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Journal of Cleaner Production 10 (2002) 321–334

Journal of Cleaner Production

www.cleanerproduction.net

Emergy evaluations and environmental loading of electricity production systems

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Abstract

Six electricity production systems are evaluated using energy and emergy (Environmental Accounting. Emergy and Environmental Decision Making. New York:Wiley, 1996. 370pp.) accounting techniques, in order to rank their relative thermodynamic and environmental efficiencies. The output/input energy ratio as well as the emergy-based emergy yield ratio (EYR) and environmental loading ratio (ELR) have been jointly used to explore and compare system performances. Generation of CO_2 has also been accounted for in order to compare renewable and nonrenewable energy sources. The production systems include both plants using nonrenewable energy sources (natural gas, oil, and coal thermal plants) and the so-called renewable energy sources (geothermal, hydroelectric, and wind plants). A method for evaluating the environmental contribution to electric production is shown to provide important information that can be used to support the environmentally sound public policy. Renewable power plants were characterized by high energy return on investment, while fossil fueled plants exhibited average energy efficiency in the 25–36% range. EYR varied from a high of 7.6/1 for hydroelectric generation to about 4.2/1 for the oil thermal plant. The renewable energy plants required the highest environmental inputs per unit of output while fossil fuel plants required relatively small environmental inputs for cooling and to support fuel combustion. Environmental loading was highest with thermal plants. Using an emergy index of sustainability, it is quantitatively shown how renewable energy source plants like wind, hydroelectric, and geothermal had higher sustainability compared to thermal plants.

Keywords: Emergy analysis; Electric power; Sustainability; Environmental loading

1. Introduction

Net energy evaluations of energy sources and transformation processes are designed to provide information concerning efficiency and potential yield. Numerous authors have called for measures of sustainability to account for renewability and environmental degradation caused by energy sources. Among the most comprehensive analyses that have been published, very interesting results can be found in Ref. [16] where the methodology of Life Cycle Analysis is applied to energy systems, as well as in the Final Report of the ExternE Project to the European Commission (R&D Programmes Joule II and Joule III) performed by a network of European Universities, where a unified methodology for the quantification of the externalities of different power generation technologies is suggested and applied [10]. Until very recently, environmental services used in production processes have not been accounted for, although Ulgiati et al. [26] suggested that environmental inputs and environmental degradation should be carefully evaluated before true, global net energy can be calculated.

Sustainability has become a global issue, apparently, because of two factors: (1) increasing awareness that there are limits to the availability of nonrenewable resources; and (2) increasing awareness that there are limits to the biosphere's ability to adsorb wastes. In this paper we evaluate the amount of environmental sources that are necessary inputs to electric production processes as a component in net energy calculations and evaluations of sustainability. In a companion paper, to be published soon after, we evaluate the environmental services required for the disposal of pollutants [24].

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PII: S0959-6526(01)00043-9

1.1. Net energy

With an increased awareness of global issues stemming from human use of resources, it is increasingly important to reevaluate net energy methodologies. It is important that net energy evaluations include direct and indirect nonrenewable energy, materials, and labor. In addition as we recognize the importance of environmental integrity, environmental inputs to energy production processes should also be accounted for as services performed by the environment. The environment provides free inputs that are necessary for electric production processes. Oxygen for combustion as well as cooling air and water, are vital, required inputs for the thermal power plants. Without oxygen there would be no production and without cooling, efficiencies would rapidly decline and production would eventually stop all together. In addition, dispersal and absorption of emissions from the combustion process are necessary services that are provided by the environment.

Alternative sources of energy, especially those that use the so-called renewable energies of the biosphere are attractive since, on the surface, they seem to provide net energy at little cost in nonrenewable energy use (net energy=energy yield−fossil energy invested) and thus seem to be more sustainable. Yet just relying on renewables for some portion of inputs to energy production processes does not guarantee net energy or sustainability. Net energy calculations should account for use of nonrenewables both directly and indirectly, and also account for environmental renewables that are used at rates that render them nonrenewable.

If net energy is only calculated at the production process and does not include larger spatial and temporal dimensions, it is an incomplete analysis and cannot provide necessary information to public policy decision processes that must take into account these larger scales. An energy source that provides a high thermodynamic net energy at the plant but that pollutes air and water, may have a lower overall global net energy than a process with lower thermodynamic net energy, but which does not degrade the local environment. Some kinds of pollution (here, release of heat and chemicals) are a major concern in the small space–time scale of human dominated systems, while they may not be at larger scales, due to recycling by nature. It therefore seems appropriate to have a consistent space–time scale for policy making regarding energy sources.

1.2. Environmental loading

Environmental inputs to energy production and transformation processes should be accounted for if net energy and sustainability is to have a global dimension. The environment provides free necessary inputs (sometimes on a renewable basis) for electric production systems and is a sink for emissions. Both ‘services’ need to be accounted for if global sustainability of energy sources is to be evaluated and compared.

When a process demands environmental services, it exerts a ‘load’ on the environment. Environmental loading (quantitatively defined in Section 2.4) is the concept that once an environmental service is used by a process, it is not available for another process. In the most general case, the environment has a renewable capacity to support economic processes and human endeavors but in so doing this capacity is used or consumed. If a process consumes all the renewable support function, then the other processes cannot be added to the support base at the same time without seriously degrading the local environment. Thus there is a carrying capacity to economic development [4]. Environmental loading is much like the load on an electrical circuit. When all the available power is consumed, additional loads cannot be added to the circuit without causing an overload.

