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Quantifying the environmental support for dilution and abatement of process emissions
The case of electricity production

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Abstract

Strategies to deal with thermal and chemical emissions from electricity production processes are compared. Accounting for the environmental services required to dilute emissions is suggested as an unavoidable step towards correct evaluation of sustainability of processes. Calculations are performed in several case studies by means of the emergy accounting methodology. An emergy-based yield indicator decreases by 40–70% coupled to a parallel increase of a loading indicator, when the environmental services required for the dilution of pollutants are correctly accounted for. As a consequence of including environmental services, a lower sustainability is calculated for each investigated process when compared to evaluations that do not include them. Accounting for environmental services also provides a way to evaluate the carrying capacity of the environment in relation to human dominated processes. The requirement for environmental services to effectively recycle by-products at different space–time scales translates into the need for a suitable support area for the process under study. Two support areas are suggested, one using local constraints, and a second using global constraints. The former is suggested as a near term, regional carrying capacity, while the latter is a long term, global carrying capacity.

Keywords: Environmental services; Emergy accounting; Electric production processes; Carrying capacity

1. Introduction

The environment is both a source and a sink. It is a source of resources for economic processes and a sink for by-products from these same processes. The source, or supply side, is, more or less, well understood and has been quantitatively evaluated in both economic and energy terms. Limits are easily understood (when there is no more water, or oil there is no more...period), and planning for future shortages can be carried out based on these limits. However, while the sink side has also been recognized, quantitative evaluation has been elusive and thus planning for appropriate uses of environmental support have been hindered. In this paper, we suggest a quantitative method for evaluating environmental support in absorbing and diluting by-products, using some electric power production systems in Italy as case examples.

1.1. By-product flows and cycles

The flows of energy and matter drive all biosphere processes. Energy flows into and out of systems, but in the process it is degraded to low temperature heat, according to the second law of Thermodynamics. The same happens with material inputs, whose chemical and physical characteristics may undergo huge changes as they are upgraded or degraded in biosphere processes. Ecological systems converge, diverge, cycle and recycle materials and energies, changing their forms and concentrations in the process. At every transformation, different by-products are yielded all of which participate in the global biosphere cycles at different space and time scales, and which eventually are recycled and feedback to new production processes. The by-products released

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from human controlled processes are no different. Yet this point of view is often rejected by society which defines some outputs from processes as 'useful' and others as 'pollutants'. It may be useful to think of a pollutant as something that exists at higher concentrations than are normally found in biosphere cycles, but that still participates in the continuous cycles that are characteristic of all materials. From this point of view, they are process by-products, while they are waste emissions in the shorter space–time scale of humans.

By virtue of their higher concentrations, pollutants have the potential to cause change in environmental systems that ultimately affect human society through changes in support functions [1–3]. It is these changes that society tries to avoid by controlling emissions and monitoring average concentrations of heat and chemicals in different sectors of the biosphere. By doing this, society tries to keep its life support system intact, thinking not only of the present, but to a certain degree of future generations as well.

So the question is how to fit the economies of humans to the patterns and processes of the biosphere, adopting mechanisms that can take advantage of the biosphere's capacity to absorb waste by-products, without overload. There is a long-standing saying with engineers who deal with undesired by-products...'The solution to pollution is dilution.' Unfortunately, while this statement may sometimes be true, it has become overused, even abused, as by-products at increasing rates have been released to the biosphere, where concentrations have increased and begun to threaten human well being. Furthermore, metabolic cycles have the tendency to concentrate many of these compounds, which may become dangerous if concentration occurs at time scales comparable with time scales of living processes. Clearly, what is required is a quantitative evaluation of the area of environment required to absorb the waste by-products of human society. If a suitable area is allowed, re-concentration processes of undesired compounds might also occur at slower rate. In essence, it takes the entire biosphere for the production processes of the global population, but at a more local scale it is important to understand and design into public policy the role the environment plays in absorbing, diluting and finally recycling wastes. If it is recognized and factored into planning and policy, society may reverse current trends that result in overloading the capacity of life supporting environments to absorb the undesired emissions.

1.2. Environmental services

All processes require material and energy inputs. Nonrenewable and purchased inputs are usually recognized and accounted for as 'driving' inputs, i.e. inputs that are needed for the process to take place (fuels, electricity, machinery, fertilizer, etc). On the other hand, free environmental inputs are often not recognized as driving inputs, even if they are also fundamental services, like topsoil used up in agriculture, or cooling water in power plants. However, in recent years, as a result of increasing attention to the limits of environmental support, the concept of environmental services is gaining a more attention. An increasing number of scientists, economists and policy makers recognize that 'Nature's *free* services form the invisible foundation that supports our societies and economies … Yet economies unwittingly provide incentives to misuse and destroy nature by underappreciating and undervaluing its services' [4]. Without organic matter in topsoil agricultural yield can be lower, or without cooling water, performance of power plants can be much reduced. In both cases the value of the input can be measured by the amount of 'effort' that is required to make them. In the case of topsoil it may take hundreds of years to make 1 cm [5] and in the case of the power plants, it takes a very large convergence of environmental services to provide the water necessary to cool them [6].

Many environmental services are even less likely to be accounted for. These are the free services provided by the environment in absorbing and disposing of waste by-products and are of fundamental importance to a sustainable production pattern. They are often not accounted for because, in the short run, most production processes can occur without the service of by-product disposal, even if the surrounding environmental characteristics may change. However, most often they remain unaccounted for because the environment provides the service free of charge, that is until such time the environment becomes overloaded. Once overloaded and the free service from the environment must be replaced by technology, costs for their replacement are often accounted for.

On the other hand, if the generation of by-products is balanced by the environment's ability to dispose of them, then development and environment can be balanced. When the environment is accounted for, performance of a production process is more time and location dependent, as it should be. For instance, it is well known that a thermal engine performs differently according to the surrounding environmental temperature, because the temperature of the surroundings affects the ability of the environment to act as a heat sink.

