EVALUATION OF EMBODIED ENERGY IN ENERGY PROCESSES THROUGH AN ECONOMIC EMPIRICAL APPROACH: *PANERGY*

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Extended Abstract

Overview

One of the major tasks Energy Planners have to face is how to give priorities to the different available energy technologies in order to maximize both economic effects and energy saving and minimize, at the same time, the environmental impact.

The most suitable assessment indexes are EROEI or *Energy Return on Energy Investment,* which gives a measure of the energy gain in a process and then refers directly to the primary source consumption, and SEI or *Specific Environmental Impact,* which measures the amount of a definite kind of pollutant emitted per energy supplied and, if referred to CO_2, is a measure of the impact on global warming. In evaluating both indexes one must account of the overall energy spent; not only that supplied in the process itself, but also that embodied in the generating device, and then employed for the construction, operation and dismantling of the plant, and that consumed for the completion of the fuel cycle (extraction, refining, transport and treatment).

Fig. 1 explains how the original content of an energy source degrades before reaching the end user and why the energy investment in a power generation technology must account of the fuel cycle, the plant life cycle and the generation process at the same time.

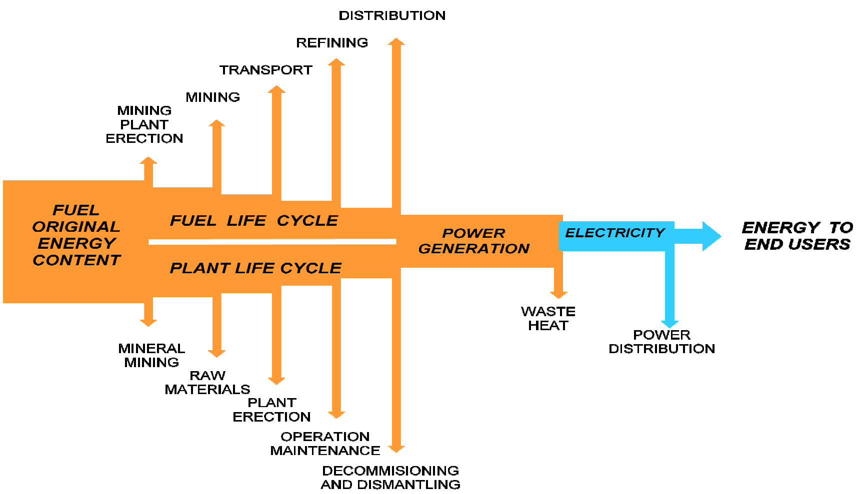

Fig. 1 – Energy degradation from mine to end users

The most direct and rigorous way to calculate the overall energy investment is to apply the Life Cycle

Analysis (LCA). It consists in splitting the overall sequence into elementary phases and evaluating the energy spent in any single step. That is a time expensive methodology and, for very complex processes, quite unreliable because errors and omissions are likely; moreover, often, most of the analysts consider only the direct energy involved in sigle steps neglecting any other indirect contribution.

Since the 80s D.M. Scienceman and H.T. Odum introduced the concept of *Emergy* (embodied energy) to signify the overall energy input (direct and indirect) to build up a service or a product. In assessing energy processes or technologies this concept allows giving a more comprehensive vision of the problems.

Nevertheless the measure of *emergy* is not a simple task since it has to pass through LCA with the addition of a further complication given by the need of evaluating the indirect energy contributions. It must be told that, due to the difficulty to calculate these contributions, the concept of *emergy* has become, in last years, more a field of theoretical disputes than a practical tool to understand the energy fluxes.

Method

The approach proposed in the present work is the evaluation of embodied energy through economic considerations.

The analysis of the cost of a product/service can be carried out splitting it into three main shares accounting respectively of labour, materials and energy (direct). Labour means not only the manpower directly engaged but also the immaterial contributions associable to the product, like services, taxes and financial duties (indirect labour).

Looking more in detail into labour and material costs, one can observe that they can be split again into a second level share of labour (direct and indirect), materials and energy. Going ahead, step by step, one finds that, in terms of cost, the fraction of energy is progressively increasing while labour and materials are vanishing.