In the specific case of electric power production there are two different possible avenues of renewable environmental contribution to the process: (1) direct use and conversion of a renewable energy source like wind, elevated water, or geothermal heat; and (2) the consumption of environmental support like oxygen and cool water. In the first case it is easy to visualize that once the source of renewable energy is tapped and being maximally utilized, there is no additional energy left for further exploitation. The contribution from the environment is measured by the emergy of the source, be it wind, elevated water or thermal heat.

In the second case, one form of environmental support toward electric power production is the environment’s renewable capacity for cooling (i.e. being a heat sink, according to the second law of thermodynamics) which represents a necessary input to the process and in turn is a load on the environment. There are two main avenues for cooling thermal power plants, viz. air and water. In both cases what is being consumed by a power plant is the capacity to cool. If, for instance, water from a river or an estuary is used to cool a thermal power plant, it is no longer available for cooling in a second nearby plant since its capacity to cool has been consumed by the first. A measure of the service that the environment provides in this case is the value of the heat that is added to the water, under the assumption that the cooling the water does is in direct proportion to the heat that is added. The same rationale holds for air. We neglect here other cooling pathways, like long wave radiation, for the sake of simplicity.

Among other environmental services, Ulgiati and Tabacco [25] have highlighted the importance of atmospheric oxygen as a vital input to combustion processes.

1.3. Sustainability

Sustainability of energy sources is difficult to measure and is often decided in a qualitative manner assuming that if an energy source relies on renewable energy for a portion of its inputs it must be more sustainable than the one that does not. However, this does not recognize that measures of sustainability need account for renewability as well as for net energy [4]. Some proposed energy sources, biomass for instance, are attractive because it is assumed that since they utilize some renewable energy, they are more renewable than fossil fuel sources. However, when net energy evaluations are incorporated in sustainability judgements of biomass, it is quite apparent that biomass is most often not sustainable, and that the fuels invested in the process of growing and converting biomass to a fuel would give higher net energy if used directly [11,12,23].

The release of greenhouse gases has been suggested as one means of evaluating sustainability of energy sources, where those sources that release fewer gases are more sustainable than the others that release more. Monitoring greenhouse gases may be helpful in addressing environmental concerns related to global warming. However, relying only on CO_2 emissions to measure sustainability ignores net energy and other uses of environmental services that may, in the long run, be far more destructive and threaten human well being than the tons of CO_2 released.

Clearly, judgements of sustainability must include net energy, environmental loading, and production emissions that must be ‘treated and recycled’ by the environment. Ultimately, the carrying capacity of the local and global environment for economic development must be understood and factored into policy discussions of sustainability.

1.4. Emergy valuation

Conventional energy analysis is a well-known approach, and hence we do not provide a description of the methodology here. A more recent method of evaluation, called emergy accounting, uses the thermodynamic basis of all forms of energy and materials (measured by their heat content, mass or energy, i.e. the available energy of each flow relative to the environment), but converts them into equivalents of one form of energy, usually sunlight [19]. Emergy is the amount of available energy of one kind that is required to make something and is used up in a transformation process. For those who are accustomed to thinking in terms of entropy, it may also be considered as a measure of the entropy that has been produced over the whole process [18]. The units of emergy are emjoules, to distinguish them from joules. This distinction is, in principle, required to foster recognition of the quality difference among different forms of energy, which cannot be properly expressed just by their combustion enthalpy. Most often emergy of fuels, materials, services, etc. is expressed in solar emjoules (abbreviated seJ). Emergy then, is a measure of the global processes required to produce something expressed in units of the same energy form. The more work done to produce something, that is, the more is the energy transformed, the higher the emergy value of that which is produced.

To derive the solar emergy of a resource or commodity, it is necessary to trace back through all the resource and energy flows that are used to produce it and express these input flows in the amount of solar energy that went into their production. This has been done for a wide variety of resources and commodities as well as for the renewable energies driving the biogeochemical process of the earth [19]. When expressed as a ratio of the total emergy used to the energy of the product, a transformation coefficient results (called transformity, whose dimensions are seJ/J). As its name implies, the transformity can be used to ‘transform’ a given energy into emergy, by multiplying the energy by the transformity. For convenience, in order to prevent the emergy calculation in resources and commodities every time a process is evaluated, transformities calculated earlier are used. Examples of this procedure are given below, in the case studies that are presented.

There is no single transformity for most products, but usually a range. There is probably a lower limit, below which the product cannot be made, and there is some upper limit above which the process would be not feasible at all, although in theory, one could invest an infinite amount of fuel in a process and thus have an infinitely high transformity. Average transformites are used whenever the exact origin of a resource or commodity is not known or when not calculated separately.

Emergy measures thermodynamic and environmental values of both energy and material resources within a common framework. Transformities provide a quality factor as they account for the convergence of biosphere processes required to produce something. Embodied in the emergy value are the services provided by the environment, which are free and outside the monied economy. By accounting for quality and free environmental services, resources are not valued by their money cost or society’s willingness to pay, which often are very misleading.