1.3. Three strategies for dealing with undesired by-products

Given a relatively fixed space–time perspective, humans recognize as useful some outputs from processes, while others are dealt with as wastes and pollutants. This assumption is only true within the space–time scale of the human perspective and even changes from time to time whenever an economic use can be found for a by-product. Nevertheless, there are three different strategies that may be adopted in the presence of unwanted by-products from production processes.

1.3.1. Business-as-usual strategies (i.e. do not account for waste by-products at all)

If this strategy is followed, no constraints need to be put on industrial processes and more waste heat and by-products are likely to be released per unit time and area. Nature will take care of their disposal, as it always does. However, as this process may occur at larger space–time scales than the human economy, the concentration of the outputs in the local environment and finally in the biosphere may steadily increase and seriously affect humans and the environment.

1.3.2. Fixing strategies (i.e. investing resources in abatement or to speed recycle and disposal processes)

As emissions are sometimes considered dangerous, their abatement, disposal and recycle is planned and operated by means of industrial activities supported by new resource investments, F_2 (Figs. 1 and 2).

The fixing strategy is an entropy trap. In order to fix, that is, to invest resources in fixing, disorder must be created as a result of the investment. The hope is that the disorder created in a fixing strategy is less than the disorder that would have been caused by a release to the environment. Ulgiati et al. [7] pointed out that any resource investment applied in order to recycle and process by-products of energy and resource use is likely to decrease the net yield as well as the end-use yield ratio. A lower yield ratio will have, as a consequence, a larger resource input requirement to provide the same support to the economic system. The increased inputs will translate into a larger resource use as well as a larger demand for disposal investments. These will in turn translate into further chemical emissions from the disposal process, or ultimately into a release of waste heat [1]. It therefore appears that the strategy of dealing with unwanted by-products by means of additional investments cannot help to solve the problem in the large scale (due to the internal by-products loop and increased demand for input resources), even when it appears to solve a problem in the small scale.

1.3.3. Carrying capacity assessment strategies (i.e. accounting for environmental services and adapting development to their space–time scales)

To avoid the entropy trap of the fixing strategy requires that by-products be absorbed and recycled with little or no additional resource investment. This might be accomplished by capitalizing on free environmental services and taking advantage of the existing cycles and processes of the biosphere. What is needed is a careful analysis of the environmental area that is required to absorb, dilute and process the undesired by-products

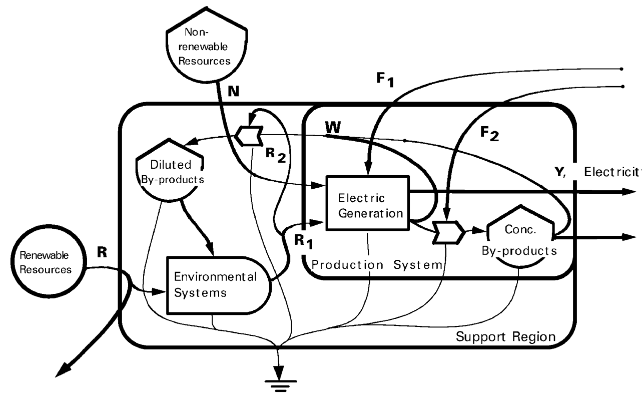

Fig. 1. Electric generation is driven by nonrenewable emergy inputs, N, and purchased inputs, F_1. A renewable input, R_1, is very often directly required for the process to occur (for instance, cooling water). Waste outputs, W, of a production process are diluted and recycled by nature, by means of a renewable emergy investment, R_2 (system symbols after Ref. 9. As space–time scale of natural cycles may be larger than those of the existing assets and species, waste outputs, W, may accumulate and be a source of stress. A resource investment, F_2, is provided by the economy to speed the process of waste disposal and recycle, in order to avoid their concentration increase. The investment shortens the space–time scale of the recycle, but the problem may be translated into the new problem of dealing with the consequences of the investment (minor returns, and unwanted by-products from the investment). R_1, renewable inputs supplied by the local ecosystem and used by the plant in the production of electricity (cooling water and air, oxygen for combustion, direct solar radiation). R_2, Renewable input supplied by the local and surrounding ecosystems and serving for the dilution and the abatement of plant emissions. R, total renewable input to the process [R=max(R_1; R_2)] as these inputs are driven by the same (solar) source. N, non-renewable inputs (such as coal, oil, and natural gas or groundwater that is used faster than it is recharged). F_1, goods and services from the economy that are used to construct, operate, and maintain the power plant (construction materials, machinery, general supplies, human services, etc.). F_2, goods and services from the economy that are used for processing and at least partial abatement of plant emissions. Y, output of a process. Here, the electricity yielded by the plant. By definition, the output is assigned an emergy Y=R+N+F. W, chemicals released by the power plant to the atmosphere (from combustion, deep heat reservoirs, etc.).

without causing significant changes in the environment. A methodology for calculating carrying capacity for economic development was previously presented [8] that included both economic and ecological considerations.

