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EMERGY BASED ANALYSIS OF ITALIAN ELECTRICITY PRODUCTION SYSTEM

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Abstract

The continuously increasing demand for electric power together with the demand of environmental friendly technologies require a deep acknowledgement of the directions to give to electric power production in order to satisfy both necessities.

The aim of this work is to evaluate the sustainability of Italian electric system by using the emergy function, a methodology developed in the early 80s by Odum, and its correlated indices. Emergy is a thermodynamic based function that calculates all the fluxes of energy requested to obtain a product going backward to the solar energy invested.

We analyzed all the inputs concurring to the yield of electricity taking into account not only the final phases of the production but also all the sources and materials that had been necessary for the system to operate. We have performed a wide analysis of all the different types of production focusing on thermoelectric sector.

We have obtained not only a thermodynamic analysis of electricity production but also an evaluation of the sustainability of the entire process and a scenario for a correct exploitation of resources.

Keywords: emergy, sustainability, thermoelectric production

Introduction

The assessment of sustainability requires alternative and integrated approaches for a deeper understanding of the complex network of interactions occurring between humans and the environment, mainly based on thermodynamics.

Instead of using state functions it is useful to shift towards the use of trends or evolutionary functions such as Odum's emergy [1] or Jørgensen's exergy [2] or ecological footprint [3].

Unlike classical energy and economic analyses that only consider items that can be quantified in energy or money terms, thus omitting most free inputs from the environment, emergy analysis [1] is a thermodynamic methodology (introduced by Odum

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(Faculty of Environmental Engineering, University of Florida, USA) in the 1980s) which considers both the economic and environmental aspects of a system by converting all inputs, flows and outputs to the common denominator of solar energy, the basic energy behind all the processes of the biosphere.

This is a primary factor because, although the market only considers monetary value, the economy is also based on quantities from the environment, which must be considered and assigned a value, if resources are to be exploited sustainably in the long run.

As Ruth points out [4], economies are open thermodynamic systems contained in an ecosystem (the biosphere) with which they exchange matter and energy. Economic systems and ecosystems are in a practically steady state, far from equilibrium, and only evolutionary dynamic models based on quantity and irreversible, non conservative functions can help us to understand the complexity of the interactions between 'natural capital' and man-made capital [5], between biosphere and system of production, between nature (which we are part of) and economic activity.

The present study uses various sustainability indices, including thermodynamic ones, to evaluate Italian electricity production in relation to its sustainability.

The theory of sustainability, founded by Daly, has two basic principles [5]:

I. Resources should be consumed at a speed that allows nature to replenish them.

II. Production of goods should not create waste and pollutants that cannot readily be absorbed by the surrounding system, so they do not build up.

The second principle is the most immediate, at least as far as immediate and local effects are concerned, but not as far as global and/or long term effects, such as global warming and ozone depletion, are concerned. It is easily monitored by measuring emissions of contaminants into air, water and soil. These measurement techniques have already been developed.

The first principle is less easy to measure. What does it mean to consume electricity, for example? Does it mean consuming coal, oil or water which then goes back into circulation? Does it mean consuming aeolic, solar or nuclear energy? If we are concerned with sustainability, the quantity of energy is important, but so it its quality.

In 1998, the year of the data used for this analysis, the balance electricity production in Italy recorded a demand for 288 TWh against a domestic production of 247 TWh. The difference (41 TWh) was imported from other countries.

More than 80% of domestic production was generated by thermoelectric power stations. At present, it is impossible to stop using fossil fuels, despite the fact that they are unacceptable from a sustainability point of view. Petroleum products, natural gas and coal do not meet the sustainability principles declared by Daly [5] because they are non renewable resources (principle of sustainable yield) which produce atmospheric emissions at a rate that does not allow the environment to absorb them (principle of sustainable absorption capacity). However, there are distinctions between these fuels in terms of emissions and local availability. Thirty percent of the natural gas consumed in Italy is a local resource and it emits 24% less CO_2 than fuel oil and 30% less than coal, which are almost totally imported (94 and 99%, respectively).

The aim of this analysis was to provide a picture of thermoelectric production in order to identify the technologies that exploit resources more efficiently, from the point of view of sustainability, and to indicate appropriate development scenarios. Many Italian thermoelectric power stations are rather antiquated. Besides old power stations of simple conception, there are also much more modern and efficient thermoelectric stations which exploit the cogeneration of heat. In replacing plants that have reached the end of their productive cycle, it is necessary to determine which new technologies are the most suitable. The new plants not only need to meet legal and economic criteria, but also those of sustainable development.

