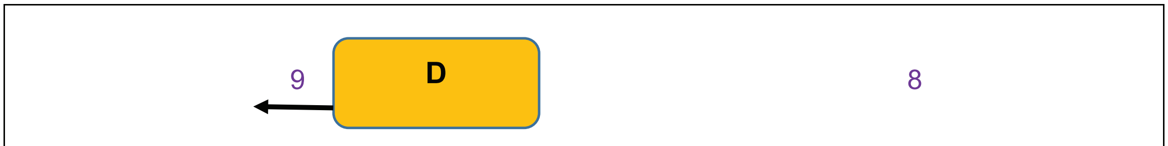


Figure 2 – Generic process scheme

3 – THE PROBLEM OF THE EXTERNALITIES

In Economics, *an* ***externality*** is *"a fact or an event that impacts a system or a procedure and that is not directly involved in the 'state of the universe' that causes that event"*.

In Engineering Economics it is customary to separate ***internal*** production costs, directly related to the machinery used, the physical parameters of the process and of the participating streams, from ***external*** costs, grouping under this denomination all cost items not depending directly from the installed process. Examples of external costs are land preparation, transportation, electrical connection to the grid, wages and salaries, start-up costs, financial flows, disposal of discharges, etc.

Engineers have borrowed the term "externality" from Economics, making it more precise and itemized. In a cost/benefit evaluation, there are thus three types of "externalities":

a) *Labour*, i.e., the cost of wages and salaries, usually expressed in €/yr or €/unit;
b) *Capital*, i.e. the financial costs necessary to operate the process: repayment of loans, amortization, differed cash flows, etc.
c) *Environmental costs*, neglected until the '70s and still lacking a universally accepted definition: in general, these are the monetary costs caused by actual or potential environmental harm caused by the process operation (most commonly, "emissions" and "discharges").

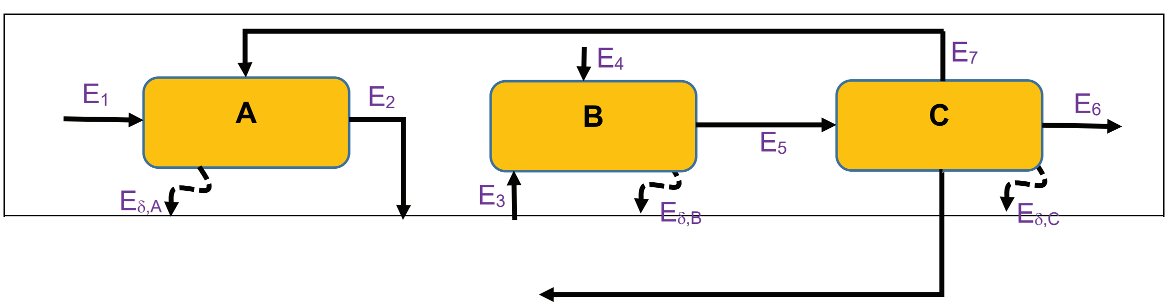
TE needs special additional procedures to handle these costs:

a) Capital costs are calculated as repayment rates on the TIC (Total Installed Costs) and accounted for in Z_K;
b) Scheduled maintenance, insurance, taxes, start-up, etc. costs can be added to Z_K and possibly adjusted to annual rates;
c) Labour costs can be included -with some caution- in Z_K as well;
d) Environmental costs can be accounted for in three different ways:
   - Z_{ENV} is set equal to the foreseen "pollution fees" set by national or international regulations;
   - Z_{ENV} is set equal to the calculated "remediation" costs directly and indirectly related to the process effluents;
   - Z_{ENV} is set equal to the avoidance costs, i.e. to the remedial actions to be taken within the process boundaries.

Depending on the mode of calculation, Z_{ENV} may vary of orders of magnitude; it is generally accepted that there are non-trivial problems in its calculation [Innes 2013]

4 – EXERGY COST, EXERGO-ECOLOGICAL COST, EXERGY FOOTPRINT

The following example is a simplified rendering mainly based on the works of Valero & coworkers [reff]. Notice though that already Rant [1955], Szargut [1965] and Gaggioli [1980] proposed the same -or a very similar- approach.