Since the business-as-usual strategy leaves humanity with potentially dangerous increases in environmental loading, it is not acceptable. The fixing strategy has been demonstrated to be an entropy trap since increased fixing will require more resources which will require more fixing, etc. The carrying capacity assessment strategy accounts for the free work of the environment, and suggests that the overall density of development should be related to the environment ability to process and cycle by-products. To dilute and absorb these by-products, a large environmental service is required. For this to occur, a support area larger than the actual plant area is required. If a suitable support area is not made available,

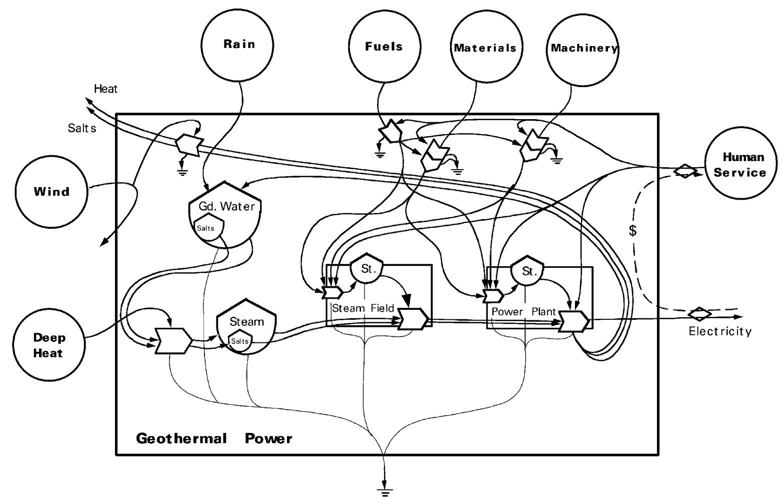

Fig. 2. Energy system diagram of a geothermal power plant.

production will become a source of stress to local environment and population. This carrying capacity strategy may enhance planning and policy making regarding, not only power plant siting, but all human uses of environment.

In a previous companion paper [6] the methodological approach and comparison of power plants was demonstrated by means of calculated emergy indicators (Transformity, Emergy Yield Ratio, Environmental Loading Ratio, etc.) in addition to the energy-based ones. The indicators were calculated only accounting for purchased inputs (fuel, plant materials, labor, etc.) and for the environmental inputs used directly for plant cooling (wind, river water, oxygen for combustion, etc.). In this paper the role of environmental services in disposing of chemicals that are released after electricity has been produced is explored and a method of quantitatively determining carrying capacity is presented.

2. Methods

Performance indicators in the electricity production case studies were calculated by means of the Emergy Accounting methodology [9]. It appears to fit the goals of both accounting for environmental services and providing a scientific measure of the support environment required (and related constraints) for economic processes.

By definition, *emergy* is the amount of energy of one form directly or indirectly required to provide a given flow or storage of energy or matter. A *transformity* is the ratio of the emergy needed to produce a flow or storage to the actual energy of that flow or storage. In other words, the transformity measures the input of emergy per unit output. Emergy is often expressed in solar emergy joules (seJ, solar emjoules), while the transformity is usually expressed in solar emergy joules per joule of output flow (seJ/J). The concept and use of the transformity as a quality indicator is stressed in [10], together with definition and use of other emergy-based indicators.

2.1. Emergy accounting and emergy-based indicators

Emergy accounting is organized as a top down approach where first systems diagrams of processes are drawn to organize evaluations and account for all inputs and outflows from processes. Tables of the actual flows of materials, labor and energy are constructed from the diagrams and all flows are evaluated. The different units for each flow are multiplied by transformities to convert them to solar emergy. Comparison between flows of different materials and energies are possible once expressed in emergy units. In fact, the different inputs to a process can be summed to evaluate the total emergy requirement, which is then divided by the energy of the product to yield a product transformity. An emergy-algebra is used for calculations, to avoid double counting of flows generated by the same source [9]. Finally, several emergy-based indicators to assess a process's performance are calculated. Several previous papers describe, in detail, emergy indices that are used for comparison [7,8,11]. Formulae for the calculation of these emergy indicators are shown in the first column of Tables 5 and 6.

Among the existing emergy-based indicators, the Environmental Loading Ratio (*ELR*) is critical to the evaluation of environmental services. The *ELR* is the ratio of the sum of non-renewable and purchased emergy to the renewable emergy inputs to a process. It is an index of environmental loading indicating an excess investment of nonrenewable compared to locally renewable emergy [11].

2.2. Emergy accounting of electricity production.

The emergy support to six power plants in Italy was evaluated.[1] Three of the plants were driven by fossil fuels (coal, 1280 MW; oil, 1280 MW; methane, 171 MW), while the other three were powered by renewable sources (wind, 2.5 MW; geothermal heat, 20 MW; hydro, 85 MW). The methane and coal plants were located in Northern Italy, the oil and geothermal plants in Central Italy, while the hydro and wind plants in Southern Italy. Two of the plants (wind and geothermal plants) were constructed around 1995, so their design can be considered updated, but a long performance series is lacking. Two of them (oil and coal plants) have been in operation for about 20 years, while two others (hydro and methane) were built more than 25 years ago, but they have been completely remodeled and their performance improved.

An energy and carbon balance evaluation for these same plants was given in [6]. Comparison of emergy indices for the power plants without accounting for the environmental services required to deal with emissions can be found in the same paper.

2.3. Accounting for environmental services

Fig. 1 is a aggregated systems diagram of electric production showing the flows of renewable emergy input (R_1), the nonrenewable emergy input (N) and the purchased inputs from the economy (F), all of them driving the electricity production. The outputs from the production system are electricity (Y) and waste by-products (W). The regional system (larger frame) contains environmental systems and the storage of chemical and heat by-products from the production system. Environmental services required (R_2) for the disposal of by-products are shown as the interaction of environmental systems and by-products. The environmental services required can be quantified as the renewable emergy necessary to drive the dilution process. Environmental services were accounted for in the following manner:

(a) from average performance parameters or from actually measured data the amount of released chemicals (SO_2, NO_x, CO, ash and unburnt hydrocarbons) was determined.

(b) volume and mass of air that is required to dilute these emissions was calculated for two concentration levels: (i) acceptable concentrations, according to local legal limits or to international Environmental Protection Agencies, or (ii) close to average values in the biosphere. The lower the concentration threshold, the higher the dilution mass required, according to:

$$M=d^*(W/c) \quad (1)$$

where M is the mass of dilution air, d is air density (1.23 g/dm^3), W is the annual amount of a given emission from the plant, and c is the acceptable or background concentration from agreed regulations or scientific literature.