Methods

The concepts of solar transformity and solar emergy [1] are the basis of a method of systemic analysis for determining the best alternatives for use of resources in terms of environmental impact and the best domestic and international policies for a better balance between human society and nature.

Since many joules of low quality energy are needed to obtain a few joules of high quality energy, the concept of transformity was introduced to obtain a hierarchy of energy quality. The transformity is the quantity of energy of one type needed to obtain a joule of energy of another type. In order to compare all types of energy on a common basis, solar transformity is used (henceforth simply transformity). Solar transformity is the quantity of solar energy needed to produce a joule of a particular product, either directly or indirectly.

Solar emergy (henceforth simply emergy) is defined as the quantity of solar energy needed to obtain a product or a flow of energy in a particular process, either directly or indirectly. Its units are solar emergy joules (sej), which are joules, but of a particular type (solar energy). Transformity is therefore the emergy of a product divided by its energy content.

Emergy analysis is performed listing all the inputs necessary to the process and multiplying the quantity of each input by the respective transformity. In this way, adding all the independent contributions, the total emergy is obtained. The transformity of the product is obtained dividing the emergy required for the process by the energy content of the output.

The indices of emergy analysis and their application to electricity production

The main emergy indices for analyzing a production process are transformity, emergy yield ratio (*EYR*) and environmental loading ratio (*ELR*). If we analyze a product obtained by different processes, a lower transformity indicates greater efficiency: less solar energy input (direct or indirect) is needed to obtain a unit of product.

EYR is the emergy of the product divided by the emergy of the inputs from the economic sector (i.e. not supplied locally by the environment). In the analysis, the only energy resources we shall consider to be local are fossil fuels extracted in Italy. If the emergy yield of the process is less than that of alternative processes, the return per unit emergy invested is less. If the yield is slightly greater than one, the process cannot provide net emergy because it only returns to the economy the amount it received.

ELR distinguishes the fractions derived from the economic sector and local non renewable sources from the local renewable fraction. In the case of thermoelectric electricity production, this index is uninformative because a number that tends to infinity is obtained for all processes, since the renewable fraction in the denominator is equal to zero.

Besides these traditional indices of emergy analysis, we also looked at the investment required to produce a joule of electrical energy (EI J^{-1}). By investment we mean everything but energy resources, including plants and everything necessary for a power station to function. This index is interesting to see the incidence of maintenance and construction of the plant, irrespective of the fuel and its source.

The nine electricity production processes active in Italy in 1998 were analyzed. The transformities used for coal and natural gas were obtained from literature [6]. The transformity of oil was calculated again because values in literature do not distinguish different refinery products. Since the analysis is very sensitive to the input fuel, we used maximum yields of the various fractions to obtain a more accurate transformity.

Fuels, as well as all the inputs needed to exploit the energy resource, namely human labor, water for industrial uses and for cooling, were estimated from data provided by ENEL [7, 8] (the Italian Electricity Company); plant running and maintenance costs were estimated from De Paoli and Lorenzoni valuation [9].

Water consumption for cooling in the cases of Steam Boiler and of Gas Turbines technologies should be mentioned. Steam Boiler accounts for the major fraction of this input. We calculated the appropriate transformity based on the water source. Only part of the water used is consumed, becoming vapor; the rest returns to the source practically unchanged. The first fraction, about 15% of the total, was considered in the analysis.

Results

Since the calculations are substantially the same, we only report one in detail, namely that involving steam boiler (Table 1). This process is the principle one used in Italy (70% of total production) and is based on a variety of fuels. The various fuels consumed by thermoelectric power stations in Italy are listed in Table 2 with their quantities and transformities.

Table 1, which lists all the inputs concurring to the functioning of the system, shows that the greatest contribution to final emergy comes from natural gas and fuel oil. It is also interesting that although gas derivatives provide a quantity of energy one order of magnitude lower than that of coal, they and coal have similar emergy fractions. Gas derivatives come from refineries, the chemical industry, arc furnaces and so forth: all complex processes that result in high transformities. However, since they are by-products or wastes that would otherwise have to be disposed of, their use for electricity production is justified.

