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The emergy analysis of the Province of Siena in the SPIn-Eco project

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Abstract

The assessment of environmental sustainability of ecosystems, productive processes and territorial systems requires a holistic approach, based on thermodynamic functions and able to consider all the complex mechanisms which are involved in a system. Many of the most used indicators focus their attention on single aspects and do not consider the system as a whole. The SPIn-Eco project uses a holistic and integrated approach so as to assess the sustainability of the Province of Siena with a set of environmental tools. One of these is the emergy analysis. This environmental accounting methodology is able to compare the value of human and natural systems on a common basis: the quantity of solar energy directly and indirectly required for a process. This quantity, called emergy, represents the memory of all the energy, matter and time that the biosphere used up to make a product available. The emergy indicators permit one to evaluate the efficiency, the environmental stress and the sustainable use of resources involved in a single process or in systems at various scales. The indicators define a Province with a low environmental loading ratio, which is the ratio between non-renewable and renewable resources, due to a low anthropic activity, well integrated with the characteristics of the territory, to a low population density and internal production of electricity by means of geothermal heat. The Province of Siena has the lowest emergy per area of the Italian territories examined up to now. It is mainly sustained by non-renewable resources (91%), of which 62% are from local resources (mainly from extractive materials) and 29% is imported through commerce. These results show a low dependence on external resources and suggest a careful monitoring of material extractions. This avoids a systematic loss of natural capital. Moreover, they suggest

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developing processes of material recycle and recovery. The renewable use (9%) is not so low compared to the other Italian territories.

1 Introduction

A territorial system can be studied as a complex system. The non-linear interactions between its structural elements, the multiplicity of decision makers and time-scales, its structure based on many levels of organizations, its openings to the outside, its irreversible dynamics are peculiar features of a complex system. This system requires resources and energy to enhance internal order and to self-organize, while increasing the entropy of their surroundings. The increase in entropy exceeds the internal entropy decrease of the system, so that the second principle of thermodynamics is observed. Hence a territory behaves like a dissipative structure [1].

From a thermodynamic point of view, the dissipation of resources, such as fossil fuels, means positive entropy changes in the environment associated with greenhouse gas emissions and the co-products commonly called wastes. Humans need to decrease the speed of exploitations of resources, and aim for development compatible with the biophysical limits of the planet. The Earth is a finite system and as a consequence it has physical constraints: its resources as well as its capacity for absorption and regeneration are not infinite. The existence of constraints means that the planet has a carrying capacity, namely a capacity to sustain human and other forms of life (plants, animals...) that are interdependent: this is the basis of sustainability [2].

In this paper, we analyze a complex system (the Province of Siena) in a steady state, far from equilibrium. The province of Siena is located in the south-east of Tuscany, and covers an area of 3.821 km^2. It is one of the most extended provinces in Italy and the second in Tuscany after Grosseto. It is composed by 36 communes and is about 93% hill and the rest (7%) mountainous. Siena has a population density of 66 people/km^2, one of the lowest in Italy that has a population density of 191 people/km^2. The economic structure of the system is characterized by a prosperous agriculture, especially for wine and oil, by tourism and by a well developed service sector. The productive system is characterized by craft firms, especially in crystal production. To assess its status, it is necessary to analyze all the fluxes of energy and matter of the system, both those associated with negative variations in entropy that permit self organization of the system and those associated with positive changes in entropy that represent the entropy waste produced by the system. The assessment of the environmental sustainability of the Province of Siena requires a holistic approach because of the complexity of the system. Here, we have used an environmental accounting methodology, the Emergy Analysis. The aim of the paper is to give a comprehensive assessment of the environmental sustainability system using the emergy approach.

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2 Emergy analysis

The methodology was developed by H.T. Odum [3,4] of the University of Florida, (USA) in the early 1980's. The solar emergy (from now on simply emergy) of a flow or storage is defined as the solar energy directly or indirectly required to generate that flow or storage. It is an extensive quantity and its units are solar emergy joules, sej. In order to convert all the flows, involved in the process, into this common base a conversion factor is used: the (solar) transformity, defined as the emergy per unit flow or unit product. It is an intensive quantity measured in sej/J. Emergy can be considered as an energy memory because it takes into account all the energy, past and present, needed to produce that product or flow. As the emergy analysis is useful to check applications of the first Daly's rule, it is recognized as an important tool to define the sustainability in the long run and measure the human impact on nature [5].