This process is better understandable looking at the scheme reported in fig.2.

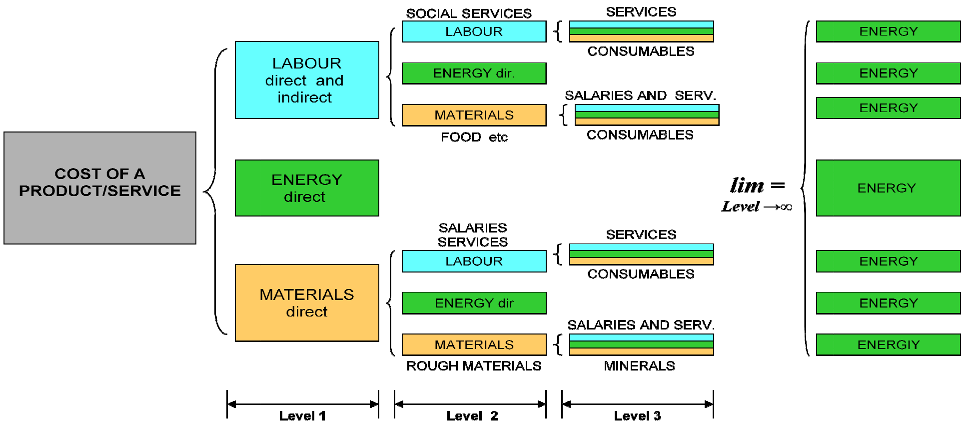

Fig.2 – The Product cost tree

Mathematically the cost tree can be described as

$$L = C_0 \sum_{j=0}^{n^2} \left(\prod_{i=0}^{n} \gamma_i\right)_j \qquad (1)$$

$$M = C_0 \sum_{j=0}^{n^2} \left(\prod_{i=0}^{n} \delta_i\right)_j \qquad (2)$$

$$E = C_0 \left[1 - \sum_{j=0}^{n^2} \left(\prod_{i=0}^{n} \gamma_i\right)_j - \sum_{j=0}^{n^2} \left(\prod_{i=0}^{n} \delta_i\right)_j\right] \qquad (3)$$

Where L, M and E are the incremental costs of Labour, Materials and Energy respectively, γ and δ are the fractions of cost devoted to labour and materials at each step and C_0 is the cost of the product/service.
Since γ_i and δ_i vanish when n → ∞, eq.s 1,2 and 3 tell that the totality of the cost must be attributed to energy. As a result, if *k* is the cost of energy in a given economic context:

$$P = C_0/k \qquad (4)$$

Where P is the overall energy embodied in the product. Since it is the only component of the cost we decided to call it *Panergy (everything is energy)* and eq.4 expresses its theorem.
One must note that panergy is the sum of different energy kinds depending on the combination of sources used in the reference social and economic context. The composition of energy kinds related to a definite context is embodied in the contextual cost of energy *k.* An attentive analysis of the concept will easily point out that *panergy* does not coincide with the Odum *emergy* because this one is referred only to sensible, or immediately measurable, energy while panergy embodies a more extensive ensemble of categories.
Eq.4 can help to determine the product's panergy (or the overall energy invested in it) once the right value of *k* is known. Unfortunately this value cannot be established easily.
A help is available if we are in a context where the market is stable, competition is fully developed, social environment is homogeneous and the product under examination is mature, then costs and prices, at each step, evolve at a constant ratio and eq. 4 can be translated in the following corollary:

$$P = \Sigma/h \qquad (5)$$

Where *Σ* is the market price of the considered product/service (known) and *h* is the energy price applied to the end user in the reference context (also known). So the energy investment can be immediately and empirically determined, and its accuracy depends on the degree of correspondance between the context features and the assumptions made.