(c) finally, the emergy value of required environmental services (R_2 in Fig. 1) was determined, by calculating the kinetic energy of the mass of dilution air, using average values for wind speed in the area. This energy is a measure of the wind energy needed to spread and dilute pollutants. When multiplied by the wind transformity, it gives a measure of the environmental service that is required (R_2), in units of emergy.

2.4. Calculating carrying capacity using environmental loading ratio

The support area required by a production process can be determined by ‘balancing’ the environmental loading produced by the process with the overall emergy of environmental support in the region [8]. This in essence computes a carrying capacity of a local environment for a given production process.

Once the required emergy of environmental services (R_2), is known, the area of land necessary to balance the development can be calculated from the average annual flux of renewable emergy per year per unit area of landscape (R in Fig. 1). Renewable emergy/area is a location specific parameter, that must be calculated from the analysis of the larger region where the development is located and the biosphere as a whole. The area of support, A_S, necessary to provide environmental services for pollutant dilution, thus the carrying capacity, is calculated as follows:

$$A_S=R_2/R \quad (2)$$

where A_S is the support area required; R_2 is the required amount of renewable emergy (environmental service) necessary to dilute and dispose of process’s by-products (as calculated above); R is the renewable emergy flow per unit area in the region. We have stressed the meaning of Eq. (2) in [8], where it was derived from the assumption that the Environmental Loading Ratio of an economic development (here, the power plant) should equal (or be lower than) the average *ELR* of the regional econ-

[1] Data were obtained from a research that we performed in 1996 and updated in the year 2000 for the Italian ENEA—National Agency for New Technologies, Energy and the Environment [15]. Data for main plant components were kindly supplied by the Companies producing and operating them. These companies are (i) a public National Electric Company (ENEL), (ii) a local, city owned, Electric Company (AEM, Torino) and (iii) a private Industrial Company involved in the design and construction of wind electric plants (Riva Calzoni S.p.A., Bologna).

omy in which the development takes place. Of course, this balance is specific to economy we are dealing with. If the same evaluation is performed requiring the final *ELR* of the development to equal the (lower) *ELR* of the whole biosphere, a larger support area is needed, to dilute the environmental impact of the development. If both calculations are made, a range of support area values is obtained. If the local *ELR* is used, the calculated support area might be considered sustainable at the scale of the local economy and if the global *ELR* is used the support area is globally sustainable.

3. Results

3.1. Inputs driving the electricity production

Fig. 2 shows the energy systems diagram of a 20 MW geothermal power plant, and Table 1 gives a detailed emergy accounting. The same procedure was used for the other plants investigated and details are available on request. An average of 80 ton/hour of hot fluid, at a temperature of 238°C, is extracted from an average depth of 1000 m. Each kg of fluid supplies about 2.8 E6 J of heat to the plant. After the heat has been extracted, most of the water is evaporated through cooling towers, while about 15 ton/hour are re-injected at a temperature of 25°C. Plant operating time is about 7850 hours per year. Chemicals extracted with underground fluid are released to the atmosphere through the cooling towers.

A conventional energy output/input ratio of about 21:1 and an avoided/released CO_2 ratio of 1.4:1 were calculated for this plant. The low avoided/released CO_2 ratio of the geothermal plant is due to a significant amount of CO_2 released from the deep aquifer waters that are used as the steam source and then vented to the atmosphere through the cooling towers. The total release is 655 g CO_2 per kWh.

It is also possible to account for the annual emissions due to construction and maintenance, roughly estimating them from the calculated Energy Ratio. The annual energy input for construction and maintenance would be 1:21 of the total annual electric yield, i.e. 374 ton oil equivalent per year. This would translate into an annual emission of approximately 18 ton SO_2 and 5 ton NO_x (i.e. 0.9 ton SO_2 and 0.02 ton NO_x per MW) due to construction. The environmental services needed to deal with these emissions can be considered negligible, in comparison to those required to deal with direct emissions through the cooling towers (see Table 2). For the sake of simplicity, we did not account for required environmental services due to construction in all of the plants that we have investigated. Our data do include, however, construction materials, source energy, labor and services in construction as well as operation and maintenance, environmental inputs, and process outputs including electricity and pollutants. We do not describe these data in detail, but they are available on request.

Construction inputs divided by plant lifetime, annual operating inputs (labor, maintenance materials, human services), as well as direct and indirect environmental inputs (geothermal heat, water, wind for cooling and dispersal of emissions, etc.), are quantified in Table 1, assigned a suitable transformity and converted to emergy units. The calculated transformity of the geothermal electricity is 1.47E5 seJ/J, also accounting for the emergy supporting human labor and services. As far as the geothermal plant is concerned, the emergy input invested in construction is about 7.15% of total annual emergy; renewable flows (also including geothermal heat) are 84.55%, human labor and services 2.44% and miscellaneous items 5.87%. For comparison, construction inputs of the coal plant are only 0.44% of the total, renewable sources 23.25%; human labor and services 4.56%, fuel 61.41% and miscellaneous items 10.34%.

Table 2 shows the amount of the main emissions of the geothermal and the fossil powered plants, to be used for calculation of the dilution air required, according to Eq. (1). Emissions of the hydroelectric and wind plants are not shown in this table. In fact, they do not release significant amounts of chemicals during their operating phase, and construction-related emissions are negligible. The oil invested in construction, discounted over a 20–25 years lifetime, translates respectively into about 0.1 ton and 0.4 ton SO_2 per Mw per year for the hydro and the wind plant. These figures are absolutely negligible compared to the 26.7 ton SO_2 per Mw per year actually released by an oil powered plant in its operating phase. The same consideration holds for NO_x and other chemicals.