This environmental accounting methodology can be used to assess the complex relationships between the economic system and its supporting environment because the work of both is expressed in equivalent terms. In this way we can also consider the energy flows that are "free" and generally neglected in the traditional energy and material balances. Moreover, a set of emergy-based indicators is proposed to evaluate different scenarios comparing their emergy inputs [4]. The total emergy of the system (U) is divided into the renewable (R) and the non-renewable (N) part, and the local (L) and imported from outside inputs (F). The emergy yield ratio (EYR) is the total emergy (U) divided by the emergy of those inputs to the system that are fed back from the economy (F):

$$EYR = \frac{R + N + F}{F} = \frac{U}{F} \tag{1}$$

This ratio indicates whether the process can compete in supplying a primary energy source for an economy. If the ratio is lower than alternatives, less return is expected to be obtained per unit of emergy invested.

The emergy investment ratio (EIR) is the ratio of the emergy fed back from the economy (F) to the indigenous (renewable R and non-renewable N) emergy inputs:

$$EIR = \frac{F}{N + R} \tag{2}$$

This ratio indicates whether the process is economic as a utilizer of the economy's investments in comparison to alternatives. The physical meaning of this index is to evaluate the emergy input from the economy needed to exploit a unit of indigenous local resources.

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The environmental loading ratio (ELR) is the ratio of purchased and non-renewable indigenous emergy to renewable (free) environmental emergy:

$$ELR = \frac{N + F}{R} \tag{3}$$

A high ratio suggests a high technological level in emergy use and/or a high level of environmental stress. It is like an alarm-bell for a state of non-equilibrium which could become irreversible in the long run. Emergy use per person suggests a measure of the standard of life in a country intended as availability of resources and goods. The empower density (ED), the emergy flow per unit area, is a measure of spatial concentration of emergy flow within a process or system. A high empower density can be found in processes in which emergy use is large with respect to the available area. This suggests that the land is a limiting factor for the future economic growth.

3 Results and discussion

The inputs to the system are transformed in the same unity, the solar emergy joule (sej) by using the transformity. That is, each resource can be weighed in order to consider the memory of the all energies to make it available. The total emergy flux which supports the Province of Siena is 9.68×10^{21} sej/year, the main inputs are shown in figure 1.

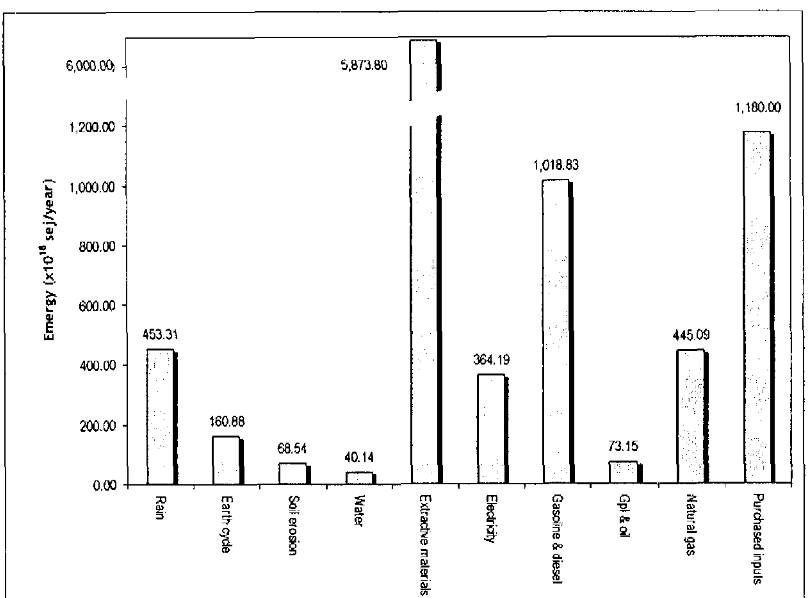

Figure 1: Emergy fluxes of the system.