Table 1 Emergy analysis of steam boiler technology

		Unit/ year	Unit	Transformity/ sej unit^{-1}	Emergy/ sej year^{-1}	Ref.
Inputs						
	Fuels					
	Coal	$2.10\cdot10^{17}$	J	$4.00\cdot10^{4}$	$8.41\cdot10^{21}$	[7]
	Secondary gas	$1.30\cdot10^{16}$	J	$2.66\cdot10^{5}$	$3.47\cdot10^{21}$	[10]
	Natural gas	$2.43\cdot10^{17}$	J	$4.80\cdot10^{4}$	$1.16\cdot10^{22}$	[7]
	Gas oil	$2.39\cdot10^{15}$	J	$6.46\cdot10^{4}$	$1.54\cdot10^{20}$	[10]
	Lignite	$7.95\cdot10^{14}$	J	$3.70\cdot10^{4}$	$2.94\cdot10^{19}$	[7]
	Diesel oil	$8.02\cdot10^{17}$	J	$5.91\cdot10^{4}$	$4.74\cdot10^{22}$	[10]
	Orimulsion	$1.92\cdot10^{16}$	J	$5.40\cdot10^{4}$	$1.04\cdot10^{22}$	[7]
	Capital costs	$2.86\cdot10^{12}$	£	$1.25\cdot10^{9}$	$3.58\cdot10^{22}$	[11]
	Human labor	$8.54\cdot10^{12}$	J	$7.38\cdot10^{6}$	$6.31\cdot10^{19}$	[11]
	Water (industrial use)	$3.19\cdot10^{13}$	g	$6.64\cdot10^{5}$	$2.12\cdot10^{19}$	[10]
	Operating and maintenance costs	$5.78\cdot10^{11}$	£	$1.25\cdot10^{9}$	$7.22\cdot10^{20}$	[11]
	Water (cooling)	$4.00\cdot10^{15}$	g	$1.61\cdot10^{5}$	$6.44\cdot10^{20}$	[10]
Product						
	Electric energy	$1.36\cdot10^{5}$	GWh	$5.67\cdot10^{17}$	$7.72\cdot10^{22}$	
		$4.90\cdot10^{17}$	J	$1.57\cdot10^{5}$		

A mean transformity of $1.56\cdot10^{5}$ sej J^{-1} for Italian electricity production was obtained considering all types of plant (Table 3). This is equivalent to $5.62\cdot10^{17}$ sej GWh^{-1}, from a total emergy flow of $1.12\cdot10^{23}$ sej year^{-1} in 1998. The results we obtained are comparable to the ones presented by Odum [1], $1.60\cdot10^{5}$ sej J^{-1} for a coal power plant in United States, and $1.97\cdot10^{5}$ sej J^{-1} for an oil power plant in Thailand. This confirms the relevancy of the emergy analysis, which even though it is not state-function, it yields similar results for processes performed in different country with different economies.

The comparison between the nine technologies within the Italian system we analyzed, indicates that the transformities in the thermoelectric sector are variegated, the highest being double the lowest. In order to compare the cogenerative technologies with those producing electricity only we have esteemed (as conventionally done) that in a cogenerative cycle only 44% of the input energy is actually transformed in electricity. The rest is heat used for other aims.

Table 2 Fuel used in thermoelectric sector

Fuel	Unit/year/ 10^{15} J	Transformity/ 10^4 sej J^{-1}	Emergy/ 10^{20} sej	Ref.
Coal	212.46	4.00	84.98	[7]
Lignite	0.92	3.70	0.34	[7]
Natural gas	570.66	4.80	273.91	[7]
Light gas oil	1.26	6.46	0.81	[10]
Gas oil	6.57	6.46	4.25	[10]
Diesel oil	889.54	5.91	526.09	[10]
Still mill gas	4.81	26.60	12.82	[10]
Blast furnace gas	27.81	26.60	74.08	[10]
Gas coke	13.23	26.60	35.24	[10]
Refinery gas	16.91	26.60	45.05	[10]
Chemical process gas	4.77	26.60	12.71	[10]
Petroleum coke	8.04	5.40	4.34	[10]
Orimulsion	19.17	5.40	10.35	[7]
Other	12.68	5.91	7.50	[10]

Table 3 Emergy indexes of electric power technologies

Technology	Energy produced/TWh	Transformity/ 10^5 sej J^{-1}	*EYR* Y/F	*EI*/ 10^4 sej J^{-1}
Steam boiler (C)	136.21	1.57	1.10	1.02
Combined-cycle (CC)	2.66	1.09	1.39	0.89
Internal combustion (CI)	0.66	1.95	1.06	2.63
Gas-turbine (TG)	0.17	1.51	1.28	1.50
Co-generation combined cycle (CCC)	22.24	1.82	1.22	0.89
Co-gener. internal combustion (CIC)	0.95	0.93	1.28	0.89
Co-gener. steam boiler (CPC)	1.19	0.81	1.51	0.92
Co-gener. condensed steam (CSC)	9.28	1.62	1.19	0.88
Co-gener. gas turbine (TGC)	2.48	1.03	1.32	0.89
Unknown	11.49	1.73	1.13	0.90
Average transformity		1.56		

The lowest transformity was achieved by co-generation steam boiler, the most efficient system in the sector. Co-generation internal combustion, co-generation gas turbine and combined cycle gave similar results. At the other extreme we have internal combustion (utilized only for isolated locations), co-generation combined cycle (because the feedback of heat in the secondary cycle makes the cogeneration less useful) and the miscellaneous category. Table 3 shows the results of all the analyses, comparing the various systems of production. All the transformities are shown in Fig. 1.