Table 3 provides a comparison among emergy input flows, output flows and indicators of the six plants investigated, under the assumption that legal dilution limits are used for calculation in Eq. (1). Data for the hydroelectric and wind plants are shown in the following tables only for comparison, as these plants have no significant emissions to be diluted. The fossil plants have much higher environmental loading ratio compared to the plants using renewable sources. This higher loading, coupled to a lower yield ratio, translates into a sustainability index lower than 1, while it is higher than 10 in the three renewable plants investigated. Table 4 compares the geothermal and fossil plants when the accepted dilution limit is the background concentration of each chemical.[2] We should be aware that if sustainability is the goal, then the use of background concentration is the true evaluation. Legal limits make a sys-

[2] An overall energy and carbon comparison Table of the investigated plants was shown in Ref. 6. Accounting for the environmental services needed for dilution of pollutants does not change the energy and carbon indicators.

Table 1
Emergy flows in a geothermal electricity production plant. (data on a yearly basis. Plant Cornia 2, sited at Castelnuovo V.C., Pisa, Italy)

#	Item	Unit	Amount	Solar transformity (sej/unit)	Ref. for transf.[a]	Solar emergy
	Items 19, 21, 22 and 23 are free renewable. All other input flows are nonrenewable.					
	PLANT CONSTRUCTION PHASE (inputs are divided by the plant estimated life, 20 years)					
1	Extraction wells, cement	g	5.71E+08	1.20E+09	[a]	6.85E+17
2	Reinjection wells, cement	g	2.85E+08	1.20E+09	[a]	3.43E+17
3	Steam lines:					
	Steel	g	2.79E+07	2.77E+09	[a]	7.73E+16
	Thermal insulating materials (rock wool)	g	3.63E+06	1.50E+09	[g]	5.45E+15
	Aluminium cover	g	1.40E+06	1.63E+10	[d]	2.28E+16
4	Water reinjection lines					
	Glass-fiber reinforced plastic	g	2.43E+06	3.00E+09	[g]	7.30E+15
5	Machinery for exploration, extraction and operation of the steam field:					
	Total machinery weight (steel)	g	0.00E+00	6.70E+09	[a]	0.00E+00
6	Buildings and assets of plant:					
	(a) Miscellaneous					
	Concrete	g	1.54E+08	5.08E+08	[a]	8.00E+16
	Inert stuffing materials	g	3.14E+09	1.00E+09	[b]	3.14E+18
	Epoxivinyl paints	g	2.27E+04	3.00E+09	[g]	6.82E+13
	(b) Construction of the main building for major machinery					
	Carbon and inox steel	g	4.14E+06	2.77E+09	[a]	1.15E+16
	Aluminium	g	1.14E+05	1.63E+10	[d]	1.85E+15
	Epoxivinyl paints	g	9.09E+03	3.00E+09	[g]	2.73E+13
	Glasses	g	3.64E+04	2.28E+07	[a]	8.31E+11
	Thermal insulating materials (rock wool)	g	8.73E+05	1.50E+09	[g]	1.31E+15
7	Steel components of the plant system (support material, valves, steam and water pipes, etc.)					
	Carbon steel	g	3.51E+06	2.77E+09	[a]	9.73E+15
	Inox steel	g	4.76E+06	2.77E+09	[a]	1.32E+16
8	Electric wires					
	Copper	g	7.53E+05	2.00E+09	[d]	1.51E+15
	Electricity insulating material (plastics)	g	4.51E+05	1.50E+09	[g]	6.77E+14
9	Miscellaneous electronic components	g	0.00E+00	2.00E+09	[g]	0.00E+00
10	Electricity	J	1.64E+10	1.47E+05	[e]	2.41E+15
11	Diesel fuel for construction machinery	J	1.94E+11	6.60E+04	[b]	1.28E+16
12	Major components of plant (turbine, generator, etc.):					
	Iron and steel	g	1.54E+07	6.70E+09	[a]	1.03E+17
	Copper	g	3.59E+05	2.00E+09	[d]	7.18E+14
	Pig-iron	g	1.36E+06	8.06E+09	[a]	1.10E+16
	Chromium	g	1.36E+05	1.00E+09	[b]	1.36E+14
	Molybdenum	g	8.98E+03	1.00E+09	[b]	8.98E+12
	Nickel	g	1.22E+05	1.00E+09	[b]	1.22E+14
	Manganese	g	3.83E+03	6.80E+10	[a]	2.61E+14
	Electricity insulating material (plastics)	g	9.09E+03	2.00E+09	[g]	1.82E+13
	Thermal insulating materials (rock wool)	g	1.82E+04	1.50E+09	[g]	2.73E+13
	Lube and insulating oil	J	5.41E+10	6.60E+04	[b]	3.57E+15
	Epoxivinyl paints	g	4.09E+04	3.00E+09	[b]	1.23E+14
13	Transport of plant materials and machinery:					
	Diesel fuel used	J	3.00E+11	6.60E+04	[b]	1.98E+16
14	Human labor and services for construction:					
	Not specialized work force	years	7.13E+00	2.49E+16	[c]	1.78E+17
	Graduated labor	years	4.55E−01	4.98E+16	[f]	2.26E+16

(continued on next page)

Table 1 (*continued*)