From figure 1 it is possible to understand that the extractive materials have the largest emergy content. Imports also have a relevant emergy content although smaller than the one of extractive materials. This represents the 12% of the total emergy of the province. As far as the energy consumption is concerned the most significant input is due to diesel and gasoline consumptions. Methane has an important role too, since it is the most used resource for heating in the Province of Siena. According to their use and origin, all the inputs are divided into:

- Local renewable resources (R);
- Local non-renewable resources (N);
- Imported energy (F1);
- Purchased inputs (F2);

Figure 2 allows us to compare the ratio between the different type of resources.

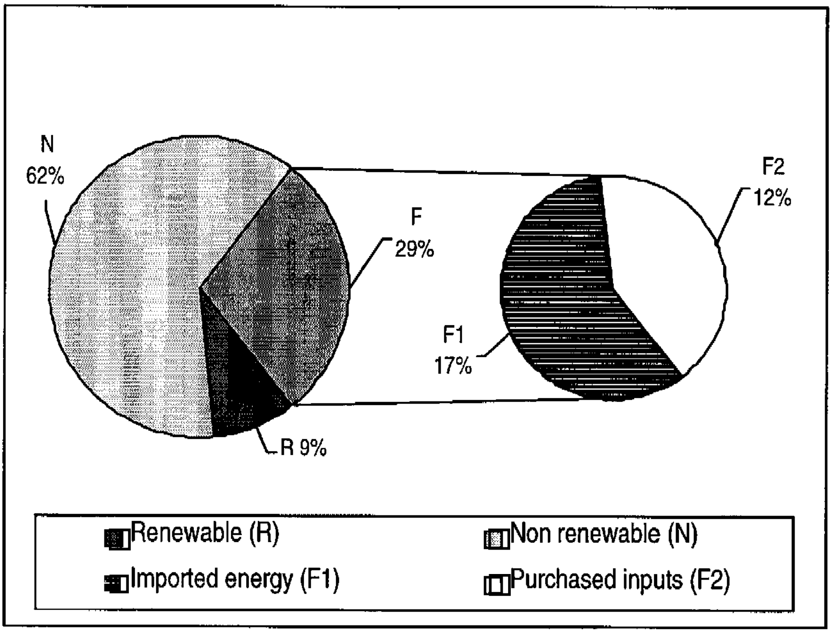

Figure 2: Composition of the emergy flows of the Province of Siena.

Analysing the emergy composition of the Province is possible to say that there is a disequilibrium between local e non-local resources: the local resources (the first one) are twice and half larger the second ones. This means that the system is sustained mainly from local resources. Within local resources, non-renewable resources (62%) are by far larger than renewable ones (9%). The total contribution to renewable resources has a low percentage in emergy terms with respect to resources used. However, Emergy analysis permits to quantify the fundamental support given by these resources to the system. This is not considered in the traditional analyses since they disregard the free input from nature. The percentage of renewable resources (9%) is very high with respect to other provinces analysed by our group. The reasons for that are: first, in the Province of Siena there is an important and consistent production of electricity from geothermic resources that is regarded mostly as renewable. Second, the system is characterised by a low use of resources. The high percentage in the use of local non-renewable resources is due to extractive materials. In particular, as far as constructions materials are concerned, the extractive materials represent the 50% of the total emergy content of the extractions. The extraction of materials has a lower impact in terms of greenhouse emissions than the ones of oil and methane. The Economy of the Province is centred on tourism and services rather than manufacturing. Hence, it imports low quantity of raw materials and means of production (F2). The demand of electricity in the Province is quite low and it is mostly satisfied by the local production (90%) through almost renewable resources. According to the emergy analysis, about 75% of the electricity produced from renewable (mostly geothermic and a low percentage of hydroelectric) is regarded as a renewable resource and consequently added to R. On the other hand, the remaining electricity (25%) is added to F1, representing the assets necessary for local productions. These percentages are the results of a study on the Italian electric system [6]. The imported energy has been considered non-renewable (F1) because the national production is almost totally due to non-renewable resources. In this paper we have only considered some of the numerous indicators, which can be produced by the emergy analysis. In particular, we have taken into account the most important ones according to our point of view. The indicators obtained from emergy analysis of the province of Siena are summarized in table 1.

Table 1: Emergy flows and indicators of the Province of Siena.