2. Methods

Emergy and energy accounting require systems diagrams to organize evaluations and account for all inputs to, and outflows from, processes. Fig. 1 is a systems diagram of a thermal power plant that has been somewhat aggregated, but shows system boundaries that were used

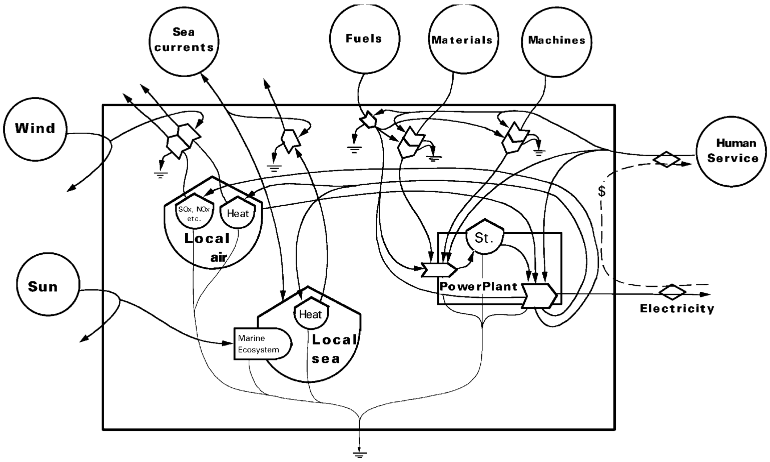

Fig. 1. Energy systems' diagram of a thermal electric power plant. The diagram shows the environmental renewable and nonrenewable inputs to the process, as well as purchased inputs from the economic system. A local air storage, supplying oxygen to and diluting chemicals and heat released by the process, is shown. A local sea water storage, serving as a sink for process heat, is also shown. Environmental inputs of sun, wind and currents from outside the system contribute to the renewal of local storages of air and water.

in the analysis of the six power plants. Evaluation tables of the actual flows of energy, materials, and labor were constructed from the diagrams, eventually aggregating flows for the sake of simplicity. Each input in the diagram is an item to be evaluated in the table. All material, energy, environmental services, and labor were evaluated in their common units (J, kg, m^3, $, etc.). Data from the evaluation tables were used to calculate several indices as a means of comparing the various power plants and lending insight into their overall sustainability. In the following sections, methods of analysis are explained in detail.

2.1. Evaluation of electric power production systems

Data for six electric power production systems in Italy were obtained from research performed in 1996 and updated in the year 2000 for the Italian ENEA — National Agency for New Technologies, Energy and the Environment [8]. Data include construction materials, source energy, labor in construction as well as operation and maintenance, environmental inputs, and process outputs including electricity and pollutants. Data for main plant components were kindly supplied by the Companies producing and operating them. Energy system diagrams were drawn for each production process to organize data collection and to ensure that all necessary data were collected (Fig. 1). Conversion factors used and reference studies from which they have been extracted are clearly listed in each table.

Tables 1 and 2 are given as an example of how energy-, emergy- and carbon-flow calculations are performed. The evaluation tables are for one of the systems evaluated for this study, a 1280 MW oil fired power plant. All plants were analyzed using the same procedures as outlined here. Input data for each item (row) in the evaluation tables were the actual operational data of each plant and were converted into appropriate units using specific calculation procedures, most of which are described in Ref. [19]. Numbered footnotes to the table describe the data sources and calculation procedure. We do not show in this paper the whole set of calculation procedures leading to the results in Tables 1 and 2, however, they are available on request. Input data in Tables 1 and 2 were multiplied by suitable conversion coefficients (unit oil equivalents, for energy evaluation in Table 1; transformities, for emergy evaluation in Table 2), to yield energy and emergy values associated with each input item. Energy values (expressed as grams of oil equivalent) were then converted into grams of released carbon dioxide, by means of an average oil to carbon dioxide conversion coefficient derived from a typical reaction stoichiometry (Table 1). Energy, emergy and CO_2 flows were then summed, yielding a total that is divided by the amount of the product to yield its energy cost, its transformity and its associated carbon emissions. Finally, data are used to calculate other energy-, emergy-, and carbon-flow indicators discussed in the following sections.

Five of the power plants were analyzed in the same manner as the plant described in Tables 1 and 2. The methane fired plant had a discontinuous performance due to technical and management problems during the time frame of the analysis; therefore we estimated its performance by means of average data. All inputs to the electric production systems were expressed on a yearly basis, so total amounts of fixed capital equipment, buildings, etc. were divided by their estimated useful life (25–30 years, depending upon the case). Outputs and electrical production were also expressed on an annual basis. CO_2 production was calculated for direct fuel combustion in thermal plants and estimated for goods and

Table 1
Energy and carbon balance of thermo-electric production in Italy (data on a yearly basis; plant sited at Piombino, Italy)