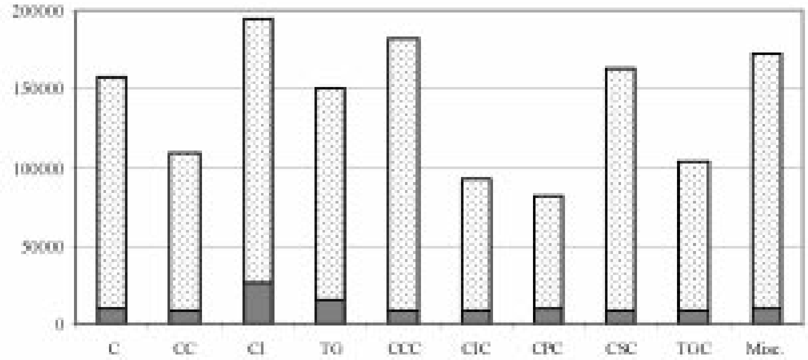

Fig. 1 Values of the transformities of the different thermoelectric productions, distinguishing the contributions due to fuels (dotted part of the bars) and to other resources (darker part)(abbrevation as in Table 3)

These results show that cogeneration systems are generally the most efficient and they are also the most modern. The best of these, in terms of transformity, was co-generation steam boiler, which also had one of the lowest emergy investments per joule of electricity. The fact that the investment values obtained are similar is essentially due to the very high emergy values contributed by the primary energy source used with respect to the resources required for its exploitation.

We obtained many *EYR*s close to one. In this sector, the values are mainly determined by different use of non renewable resources. When methane is the main fuel, *EYR* is higher because a higher proportion of this particular fuel is produced in Italy.

Conclusions

The sustainability of the thermoelectric sector is intrinsically linked with the fuels one, which are, by definition, not sustainable with respect to the two Daly's principles. A thorough sustainability analysis should also compare this sector with other technologies able to produce the same output. This was not the focus of our paper.

However, within the thermoelectric power sector, distinctions can be made in terms of efficiency and use of local resources. Moreover, if a type of plant enables the quantity of fuel to be halved, it is automatically twice as sustainable, by virtue of fuel saving and fewer emissions.

These results give a general picture of Italian thermoelectric production, seen through emergy analysis. They suggest guidelines for improving the sustainability of Italian electricity production. Development should privilege technologies that use a high proportion of local resources (higher *EYR*), are efficient in transforming the resources used into electricity (lower transformity) and fully exploit the primary energy source (low EI J^{-1}).

References

1 H. T. Odum, Environmental Accounting, Wiley and Sons, Chichester 1996.
2 S. E. Jørgensen, Integration of ecosystem theories: a pattern, Kluwer Academic Publisher, The Nederlands 1992.
3 M. Wackernagel and W. Rees, Our Ecological Footprint: reducing human impact on the Earth. The new catalyst bioregional series, Vol. 9. New Society Publishers, Philadelphia 1996.
4 M. Ruth, Integrating Economics, Ecology and Thermodynamics, Kluwer Academic Publishers, Dordrecht 1993.
5 H. E. Daly, Steady-State Economics, Freeman, San Francisco, 1977.
6 H. T. Odum, Science, 242 (1988) 1132.
7 ENEL, Rapporto ambientale 1998, ENEL, Rome 1999.
8 ENEL, Dati statistici sull'energia elettrica in Italia 1998, ENEL, Viterbo 1999.
9 L. De Paoli and A. Lorenzoni, Economia e politica delle fonti rinnovabili e della cogenerazione, Franco Angeli, Milan 1999.
10 S. Bastianoni, M. Marchettini, I. Principi and E. Tiezzi, Sviluppo di un modello di analisi emergetica per il sistema elettrico italiano, Final Report for CESI, Siena 2000.
11 S. Ulgiati, H. T. Odum and S. Bastianoni, Ecol. Model., 73 (1994) 212.