Emergy flows and indicators	Unit	Expression	Province of Siena
Emergy flows			
Renewable sources	sej/year	R	8.30×10^{20}
Non-renewable sources	sej/year	N	5.98×10^{21}
Imported energy	sej/year	F1	1.69×10^{21}
Purchased good	sej/year	F2	1.18×10^{21}
Total imported emergy	sej/year	F = F1 + F2	2.87×10^{21}
Total emergy	sej/year	U = R + N + F	9.68×10^{21}
Emergy Indicators			
Environmental loading ratio (ELR)	-	(N + F) / R	10.65
Emergy density (ED)	sej/m2/year	U / area	2.53×10^{12}
Emergy used per person	sej/person/year	U / population	3.83×10^{16}
Emergy yield ratio (EYR)	-	U / F	3.38

The value of EYR (3.38) confirms that the Province of Siena can be well described as a consumer of local resources rather than a transformer of imported goods and services.

In order to assess the relative sustainability of the Province of Siena we have compared the ELR and ED of the Province of Siena with other Italian provinces, considering the value of Siena as the reference number (table 2).

Table 2: Comparison of the ELR and ED of some Italian provinces with Siena.

Province	**ELR/ELR_{Siena}**	**ED/ED_{Siena}**
Alessandria	2.46	1.98
Ancona	6.54	3.96
Asti	2.01	1.68
Bologna	6.18	3.84
Cuneo	2.29	2.25
Forlì-Cesena	6.42	3.57
Modena	3.27	2.86
Novara	4.12	3.80
Pesaro	3.67	2.22
Pistoia	3.29	4.17
Ravenna	2.69	3.94
Siena	1.00	1.00
Torino	3.70	3.49
Verbania	0.82	1.18
Vercelli	2.17	2.09
Viterbo	1.64	1.73

The greatest value of emergy density is detected where there is the greatest anthropic pressure, that is, where there is a great demographic density and people are busy in dynamic productive and industrial activities. The value of ELR (10.65) and emergy density ($2.53x10^{12}$ sej/m^2/year) reflect a low pressure on the territory, one of the lowest ever seen in Italian systems up to now. With the exception of Verbania, the other territorial systems have value of ELR from 1.5

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to 2.5 and much greater than the Province of Siena. ED has the lowest value with respect to the other systems considered. The value of these indicators follows the intensity of the urbanization and the density of productive activities that cause an accumulation of emergy per unit of territory.

The emergy per person ($3.83x10^{16}$) can be considered as an availability of resources if we take into account renewable sources and as a consumption of resources when it refers to non-renewable sources. In fact, in the second case the resources used are not available in the future because of its non-renewability. The assessment of this indicator must be done by considering the ELR and the ED. In the case of the Province of Siena the emergy per person can be partially seen as a availability since the values of ELR and ED are the lowest ones. The results obtained are coherent with a system with a low population and an economic structure mostly represented by small and crafts factories. Siena has in fact an economic structure principally centred on services and a low population density. The values of the emergy indicators describe the Province of Siena as a complex system characterised by a low stress, which is the result of an anthropogenic activity highly integrated with the features of the territory. Nowadays, natural resources do not represent the limiting factor but rather contribute to the richness of the territory.

4 Conclusions

The results obtained show that the system is sustained by a flux of renewable resources (91%), of which 62% local (mostly extractive materials) and the remaining 29% imported from the commerce. The Province should manage the extractive sector in order to avoid the depletion of the natural capital of the territory, it could be appropriate to reduce the quantity of extractive materials trying to improve crafts activity in order to enhance the value of the final products. The comparison with other systems show that the province has good value of environmental sustainability due to the low population density and to the low presence of intensive industrial activities.

The Province of Siena should therefore identify different model of development in relation to the areas considered, further improving the use of natural resources. The Province should develop activity based on typical products as and control accurately that the renewability of these resources is not compromised. Sustainability does not mean self-sufficiency but requires the appreciation of local characteristics. A Province has necessarily to buy from the market those goods and resources that it needs. However it is reasonable to consider the peculiarity of the territory and not only to rely on economic rules and transactions.

Finally these environmental tools could be valid instruments to suggest strategic choices for the future of the territory, according to the principles of sustainability.

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