#	Item	Unit	Units/ha/yr	Oil equivalent (g/unit)	Ref. for equiv.[a]	Oil used up (g/yr)	CO_2 released (g/yr)[b]
Items 27, 28 and 29 (free environmental inputs of solar radiation, cooling water and oxygen from air), as well as items 21, 30, 31 and 35 (labor and services), are not accounted for in the energy and carbon balance.							
PLANT CONSTRUCTION PHASE							
(Goods, energy and labor have been divided by plant lifetime, 30 years)							
1	Concrete	g	3.64E+10	0.07	[f]	2.52E+09	8.11E+09
2	Iron and steel for structure	g	6.17E+08	0.96	[d]	5.89E+08	1.90E+09
3	Insulating materials (rock wool)	g	1.33E+07	2.50	[f]	3.33E+07	1.07E+08
4	Copper electric wires	g	5.26E+06	1.68	[c]	8.83E+06	2.84E+07
5	Diesel transport of material by truck	g	2.22E+07	1.23	[f]	2.73E+07	8.79E+07
6	Steam generators (steel)	g	2.57E+08	3.42	[d]	8.78E+08	2.83E+09
7	Steam condensers (steel)	g	6.27E+07	3.42	[d]	2.14E+08	6.89E+08
8	Pre-heaters for input water (steel)	g	4.12E+07	3.42	[d]	1.41E+08	4.53E+08
9	Pre-heaters for combustion air (steel)	g	3.20E+07	3.42	[d]	1.09E+08	3.52E+08
10	Pumps and valves (steel)	g	1.67E+07	3.42	[d]	5.69E+07	1.83E+08
11	Pipes (steel)	g	3.33E+07	3.42	[d]	1.14E+08	3.67E+08
12	Chimneys, mostly concrete	g	9.33E+08	0.07	[f]	6.47E+07	2.08E+08
13	Electrost. precipitators (steel)	g	2.93E+08	3.42	[d]	1.00E+09	3.23E+09
14	Turbines (steel)	g	6.86E+07	3.42	[d]	2.34E+08	7.55E+08
15	Electric generators (steel)	g	4.67E+07	3.42	[d]	1.59E+08	5.13E+08
16	Electric motors:						
	Steel		1.60E+07	3.42	[d]	5.47E+07	1.76E+08
	Copper		4.00E+06	1.68	[c]	6.71E+06	2.16E+07
17	Electric boards and panels (iron)		3.33E+07	0.96	[d]	3.19E+07	1.03E+08
18	Transformers 370 MVA						
	Steel	g	3.12E+07	3.42	[d]	1.07E+08	3.43E+08
	Copper	g	4.40E+06	1.68	[c]	7.38E+06	2.38E+07
	Cooling oil	g	2.48E+08	1.23	[a]	3.05E+08	9.82E+08
19	Oil storage tanks (steel)	g	0.00E+00	3.42	[d]	0.00E+00	0.00E+00
20	Travelling bridge crane (steel)	g	5.00E+06	3.42	[d]	1.71E+07	5.50E+07
21	Labor and services	yrs	n.a.				
22	Electricity	J	2.40E+12	7.97E−05	[e]	1.91E+08	6.16E+08
23	Diesel for yard machinery	g	4.80E+07	1.23	[f]	5.91E+07	1.90E+08
24	Diesel transport major components	g	4.80E+07	1.23	[a]	5.91E+07	1.90E+08
25	Lubricants	g	1.07E+07	2.00	[f]	2.13E+07	6.87E+07
26	Paints	g	5.00E+05	2.00	[f]	1.00E+06	3.22E+06
PLANT OPERATING PHASE							
Locally available renewable inputs							
27	Solar radiation	J	n.a.				
28	Cooling	J	n.a.				
29	Oxygen for combustion processes	J	n.a.				
Goods and services							
30	Labor						
	Graduated	years	n.a.				
	Technical and administrative	years	n.a.				
	Other technical services	years	n.a.				
31	Labor plant maintenance and other labor from outside	years	n.a.				
32	Currently replaced materials						
	Machinery and electric materials	£	6.39E+09	0.09	[b]	5.97E+08	1.92E+09
	Lubricants	g	2.98E+07	2.00	[f]	5.96E+07	1.92E+08
	Chemicals	g	1.55E+09	2.00	[f]	3.11E+09	1.00E+10
33	Energy for plant operating						
	Electricity	J	n.a.				
	Air conditioning of buildings (electr.)	J	n.a.				
34	Combustion oil	g	1.51E+12	1.23	[a]	1.86E+12	5.99E+12

(continued on next page)

Table 1 (*continued*)

#	Item	Unit	Units/ha/yr	Oil equivalent (g/unit)	Ref. for equiv.[a]	Oil used up (g/yr)	CO_2 released (g/yr)[b]
35	Additional services						
	Additional services for fuel supply	US$	n.a.				
	Additional services for plant manufacture	US$	n.a.				
	Fuel extraction & processing (as oil equiv)	J	already included in the above oil equivalent of fuel				
Electricity production							
36	Annual yield	J	2.35E+16	7.96E−05	[g]	1.87E+12	6.03E+12

[a] **References for equivalents**:

[a] Joules from lube and cooling oil were divided by 41 860 J/g of oil, yielding grams of oil equivalent.

[b] Energy intensity (energy use/GNP) was 3.91 E3 J/£ in Italy in the year 1991 (Ulgiati, 1996 [23]). When divided by 41 860 J/g oil eq., it yields about 0.09 g oil equivalent per Italian £.

[c] Dinesen et al., 1994 [7].

[d] Bowers 1992, p. 119 and p. 121 [3]. The lower figure is raw steel; the higher is manufactured steel.

[e] Assumed that the value resulting from this plant itself (item 36), by means of iterative calculations.

[f] Biondi et al., 1989 [2]; Jarach, 1985 [15]; Pellizzi, 1992, p. 112 [20].

[g] From calculations performed in this work.

[b] CO_2 emissions from oil are calculated according to reaction stoichiometry, assuming a 100% reaction efficiency. Our figure (3.22 g CO_2/g oil used, equal to 76.92 g CO_2/MJ oil) is in good agreement with those provided by Sipila et al., 1993 [21] (75 g CO_2/MJ) and Desmarquest, 1991 [6] (81.70 g CO_2/MJ oil used up, equal to 3.42 g CO_2/g oil used). Therefore: CO_2/oil ratio 3.22g CO_2 per g of oil equivalent

human services using multipliers of indirect energy consumption for their production. These multipliers were derived from a standardized comparison of literature in this field [2,15].

2.2. Energy and CO_2 indices

Two indices commonly used in energy analysis were calculated for the investigated power plants. The first was the output/Input energy ratio (sometimes called energy return of investment, EROI [13]). The second was related to CO_2 production and was the amount of CO_2 released per kilowatt hour of electricity delivered. When applicable, also a ratio of CO_2 released to CO_2 avoided has been calculated, according to the fact that renewable power plants do not require a direct combustion and therefore release a lower amount of CO_2 than a thermal plant for the same electricity output.

Energy analysis typically evaluates energy sources and the outputs from process in their heat equivalents. A ratio of these heat equivalent energies, the energy input/output ratio, is considered as a measure of the first law energy efficiency of a process. In practice it is calculated by dividing the output energy by the input energy. The total input energy in this study was derived by multiplying all goods and materials consumed in the construction (divided by the average life span of the structure and equipment) and the annual maintenance of plants by energy equivalent multipliers, and adding the annual energy consumed directly and indirectly. The output as electricity was converted to joules using the standard conversion of 3.6 E6 J/kW h.