Data and Preliminary results

Eq. 5 allows calculating rapidly EROEI and SEI of any energy system.
Using panergy as parameter, the expressions for EROEI and SEI (this last referred to the CO_2 emission) are:

$$EROEI = \frac{E_R}{P_F + P_C} \qquad (6)$$

$$SEI = \frac{1}{E_R}\left(\frac{\alpha P_F}{\eta} + \beta P_C\right) \qquad (7)$$

P_F and P_C are the panergies (or overall energy investments) of fuel cycle and plant life cycle respectively; E_R is the energy return, η is the conversion efficiency of the power generation process; α is the CO_2 generated per fuel heat value and β is the CO_2 emitted per unit of energy invested. This last item depends on the mix of energy sources employed to generate power in the reference context.
To calculate the parameter enclosed in eq.s 6 and 7 the following data are needed:

- Plant operation liftime *L (y)*
- Capital cost of plant *Σ (€/KW_{EL})*

- Operation duty factor F
- Production time $E_R = 8760\,F\,L$ *(hours)*
- Electricity price to households h_{EL} *(€/KWh$_{EL}$)*
- Fuel price referred to households h_{TH} *(€/KWh$_{TH}$)*
- System efficiency η
- α *(Kg$_{CO2}$/KWh$_{TH}$)*
- β *(Kg$_{CO2}$/KWh$_{TH}$)*

With these data the relevant relationships are:

$$P'_F = \frac{P_F}{E_R} = \frac{\eta h_{TH}}{h_{EL}} \qquad (8)$$

$$P'_C = \frac{P_C}{E_R} = \frac{\Sigma}{h_{EL} E_R} \qquad (9)$$

$$EROEI = \frac{1}{P'_C + P'_F} \qquad (10)$$

$$SEI = \frac{\alpha P'_F}{\eta} + \beta P'_C \qquad (11)$$

It is interesting to consider the panergy of the fuel itself P_F as it allows to describe the *primary effectiveness* or, in other words, for each fuel, how much of the original energy value ("at mine" or "geological ") remains at the power generator inlet and the *electric effectiveness* or which rate of the geological value is available, in form of electricity, at the user's plug.
TAB. A shows these results inside the context of Italy at December 2007 . In this context electricity price to households is 0.202 €/KWh$_{EL}$ and fuel price to households is as in table A. (Coal and Nuclear estimated starting from the original world market price)

TAB. A – Panergy (P_F), Primary Effectivness (ε_P) and Electric Effectivness (ε_{EL}) for different energy sources in Italy at Dec. 2007

Source (η)	h_{TH} (€/KWh$_{TH}$)	$P'_F = \eta h_{TH}/h_{EL}$ (KWh$_{EL}$/KWh$_{EL}$)	$\varepsilon_P = (1-P'_F)$ (KWh$_{EL}$/KWh$_{EL}$)	$\varepsilon_{EL} = \eta\varepsilon_P$ (KWh$_{EL}$/KWh$_{EL}$)
Waste (-)	<0	<0	>1.00	-
Sun (0.12)	0	0	1.00	0.12
Wind (0.75)	0	0	1.00	0.75
Hydro (0.85)	0	0	1.00	0.85
Geo (0.25)	0	0	1.00	0.25
U_{NAT} (0.30)	(0.04)	0.06	0.94	0.28
Biomass (0.35)	0,02	0.0347	0.96	0.34
Coal (0.42)	(0.029)	0.0517	0.95	0.40
Nat.gas (0.55)	0.064	0.1743	0.83	0.46
Oil (0.45)	0.075	0.1901	0.81	0.36

TAB. B shows the hierarchies of the different energy technologies in terms of saving of natural primary

resources and in terms of global warming mitigation displayed, respectively, through EROEI and SEI (CO_2). EROEI values derived with the proposed methodology result lower than the averages reported by most of the Life Cycle analysts. That is because, generally, they do consider neither the indirect energy fraction nor the fuel cycle induced depletion of the geological energy content.
As regard to SEI, it can appear astonishing that non combustion technologies (Solar PV, Nuclear, Wind and Hydro) show scores different from zero but that is due to their indirect CO_2 emission as a consequence of the non renewable energy invested in plant life cycle.
It is interesting to note that, in this context, solar photovoltaic (present generation technology) is extremely critical and is settled far away from all other competitors including the combustion ones, both in terms of primary energy consumption and global warming impact. Moreover results show that coal's global warming impact is very close to that of natural gas. All these results are opposite to the common feeling.