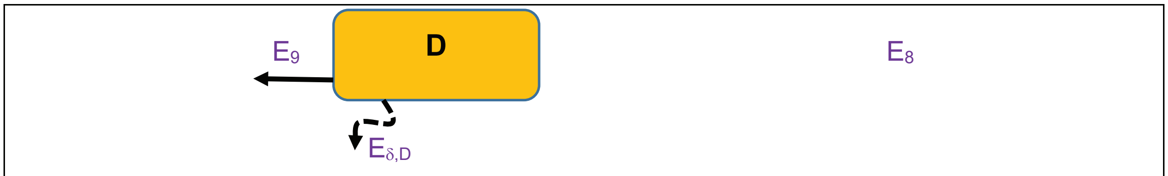


Figure 3 – Exergy flow diagram for the process of figure 3

Table 1 – Flow type identification ("production structure")

	A	B	C	D
Fuel	$E_1 + E_7$	$E_3 + E_4$	E_5	$E_8 - E_9$
Product	E_2	$E_5 - E_3$	$E_6 + E_7 + E_8$	$E_3 - E_2$

For the system of figure 3, a purely thermodynamic representation may be chosen: from the exergy flowchart an exergy <u>budget</u> can be derived ($\dot{E}_{in} = \dot{E}_{out} + \dot{E}_\delta$). In canonical form (see fig. 4), all terms in [W]:

$$
\begin{aligned}
\dot{E}_1 - \dot{E}_2 + \dot{E}_7 - \dot{E}_{\delta,A} &= 0 \\
\dot{E}_3 + \dot{E}_4 - \dot{E}_5 - \dot{E}_{\delta,B} &= 0 \\
\dot{E}_5 - \dot{E}_6 - \dot{E}_7 - \dot{E}_8 + \dot{E}_{\delta,C} &= 0 \\
\dot{E}_2 - \dot{E}_3 + \dot{E}_8 - \dot{E}_9 + \dot{E}_{\delta,D} &= 0
\end{aligned} \qquad (12)
$$

(mass- and energy balances are assumed to have been successfully closed)

Now, what is the primary exergy required for the formation of the streams $\dot{E}_1, \dot{E}_2 \ldots$ etc.? Solution:

Call k_j the *exergy cost, defined as the amount of primary exergy required to generate the unit exergy* e_j: it is clear that while the k of streams 1 and 4 must be assigned somehow because they are entering the process boundary from the "outside" (the environment in this case), <u>the k_j of all other streams depend on the cost balance of each component and on the process structure</u>.

Identify the so-called "productive structure" of each component (Table 1), and consider that an exergy cost conservation rule applies:

$$\sum_j F_j = \sum_i P_i \qquad (13)$$

Applying (132) to the single component/process **B** of figure 3:

i- Case 1, design goal is to increase E_3 to E_5: $F_1 = k_4E_4$; $P_1 = k_5E_5 - k_3E_3$
ii- Case 2, design goal is to mix E_3 & E_4 to produce E_5: $F_1 = k_3E_3$; $F_2 = k_4E_4$; $P_1 = k_5E_5$

Cost balance: $$k_3\dot{E}_3 + k_4\dot{E}_4 - k_5\dot{E}_5 = 0 \qquad (14)$$

1 eqtn., 3 unknowns, need 2 auxiliary eqtns.:
Case 1: $k_4 = CExC_4$; $k_3 = k_5$
Case 2: $k_4 = CExC_4$; $k_3 = f(k_5, k_8, k_9)$

The procedure only makes sense if extended to the entire process:

$$
\begin{aligned}
k_1\dot{E}_1 - k_2\dot{E}_2 + k_7\dot{E}_7 &= 0 \\
k_3\dot{E}_3 + k_4\dot{E}_4 - k_5\dot{E}_5 &= 0 \\
k_5\dot{E}_5 - k_6\dot{E}_6 - k_7\dot{E}_7 - -k_8\dot{E}_8 &= 0 \\
k_3\dot{E}_2 - k_3\dot{E}_3 + k_8\dot{E}_8 - k_9\dot{E}_9 &= 0
\end{aligned} \qquad (15)
$$