CO_2 releases were evaluated by multiplying the total input energy (sum of energy used directly and indirectly) by a standard conversion, 3.22 g CO_2/g oil equivalent (see Table 1 for details). Renewable energy plants (wind, hydro, and geothermal) obviously do not burn fossil fuels directly, so a net CO_2 benefit was calculated as the CO_2 avoided because the electricity generated from these plants can replace the electricity generated in fossil fuel plants. A CO_2 ratio was calculated by dividing the avoided CO_2 with released CO_2 in nonfossil, where the released CO_2 is the amount of CO_2 released to provide the materials required by the plant.

2.3. Net emergy and emergy yield

Since all forms of energy do not have the same quality [19], evaluations of energy production systems, energy use, or energy disposal should always express energies and materials in common units. Therefore it is common to express energies of different forms as coal equivalents, or thermal equivalents. Environmental services or material inputs to production processes, however, cannot be expressed in thermal equivalents, nor can human labor and services. Yet each of these inputs has an emergy value and should be accounted for when determining the net energy of energy sources. The use of emergy accounting allows the inclusion of all inputs to processes for evaluating net emergy. Once the inputs and output are expressed in units of the same form of emergy they can be compared. They can be added, subtracted, multiplied and divided. Whereas, different forms of energy and materials without transformation cannot be added (for instance try adding joules of coal to cubic meter of water, or hours of labor). By definition of emergy, the output of a process is assigned the total emergy input driving the process itself. Total emergy

Table 2
Emergy accounting of thermoelectric electricity production in Italy (data on a yearly basis; power plant sited at Piombino, Italy)

#	Item	Unit	Amount	Solar transformity (sej/unit)	Ref. for transf.[a]	Solar emergy
	Items 27, 28 and 29 are free renewable. All other input flows are not renewable.					
	PLANT CONSTRUCTION PHASE					
	(Goods, energy and labor have been divided by plant lifetime, 30 years)					
1	Concrete	g	3.64E+10	5.08E+08	[a]	1.85E+19
2	Iron and steel for structure	g	6.17E+08	2.77E+09	[a]	1.71E+18
3	Insulating materials (rock wool)	g	1.33E+07	1.50E+09	[h]	2.00E+16
4	Copper electric wires	g	5.26E+06	2.00E+09	[d]	1.05E+16
5	Diesel transport of material by truck	J	9.87E+11	6.60E+04	[b]	6.51E+16
6	Steam generators (steel)	g	2.57E+08	2.77E+09	[a]	7.12E+17
7	Steam condensers (steel)	g	6.27E+07	2.77E+09	[a]	1.74E+17
8	Pre-heaters for input water (steel)	g	4.12E+07	2.77E+09	[a]	1.14E+17
9	Pre-heaters for combustion air (steel)	g	3.20E+07	2.77E+09	[a]	8.88E+16
10	Pumps and valves (steel)	g	1.67E+07	2.77E+09	[a]	4.62E+16
11	Pipes (steel)	g	3.33E+07	2.77E+09	[a]	9.23E+16
12	Chimneys (mostly concrete)	g	9.33E+08	5.08E+08	[a]	4.74E+17
13	Electrost. precipitators (steel)	g	2.93E+08	2.77E+09	[a]	8.13E+17
14	Turbines (steel)	g	6.86E+07	2.77E+09	[a]	1.90E+17
15	Electric generators (steel)	g	4.67E+07	2.77E+09	[a]	1.29E+17
16	Electric motors					
	Steel	g	1.60E+07	2.77E+09	[a]	4.43E+16
	Copper	g	4.00E+06	2.00E+09	[d]	8.00E+15
17	Electric boards and panels (iron)	g	3.33E+07	2.77E+09	[a]	9.23E+16
18	Transformers 370 MVA					
	Steel	g	3.12E+07	2.77E+09	[b]	8.64E+16
	Copper	g	4.40E+06	2.00E+09	[d]	8.80E+15
	Cooling oil	J	3.81E+11	6.60E+04	[b]	2.51E+16
19	Oil storage tanks (steel)	g	0.00E+00	2.77E+09	[a]	0.00E+00
20	Travelling bridge crane (steel)	g	5.00E+06	2.77E+09	[a]	1.39E+16
21	Labor and services	years	3.47E+02	2.49E+16	[c]	8.65E+18
22	Electricity	J	2.40E+12	1.85E+05	[g]	4.44E+17
23	Diesel for yard machinery	J	2.13E+12	6.60E+04	[b]	1.41E+17
24	Diesel for transp. major components	J	2.54E+11	6.60E+04	[b]	1.67E+16
25	Lubricants	J	4.91E+11	6.60E+04	[b]	3.24E+16
26	Paints	g	5.00E+05	1.50E+09	[h]	7.50E+14
	PLANT OPERATING PHASE					
	Locally available renewable inputs					
27	Solar radiation	J	1.06E+16	1.00E+00	[b]	1.06E+16
28	Cooling					
	Absorption of heat released	J	2.91E+16	9.63E+02	[b]	2.80E+19
	Plankton in marine cooling water	J	4.80E+13	1.90E+04	[h]	9.12E+17
	Cooling service at chimney (wind)	J	4.53E+13	1.50E+03	[b]	6.79E+16
29	Oxygen					
	Oxygen associated to fuel extraction and refining	g	1.13E+12	5.16E+07	[f]	5.85E+19
	Oxygen associated to combustion processes and manufacture of components[b]	g	4.95E+12	5.16E+07	[f]	2.55E+20
	Goods and services					
30	Labor and services:					
	Graduated	years	8.00E+00	7.47E+16	[c]	5.98E+17
	Technical and administrative	years	1.00E+02	4.98E+16	[c]	4.98E+18
	Other technical services	years	1.97E+02	2.49E+16	[c]	4.91E+18
31	Labor plant maintenance and other labor from outside	years	1.00E+02	4.98E+16	[c]	4.98E+18
32	Currently replaced materials:					
	Machinery and electric materials	US$	3.12E+06	1.22E+12	[e]	3.80E+18
	Lubricants	J	1.37E+12	6.60E+04	[b]	9.06E+16
	Chemicals	g	1.55E+09	3.80E+08	[b]	5.91E+17