TAB. B – EROEI and SEI for different power generation technologies (Context: Italy Dec. 2007)

Technolgy	***EROEI (Panergy)***	***EROEI (LCA)*** (*)	***SEI*** *($Kg\ CO_2/KWh_{EL}$)*
Waste incineration	*24.9*	*-*	*0.056*
Hydro power (large)	*22.1*	*50-205*	*0.063*
Wind power (large)	*15.9*	*6-80*	*0.088*
Biomass (SH steam)	*22.1*	*3-27*	*0.077*
Coal (USC steam)	*13.6*	*7-29*	*0.072*
Natural gas combined cycle	*5.5*	*5-26*	*0.068*
Oil (SH steam)	*5.5*	*5-15*	*0.119*
Nuclear (PWR gen III)	*11.1*	*10-24*	*0.042*
Solar (PV gen I)	*1.1*	*3-12*	*1,266*

(*) Several authors

In the paper, evaluations related to other contexts (France *all nuclear* and Poland *all coal*) are reported. They do not show substantial differences from the results for Italy. Projections to the year 2040 under different developed scenarios are also reported, in particular to evaluate the future role of the new generation Photovoltaic technologies and *Generation IV* nuclear technology in a context of hydrocarbon shortage.
The accuracy of the proposed method depends on the validity of the assumptions taken by the theorem of Panergy inside the reference context. The following example gives an idea of the accuracy when assumptions can be considered as acceptable. Panergy analysis can be applied to the global energy management of a State: in this case the Gross Domestic Product ratio the average households price of electricity should correspond to the overall energy spent in the country. The case of study is Italy and data are referred to the year 2005 (when the speculative pressure on energy prices was less conditioning).
The expenditure of (direct and indirect) energy can be derived analitically: It is a sum whose first term refers to the Total Primary Energy Supply (TPES); this has to be accounted referring to the geological values of different sources and depends on the share of primary energy sources within the country. These shares, in the reference context, are: Nat. gas 36%, Oil 43%, Coal 9%, Renewables 7% and nuclear (imported) 5%; combining them with the values of the primary effectivnesses ε_P reported in TAB. A one finds out that the officially reported TPES figure has to be divided by 0.85 to have the geological value.
The second term consists of the solar energy converted into agricultural biomass; it has been estimated, by agricultural experts, as the 2% of the radiant energy plunging on the surface of the territory whose average figure for Italy is 1430 $KWh_{TH}/(m^2y)$.
The third term is the energy embodied in imported goods. This figure must be calculated indirectly applying the panergy theorem starting from the total non energy import expenditure of the year and dividing it by

the end user price of energy averaged among the import countries. This last figure is, with an acceptable accuracy, 0.0478 €/KWh_{TH}.

The domestic end user price of electric energy, in the year considered, is 0.2 €/KWh_{EL} and the national grid global efficiency η_G is 0.423 (electricity/primary energy) so the primary energy price can be assumed as 0.0846 €/KWh_{TH}.

TAB.C displays the results of this comparison and confirms the acceptable accuracy of the method, at least in this case.

TAB.C – Case study – Italy 2005

ANALYTICAL	*(KWh_{TH})*	**PANERGY**	
Gross Domestic Product	-	**GDP** (€)	*1417 x 10^{10}*
Price of electricity	-	**h_{TH}** [h_{EL} = 0.2 €/KWh_{EL}] (€/KWh_{TH})	*0.0846*
TPES (216 x 10^{10} KWh_{TH})	*254 x 10^{10}*		-
Import (297 x10^9 $€_{2005}$) [no energy]	*621 x 10^{10}*		-
Imported electricity (49,2 TWh_{EL})	*13 x 10^{10}*		-
Sun to bio (26.8 KWh_{rad}/m^2y- 301.400 Km^2) (*)	*807 x 10^{10}*		-
TOTAL ANALYTICAL (KWh_{TH})	***1695 x 10^{10}***	**TOTAL PANERGY** (KWh_{TH})	***1675 x 10^{10}***
Difference (%)	*+1.2*		*-1.2*

(*) most uncertain value