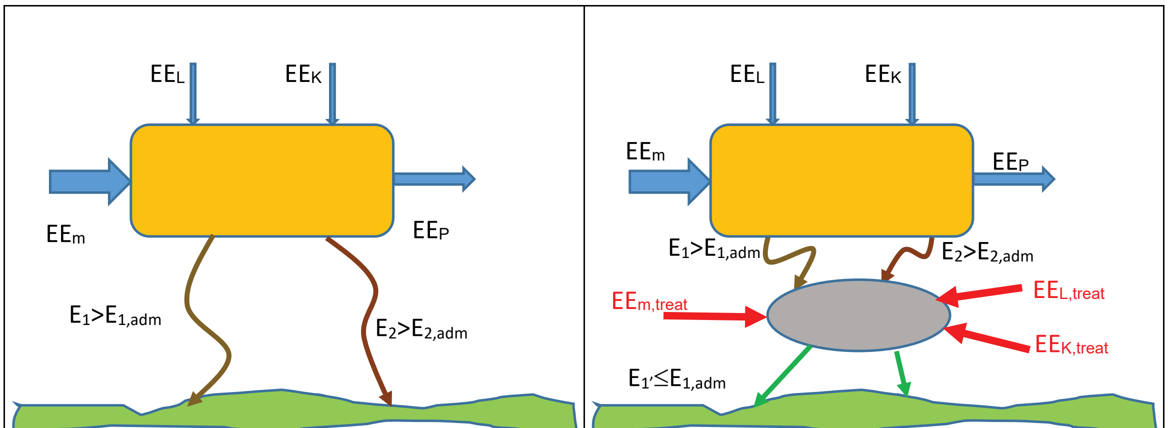
Number of equations: 4 (1 for each component); number of unknowns: 9 (1 for each stream) ⇒ Need 5 auxiliary eqtns: "exergy costing rules" that take into account the origin of the stream and its "function" in the economy of the production process.

https://doi.org/10.52202/069564-0004

Case 1: $k_1=0$; $k_4=CExC_4$; $k_3=k_5$; $k_2=k_3$; $k_8=k_9$
Case 2, $k_1=0$; $k_4=CExC_4$; $k_3=k_4$; $k_2=k_3$; $k_8=k_9$

The exergy cost method does not solve the problem of the externalities. Internalization procedures have been proposed by Szargut [1973], Frangopoulos [1997], Valero & Stanek [1998-2010]. The basic idea is mutuated from Szargut' work: link the mass flow rate of the emissions to a specific "cost of the pollution" using local or national monetary databases. As of today, the environmental externality problem has not found a universally accepted solution [Innes 2013].

The Extended Exergy formulation is an attempt to solve this problem by calculating the Labour and Capital costs in terms of the primary exergy budget of a society (a city, a region, a Country). Once these parameters (ee_L, primary exergy equivalent of 1 workhour) and ee_K (primary exergy equivalent of 1 unit of monetary circulation) are known, the environmental cost can be assessed by using a remediation approach: how much primary exergy (EE'_{fuels}, EE'_L, EE'_K) would be necessary to reduce the effluents' exergy to the limits prescribed by the locally applicable regulations. This solves the Externality problem, but the calculations depend on the availability and accuracy of an additional, very disaggregated, data set. The resulting cost of a commodity is in kJ_p/unit, kJ_p/kg or kJ_p/kJ, "kJ_p" being the primary exergy needed to generate that commodity.



Original process P and its effluents	Process P + $P_{treatment}$

Figure 4 – Treatment of the Environmental externality in EEA

This EEA cost has been called "Exergy Footprint", ExF, because it represents the burden on the Environment caused by the production. Here "burden" is literally meant to signify "the amount of primary resources subtracted from the overall Earth's budget".

5 – WHAT NEXT?

Exergy analysis generally accepted today as best analysis tool;

TE still not practiced by industry and Energy Agencies;

TE diagnostics still considered a niche topic;

Exergy cost and ExF can be valid "sustainability" indicators: ECOS community ought to push for this recognition;

Need to work with media, institutions, schools to clarify correlation between exergy consumption & degree of unsustainability;

Need to aggressively address water-nexus and material replacement & substitution issues.

6 – REFERENCES

The reference list comprises almost 300 items. Not all of them are quoted in the paper, but they represent a useful compendium of the exergy literature over the years. I will make available on a digital support upon request.

https://doi.org/10.52202/069564-0004