(continued on next page)

Table 2 (*continued*)

#	Item	Unit	Amount	Solar transformity (sej/unit)	Ref. for transf.[a]	Solar emergy
33	Energy for plant operating:					0.00E+00
	Electricity	J	0.00E+00	1.85E+05	[g]	0.00E+00
	Air conditioning of buildings (electr.)	J	0.00E+00	1.85E+05	[g]	0.00E+00
34	Combustion oil	J	6.14E+16	5.40E+04	[b]	3.32E+21
35	Additional services and investments					
	Additional services for fuel supply	US$	2.38E+08	1.22E+12	[e]	2.90E+20
	Additional services for plant manufacture	US$	1.69E+06	1.22E+12	[e]	2.07E+18
	Fuel extraction and processing (as oil equiv)	J	1.46E+16	54 000	[b]	7.87E+20
Electricity production						
36	Annual yield, with labor and human services	J	2.35E+16	2.00E+05	[g]	4.70E+21
	Annual yield, without labor and services	J	2.35E+16	1.87E+05	[g]	4.39E+21

[a] **References for transformities**:
[a] Haukoos, 1994 [14].
[b] Odum, 1996 [19].
[c] Labor evaluation, year 1995 (Ulgiati and Russi, unpublished work, 1997).
[d] Lapp, 1991 [17].
[e] Emergy intensity, year 1995 (emergy/GNP; sej/Italian £ converted to seJ/US$) (Ulgiati and Russi, unpublished work, 1997).
[f] Ulgiati and Tabacco, 2001 [25].
[g] This work, final result of calculations.
[h] Our estimate.

[b] Crude oil equivalent needed for production of components as well as for combustion in the power plant is evaluated in Table 1. 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 as oil equivalent.

assigned to the output is called emergy yield, *Y*, and calculated as the sum of renewable (*R*), nonrenewable (*N*) and purchased feedback flows of goods and human services from the economy (*F*).

Net emergy of any process is the Emergy Yield minus the investments (*F*, also expressed in emergy) to obtain it. These investments include all the inputs from the economy (materials, machinery, and human services). Net emergy accounts for all emergy requirements (inputs) to a production process including environmental contributions and energies used directly and indirectly for goods, materials and human services in construction, operation and maintenance of the production system.

2.4. Emergy indices

Several indices calculated for each power plant are based on flows illustrated in Fig. 2. The aggregated diagram shows the main inputs and outputs (lettered pathways) of electric production systems. The electricity production system is shown within a larger regional area. Evaluations of the production systems are based on the flows that cross the boundary of the smaller rectangle. Two types of environmental resources are used by the power plants: (1) renewable resources composed of sunlight, wind, or rain falling directly on the plant site (R_1); and (2) cooling water and air (the latter also supporting combustion) used by the plant in the production of electricity (R_2). Nonrenewable environmental resources (*N*)

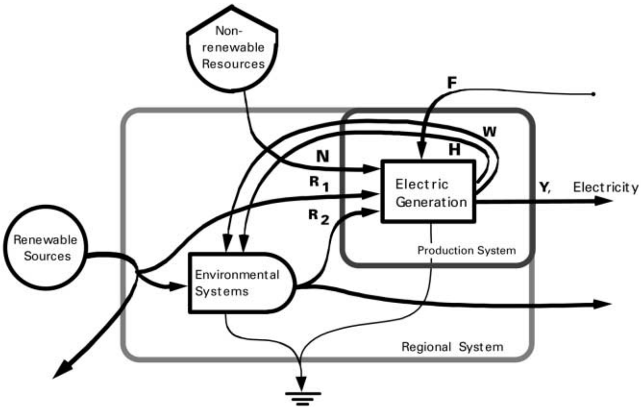

Fig. 2. Aggregated energy systems diagram of an electric power plant, with main inputs and outputs shown and used to calculate performance emergy based indicators. Legends: R_1=renewable inputs directly falling on the plant site (sun, wind, rain); R_2=renewable inputs supplied by the local ecosystem and used by the plant in the production of electricity (cooling water and air, oxygen for combustion); *R*=locally renewable input to the process=max(R_1; R_2) as these inputs are driven by the same (solar) source; *N*=nonrenewable inputs (such as coal, oil, and natural gas or groundwater that is used faster than it is recharged); *F*=goods and services from the economy (*F*) that are used to construct, operate, and maintain the power plant (construction materials, machinery, general supplies, human services, etc.); *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); *H*=Heat released by the power plant to the atmosphere and the cooling water.

such as coal, oil, and natural gas or groundwater that is used faster than it is recharged are shown as entering the production process from the storage at top. Also shown are the flows of goods and human services from the economy (*F*) that are used to construct, operate, and maintain the power plant. These include construction materials, machinery, general supplies, and human services. The electrical output (*Y*) is the yield of the process, to which the total emergy input is assigned. Also shown are the co-product outputs of pollutants (*W*) and concentrated heat (*H*). Referring to Fig. 2, the emergy indices calculated for each plant include the following:

Emergy yield ratio, $\mathrm{EYR}=Y/F=(F+R+N)/F$

Environmental loading ratio, $\mathrm{ELR}=(F+N)/R$

Emergy index of sustainability, $\mathrm{EIS}=\mathrm{EYR}/\mathrm{ELR}$

Empower density, $\mathrm{ED}=(F+R+N)/\mathrm{area}\ldots$(empower is emergy per unit time)

Percent renewable, $\%R=R/(\mathrm{F}+\mathrm{R}+\mathrm{N})$

The emergy yield ratio (EYR) provides insight into the net benefit of the various production processes to society. In fact, the higher the fraction of locally available energy sources ($R+N$) that are exploited by means of the investment *F* from outside, the higher the value of this indicator. It measures the ability of the process to rely on local resources. The EYR does not make any difference between renewable and nonrenewable flows, but only between local and imported (purchased or ‘invested’) emergy flows. We have discussed the EYR and its definition and use in Ref. [26].

The environmental loading ratio (ELR) can provide additional information to EYR. It expresses the use of environmental services by a system. Environmental service is measured as the emergy of that portion *R* of the environment that is ‘used’. When EYR is high due to a high value of local renewable resources, then ELR is small, thus indicating a small environmental stress. On the contrary, when a high value of local nonrenewable sources contributes to EYR, then ELR increases, thus suggesting a larger environmental stress. Therefore, a simultaneous increase of both EYR and ELR, indicates that a larger stress is being placed on the environment; on the contrary, when EYR increases and ELR decreases, the process is less of a load on the surrounding environment. More details on ELR and its use in carrying capacity assessments are given in Ref. [5].

As we are interested in getting the highest yield ratio versus the lowest environmental loading, a measure of this ability is provided by the ratio EYR/ELR. This ratio has been termed as emergy index of sustainability (EIS) and is an aggregate measure of yield and environmental loading, i.e. a sustainability function for a given process (or economy) under study [4].

Empower density of a process provides an indication of the relative intensity. Empower is emergy per unit time, and empower density is emergy per unit time per unit area.

Percent renewable is a relative measure of ‘renewability’ of a process and provides insight into one aspect of sustainability; the proportion of the total emergy required for a process that is derived from renewable sources.

3. Results

All the six power plants were evaluated using tables like those for the fossil fuel plant given in Tables 1 and 2. For want of space, we do not include these tables, but results of the energy and emergy evaluations of the systems are given in Tables 3 and 4.

3.1. Energy indicators of electricity production

Energy indicators (which include only fossil energies) of total energy produced, total energy invested, and energy ratio (ER) (output/input) are given in Table 3. The energy output to input ratio is less than 1 for fossil fuel plants and greater than 1 for the renewable energy plants, as expected. The hydroelectric and geothermal plants have the highest energy output to input ratios (23.81/1 and 20.83/1, respectively). Among fossil fired plants, the methane plant performs best (ER=0.36), while the coal plant shows the lowest ratio (0.25). Also given in Table 3 are data and ratios for CO_2 release. CO_2 release includes not only fossil fuels burned directly, but also those burned indirectly in support of the goods and human services used by plants. The high CO_2 release from fossil fired plants was expected and follows the national average (from a high 1109 g CO_2/kW h delivered in the coal plant to a lower 759 g CO_2/kW h in the methane plant). The geothermal plant also releases a significant amount of CO_2 (655 g CO_2/kW h) from the deep aquifer waters that are used as the steam source and then vented to the atmosphere through the cooling towers. Consequently, the hydroelectric and wind plants have the highest ratio of CO_2 avoided per CO_2 released (by substituting electricity produced for conventionally generated fossil fuel derived electricity).

3.2. Emergy indicators of electricity production

Table 4 lists the emergy indicators for the six plants. The first five rows in the table are the renewable, nonrenewable and purchased input flows, including human services, labor, and economic investment. Emergy yield of electricity is by definition, the sum of the emergy required to produce it, and is shown in the two rows, with and without the inclusion of human labor and ser-

Table 3
Comparison of energy based indicators and carbon dioxide flows for electricity production (n.a.: not applicable)[a]

	Wind (2.5 MW)	Geothermal (20 MW)	Hydro (85 MW)	Methane (171 MW) (*)	Oil (1280 MW)	Coal (1280 MW)
Total electric energy produced per year (J)	1.35×10^{12}	3.28×10^{14}	3.94×10^{14}	2.05×10^{15}	2.35×10^{16}	2.44×10^{16}
Total energy invested per year (J)	1.76×10^{11}	1.58×10^{13}	1.66×10^{13}	5.61×10^{15}	7.84×10^{16}	9.78×10^{16}
CO_2 released (g)	1.36×10^{7}	5.98×10^{10}	1.27×10^{9}	4.32×10^{11}	6.03×10^{12}	7.53×10^{12}
CO_2 released/electricity produced (g/kW h)	36.15	655.08	11.63	759.48	923.19	1109.82
CO_2 avoided, by replacing oil in thermal plants (g)	3.39×10^{8}	8.25×10^{10}	9.91×10^{10}	n.a.	n.a.	n.a.
Energy ratio (out/in)	7.66	20.83	23.81	0.36	0.30	0.25
CO_2 ratio (avoided/released)	25.02	1.38	77.752	n.a.	n.a.	n.a.

[a] Our estimate, based on average performance parameters.