#	Item	Unit	Amount	Solar transformity (sej/unit)	Ref. for transf.[a]	Solar emergy
PLANT OPERATING PHASE (inputs are calculated on an annual basis)						
15	Annual electricity input	J	2.53E+13	1.47E+05	[e]	3.73E+18
16	Human labor and services:					
	Graduated	J	2.60E-01	4.98E+16	[f]	1.30E+16
	Technical and administrative	J	1.20E+00	2.49E+16	[c]	2.98E+16
	Not specialized	J	4.17E+00	2.49E+16	[c]	1.04E+17
	Other technical services	J	5.21E+01	2.49E+16	[c]	1.30E+18
17	Maintenance materials					
	Lube oil	J	4.61E+10	6.60E+04	[b]	3.04E+15
	Epoxivinyl paints	g	5.00E+05	3.00E+09	[b]	1.50E+15
	Steel	g	8.00E+05	2.77E+09	[a]	2.22E+15
	Aluminum	g	3.00E+05	1.63E+10	[d]	4.89E+15
	Thermal insulating materials (rock wool)	g	2.00E+05	1.50E+09	[g]	3.00E+14
18	Additional human services for plant manufacture	US $	5.92E+04	1.81E+12	[j]	1.07E+17
ENVIRONMENTAL INPUTS (inputs are calculated on an annual basis)						
19	Geothermal heat	J	2.25E+15	1.49E+04	[h]	3.35E+19
20	Underground water used up	J	2.53E+12	1.82E+06	[h]	4.61E+18
21	Cooling service at towers (wind)	J	1.02E+14	1.50E+03	[b]	1.52E+17
22	Oxygen for combustion processes occurring in the manufacture of components (*)	g	1.22E+09	5.16E+07	[i]	6.32E+16
INDIRECT ENVIRONMENTAL INPUTS (inputs are calculated on an annual basis)						
23	Dispersal of released chemicals (wind) (**)	J	3.50E+13	1.50E+03	[b]	5.26E+16
ANNUAL PRODUCTION OF ELECTRICITY						
24	Electricity delivered	J	3.28E+14	1.47E+05	[h]	4.83E+19

[a] Haukoos, 1995
[b] Odum, 1996
[c] Labor evaluation in the year 1995. [Ulgiati and Russi, unpublished report, University of Siena]
[d] Lapp, 1991
[e] Assumed the value resulting from this plant itself (item 24), by means of iterative calculations.
[f] From [3], assuming that trained labor requires 2 more times emergy inflow than untrained.
[g] Our estimate.
[h] From calculation performed in this work.
[i] Ulgiati and Tabacco, 2001
[j] Emergy intensity in the year 1995 (emergy/GNP, sej/Italian lira converted to seJ/US $) [Ulgiati and Russi, unpublished report, University of Siena]
(*) Oil combustion releases CO_2, but needs a free renewable input of oxygen from the environment. According to the reaction stoichiometry, with a theoretical 100% efficiency, an approximate amount of oxygen equal to 3.25 g is needed to react with one gram of fuel.
(**) Emergy associated with the environmental services for the dilution of combustion emissions down to their biosphere background concentration.

Table 2
Summary of the main emissions from the geothermal and fossil powered plants investigated[a]

	CO_2	SO_2 g/yr	NO_x g/yr	CO g/yr	Unburnt hydrocarbons g/yr	Ash g/yr
Geothermal, 20 MW[b]		1.31E+08			3.50E+09	
Methane, 171 MW	3.32E+11	2.40E+06	9.59E+08	2.50E+02	9.28E+07	6.00E+04
Coal, 1280 MW	7.47E+12	3.85E+10	2.54E+10	1.49E+11	9.26E+08	2.19E+09
Oil, 1280 MW	5.99E+12	3.42E+10	7.33E+09	7.56E+06	3.78E+08	1.82E+09

[a] Indirect emissions from construction phase are not included.
[b] Sulphur emissions as H_2S and hydrocarbon emissions as CH_4.

Table 3
Comparison of emergy-based indicators for electricity production, also accounting for the environmental service that is needed to dilute chemicals released by plant down to legal environmental limits[a]

			Wind (2.5 MW)	Geothermal (20 MW)	Hydro (85 MW)	Methane (171 MW)[b]	Oil (1280 MW)	Coal (1280 MW)
R_1	Direct renewable input	seJ	7.28E+17	3.36E+19	1.69E+19	2.72E+19	3.12E+20	3.68E+20
R_2	Indirect renewable input[c]	seJ	0.00E+00	5.26E+16	0.00E+00	4.72E+17	1.68E+19	1.90E+19
N	Nonrenewable input[d]	seJ	0.00E+00	4.61E+18	4.45E+18	2.68E+20	3.32E+21	3.05E+21
F	Purchased input other than fuel	seJ	1.13E+17	1.00E+19	3.21E+18	5.28E+19	1.13E+21	7.63E+20
Y	Yield (R_1+R_2+N+F)	seJ	8.41E+17	4.83E+19	2.46E+19	3.48E+20	4.76E+21	4.18E+21
Tr	Solar transformity of electricity	sej/J	6.21E+04	1.47E+05	6.23E+04	1.70E+05	2.00E+05	1.71E+05
EYR	Emergy yield ratio, $EYR=Y/(R_2+F)$		7.47	4.78	7.65	6.54	4.14	5.35
ELR	Environmental loading ratio, $ELR=(R_2+N+F)/R_1$		0.15	0.44	0.451	1.791	4.29	10.42
ED	Emergy density, $ED=Y$/area of plant	sej/m2	1.19E+12	1.56E+14	1.59E+13	2.61E+15	2.48E+15	2.18E+15
$\%R$	Percent renewable (R/Y)		86.61%	69.67%	68.84%	7.83%	6.56%	8.79%
EIS	Emergy Index of Sustainability, $EIS=EYR/ELR$		48.300	10.95	16.903	0.55	0.29	0.51

[a] Wind and hydro plants do not have any significant operating emissions to be diluted. They are shown only for comparison.
[b] Our estimate, based on average performance parameters.
[c] Environmental services needed to dilute the chemicals that are released by plant.
[d] Includes the fuel delivered to plant (if any) and other nonrenewable resources (ground water, geologic structure, etc.).

Table 4
Comparison of emergy-based indicators for electricity production, also accounting for the environmental service that is needed to dilute chemicals released by plant down to background concentration of chemicals released[a]

			Wind (2.5 MW)	Geothermal (20 MW)	Hydro (85 MW)	Methane (171 MW)[b]	Oil (1280 MW)	Coal (1280 MW)
R_1	Direct renewable input	seJ	7.28E+17	3.36E+19	1.69E+19	2.72E+19	3.12E+20	3.68E+20
R_2	Indirect renewable input[c]	seJ	0.00E+00	1.57E+19	0.00E+00	3.29E+19	1.03E+21	1.16E+21
N	Nonrenewable input[d]	seJ	0.00E+00	4.61E+18	4.45E+18	2.68E+20	3.32E+21	3.05E+21
F	Purchased input other than fuel	seJ	1.13E+17	1.00E+19	3.21E+18	5.28E+19	1.13E+21	7.63E+20
Y	Yield (R_1+R_2+N+F)	seJ	8.41E+17	4.83E+19	2.46E+19	3.54E+20	5.48E+21	4.97E+21
Tr	Solar transformity of electricity	sej/J	6.21E+04	1.94E+05	6.23E+04	1.73E+05	2.33E+05	2.04E+05
EYR	Emergy yield ratio, $EYR=Y/(R_2+F)$		7.47	1.87	7.65	4.13	2.54	2.59
ELR	Environmental loading ratio, $ELR=(R_2+N+F)/R_1$		0.15	0.90	0.451	12.98	17.52	13.51
ED	Emergy density, $ED=Y$/area of plant	sej/m2	1.19E+12	1.56E+14	1.59E+13	2.65E+15	2.88E+15	2.59E+15
%R	Percent renewable (R/Y)		86.61%	69.67%	68.84%	9.30%	18.75%	23.25%
EIS	Emergy Index of Sustainability, $EIS=EYR/ELR$		48.300	2.07	16.903	0.32	0.14	0.19

[a] Wind and hydro plants do not have any significant operating emissions to be diluted. They are shown only for comparison.
[b] Our estimate, based on average performance parameters.
[c] Environmental services needed to dilute the chemicals that are released by plant.
[d] Includes the fuel delivered to plant (if any) and other nonrenewable resources (ground water, geologic structure, etc.).

tem ‘legally’ sustainable, but this is not a reliable picture, as it is demonstrated by the variability of limits over time, according to accepted policies, public opinion concerns and new scientific findings. Instead, making a plant more sustainable from the point of view of the environment requires the availability of a larger environmental support to the process, translating into an additional load on the environment due to thermal and chemical emissions. As a consequence, the Emergy Index of Sustainability (see below) of the geothermal and fossil plants decreases significantly.

Table 4 shows renewable emergy inputs between 9% and 23% for the three fossil plants. While unexpected, this figure should not be too much of a surprise since the emergy evaluation considers all inputs to processes. While in conventional energy analyses only fossil energy is accounted for as a driving input, other non-energy inputs (cooling service, oxygen) are accounted for in the emergy approach as their basic contribution to the process is also recognized.

Human labor and services are not explicitly shown in Tables 3 and 4, for the sake of simplicity. However, we have already shown [6] that their inclusion increases the emergy yield and the transformity by 3–8%, indicating that the emergy supporting human labor and services is negligible compared to the other emergy inputs to electricity production.

Table 5 summarizes and compares the main emergy-based indicators of the thermal and geothermal plants, according to three different options: (i) no accounting for environmental services to dilute by-products, (ii) accounting for dilution to accepted legal limits, and (iii) accounting for dilution to background concentration as the accepted limit. Clearly the sustainability of a process drops when its demand for environmental support to deal with emissions increases. There are no significant differences among the fossil powered plants, as their efficiency and environmental indicators are of the same order of magnitude. The geothermal plant shows the lowest transformity (1.47 E5 seJ/J) when emissions are not accounted for, signaling a higher conversion efficiency of the overall process. However, when the environmental services to deal with emissions are accounted for, all transformities increase and the methane plant shows the lowest value (1.73 E5 seJ/J), due to the relatively clean combustion of methane. For the same reason, the Emergy Index of Sustainability (*EIS*) of the geothermal plant drops from a high 48:1 to a low 2:1, not much better than the values shown by fossil plants (all less than 1). We might have expected a better performance from the geothermal plant. Its emissions (H_2S, CH_4, Radon…) do not came from combustion processes, they come from deep heat reservoirs. Yet, when these ‘natural’ compounds are moved from underground storage to the atmosphere, they become pollutants and

Table 5
Comparison of emergy indicators for selected power plants in Italy, calculated according to different dilution of emissions by environmental cycles[a]

	Required dilution		
	No dilution of emissions	Thermal and chemical emissions down to legal limits	Thermal and chemical emissions down to natural background
Geothermal			
Transformity (seJ/J)	1.47E+05	1.47E+05	1.94E+05
EYR	7.47	4.78	1.87
ELR	0.15	0.44	0.90
EYR/ELR	48.30	10.95	2.07
Thermal (oil)			
Transformity (seJ/J)	2.00E+05	2.00E+05	2.33E+05
EYR	4.21	4.14	2.54
ELR	14.24	14.29	17.52
EYR/ELR	0.30	0.29	0.14
Thermal (coal)			
Transformity (seJ/J)	1.71E+05	1.71E+05	2.04E+05
EYR	5.48	5.35	2.59
ELR	10.37	10.42	13.51
EYR/ELR	0.53	0.51	0.19
Thermal (methane)			
Transformity (seJ/J)	1.70E+05	1.70E+05	1.73E+05
EYR	6.60	6.54	4.13
ELR	11.78	11.79	12.98
EYR/ELR	0.56	0.55	0.32

[a] Calculated values include the emergy supporting human labor and services.

require dilution and abatement, as it is very well known by the people who live close by.

Finally, it is important to recall that: (i) construction inputs have been divided by plant life time, (ii) operational inputs depend upon annual plant operating time, and (iii) environmental services inputs depend on the way these inputs are supplied (for instance, sea water or river water, for cooling) as well as on plant location (for instance, wind speed may vary: to make comparison easier, we have assumed that wind speed for dispersal of emissions has always the average value of 4 m/s). All these variables may make performance indicators technology, time, and location specific, which is what usually happens with real processes. A performance comparison between several processes can be made and variability avoided by assuming standard conditions as was done in this analysis.

3.2. Support area required for environmental services

Ranges of values for support area (Table 6) were calculated according to Eq. (2), using renewable emergy flows per unit area for Italy, 4.01 E11 seJ/ (m^2 $year^{-1}$), and the whole biosphere, 1.83 E10 seJ/(m^2 $year^{-1}$). The lower values given for each of the support area attributes in Table 6 result from using the renewable emergy flows of the local economy in the calculation; in this case those of Italy. The larger values result from using global renewable emergy flows. Since the land areas of the globe represent areas of considerable convergence of emergy, their empower (seJ/time) and empower density [seJ/(m^2 $year^{-1}$)] are higher than the global average.

Results of our calculations for the geothermal power plant and the coal fired plant, given in Table 6, assume the power plants are the only source of emissions in the area. Addition of other sources, as usually happens, would require an even larger support area. Table 6 clearly shows how available environmental services and land might become limiting factors for human economies, if strict limitations to altering biosphere concentrations of pollutants were applied, instead of legal limits. After all, legal limits sometimes ‘make’ sustainable that which is not.

Data in Table 6 are self-explanatory. However, it may be important to focus on the range of support area per MW, in order to compare the plants on the same basis. The support area of the coal plant is about 5 times larger than that of the geothermal plant when the legal limits to emissions are accepted, but becomes practically the same if emissions must be diluted to their background concentration. This opens a discussion about the meaning of legal and background limits to emissions. Legal limits are originated by the human perception of emissions toxicity and effects. Toxicity may have been inadequately evaluated and limits may be affected by economic and social reasons. Instead, background concentration is the concentration of these compounds in the environment where life evolved and keeps evolving. The two plants (geo and thermal) do not release the same amount of chemicals; these chemicals are found in different concentrations in the environment and their concentration must be considered the most suitable to life evolution. Therefore, comparing the different emissions to their natural background gives a measure of the relationship of these plants to their environment that is independent from human subjective perception (i.e. larger odor means more polluting, etc.).

4. Discussion and concluding remarks

Adopting either the ‘fixing strategy’ or the ‘carrying capacity assessment strategy’, provides a better understanding of the actual contribution of given inputs (also the often neglected environmental inputs) and the global sustainability of production processes. Even if both strategies may depend upon accepted legal limits to concentrations of emissions, knowing more about the emergy costs of environmental services that are required to deal with an accepted amount of emissions may help in mak-

Table 6
Ranges of support areas and related minimum distances from power plant[a], calculated according to Italy (first figure) and World Environmental Loading Ratios (second figure)

	Legal limits to emissions	Background limits to emissions
20 MW geothermal plant		
Range of support area (m^2)	1.31 E5–2.87 E6	3.93 E7–8.60 E8
Range of minimum distance from plant (km)	0.14–0.68	2.50–11.70
Range of support area per MW (m^2/MW)	6.55 E3–1.43 E5	1.96 E6–4.30 E7
1280 MW coal powered plant		
Range of support area (m^2)	4.74 E7–1.04 E9	2.89 E9–6.32 E10
Range of minimum distance from plant (km)	2.75–12.84	21.45–100.28
Range of support area per MW (m^2/MW)	3.70 E4–8.12 E5	2.26 E6–4.94 E7

[a] Minimum distance from power plant is assumed as the radius of a circular area around the plant itself, where no other sources of emissions should be allowed.

ing choices. Sometimes a process that appears more valuable or more desirable when by-products are not considered (business-as-usual strategy), may show a lower global performance and therefore become less desirable when strategies to deal with emissions abatement are adopted.

Adapting to space–time scales of available environmental services may guide decisions regarding appropriate amounts of ecological reserves or wilderness areas, the spacing of large scale developments, or zoning issues as well as other regulations and planning policies. The strategy that is suggested here may be applied to every kind of production process, not only to electricity production.

In its decision making process regarding sustainability of economic growth, society might accept a given value of the Environmental Loading Ratio or a given Emergy Index of Sustainability, coupled with other emergy indicators for a region, and arrange policies that fit these values. To do this, the amount of emergy invested in all economic developments and the environmental services that are needed by them would be quantified resulting in an evaluation of the total amount of production processes that can be allowed in a given area. In so doing, *the focus is moved away from the scale of the individual production process toward a larger, more regional, scale that includes all production activities which usually occur in a territory or even a national economy*.

Decisions regarding trade-offs between the 'fixing strategy' and the 'carrying capacity assessment strategy' are facilitated using emergy measures. If emergy is invested in removing emissions using technology, that emergy will not be available for other processes or to power the economy in general. On the other hand, if environmental services are needed to dilute these same emissions, less production activities can be allowed in the economic system, due to the constraints provided by the requirement of suitable support area and environment. This last constraint might suggest *a landscape policy to deal with the need of providing environmental support to different activities*. Environmental support might become a limiting factor to economic activities, and carrying capacity may ultimately be defined by the ability of the environment to adsorb and recycle wastes rather than its ability to provide needed inputs. If the goal is the ambitious hope to avoid detrimental changes to our life support system, both for reasons of present population health and intergenerational equity, then the global economy may require a gradual downsizing to fit the actual carrying capacity of a region, a national territory, or the planet as a whole.

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