Table 4
Comparison of emergy flows and emergy based indicators for electricity production

		Wind (2.5 MW)	Geothermal (20 MW)	Hydro (85 MW)	Methane (171 MW)[a]	Oil (1280 MW)	Coal (1280 MW)
R	Renewable input	7.28×10^{17}	3.36×10^{19}	1.69×10^{19}	2.72×10^{19}	3.12×10^{20}	3.68×10^{20}
N	Nonrenewable input[b]	0.00×10	4.61×10^{18}	4.45×10^{18}	2.68×10^{20}	3.32×10^{21}	3.05×10^{21}
F	Purchased input other than fuel	1.13×10^{17}	1.00×10^{19}	3.21×10^{18}	5.28×10^{19}	1.13×10^{21}	7.63×10^{20}
Y	Yield (R+N+F)	8.41×10^{17}	4.83×10^{19}	2.46×10^{19}	3.48×10^{20}	4.76×10^{21}	4.18×10^{21}
Tr_1	Transformity, with human labor and services	6.21×10^{4}	1.47×10^{5}	6.23×10^{4}	1.70×10^{5}	2.00×10^{5}	1.71×10^{5}
Tr_2	Transformity, without human labor and services	5.89×10^{4}	1.42×10^{5}	5.87×10^{4}	1.60×10^{4}	1.87×10^{5}	1.62×10^{5}
EYR	Emergy yield ratio, EYR=$(R+N+F)/F$	7.47	4.81	7.65	6.60	4.21	5.48
ELR	Environmental loading ratio, ELR=$(N+F)/R$	0.15	0.44	0.45	11.78	14.24	10.37
ED	Emergy density, ED=(Y_S)/area of plant, seJ/m^2	1.19×10^{12}	1.56×10^{14}	1.59×10^{13}	2.61×10^{15}	2.48×10^{15}	2.18×10^{15}
%*R*	Percent renewable, (R/Y_S) (%)	86.61	69.67	68.84	7.83	6.56	8.79
EIS	Emergy index of sustainability, EIS=EYR/ELR	48.300	11.048	16.903	0.560	0.295	0.529

[a] Our estimate, based on average performance parameters.

[b] Includes the fuel delivered to plant (if any) and other nonrenewable resources (ground water, geologic structure, etc.).

vices. The ratio of yield to purchased inputs (EYR) is highest for the hydroelectric plant (7.65/1) followed by the wind system (7.47/1). The other plants (geothermal, methane, oil and coal) show lower EYR. The oil fired plant ranks last with an EYR=4.21/1. The geothermal system also shows a very low EYR (4.81/1), indicating a high emergy content of the resources invested from outside.

The solar transformity of the product is calculated as the ratio of the total emergy inputs to the energy of the electricity output. Transformities for wind and hydroelectric production were the lowest (5.89 and 5.87 E4 seJ/J, respectively) and are probably close to the thermodynamic minimum transformity for electricity production cycles. The transformity for electricity generated in fossil fuel plants (in the range of 1.60–1.87 E5 seJ/J) as well as the transformity of the geothermal cycle (1.42 E5 seJ/J) were over twice the transformity of the electricity generated in the wind and hydro plants. When the emergy supporting human labor and services is accounted for, transformities show an increase roughly between 4 and 15%. The values calculated without services are strictly linked to the physical and technological reality of the fuel and the plant investigated, while the fraction depending on labor and services is more affected by the economic level of a given country and may show changes accordingly.

The environmental loading is very high for the fossil fuel plants, which have ELR's between about 11.37/1 (coal) and 14.24/1 (oil). The renewable energy systems have the lowest environmental loading, all less than 1.0. The loading ratio of the coal plant appears slightly lower than the methane and oil plants. This should not be surprising, if we consider that oil and methane are fuels with higher transformity, compared with coal, therefore increasing the value of *N*, the nonrenewable emergy input. As the loading ratio is a measure of matching between the nonrenewable (and purchased) fractions and the renewable one, a higher *N* makes the loading ratio rise, signaling that the system presents an exceeding pressure of the nonrenewable fraction to the locally renewable emergy input.

The empower density (Table 4) is a measure of the intensity of activity and is evaluated as the total empower per unit area (seJ/m^2). Fossil fuel plants had the highest empower densities (range of 2.18–2.61 E15 seJ/year/m^2). In general, the empower densities of the renewable energy source plants were 1–2 orders of magnitude lower.

The renewable fraction (percent renewable, Table 4) is an index that relates renewable inputs to total inputs for a process. The wind, geothermal, and hydro plants had the highest percent renewable inputs (86.61, 69.67, and 68.84%, respectively). Instead, less than 10% of the required inputs to fossil fuel plants come from renewable sources (within the 6.56–8.79% range). It may appear surprising that a nonnegligible fraction of inputs to thermal plants is renewable, since often the fuel is considered as the only driving force of the process. This also happens at the global level of most neoclassical economic analyses, where the environment is very often not accounted for. As already stressed, the oxygen supply is a significant input to the combustion process. Oxygen is continuously cycled by the photosynthetic activity of green plants, driven by solar radiation. Also the cooling service from river or sea water as well as from wind are vital renewable inputs to a plant activity.

Values of the EIS are given in the last row of Table 4. The EIS is a ratio of the emergy yield per unit environmental load. Plants with high yields and low environmental loads have the highest EIS. The wind power plant had an EIS of 48.30/1, the highest of the renewable energy plants, followed by the hydroelectric plant (16.90/1) and the geothermal plant (11.05/1). The fossil fuel plants always show EIS's of less than 1.0 (methane ranking first, followed by coal and oil).

4. Discussion

As the limits to available energy supplies are increasingly felt, and issues of sustainability continue to occupy the forefront of the policy arena it will become increasingly important to develop energy policies, suggest regulations, and incorporate financial tools that favor or penalize the existing power generation facilities as well as make intelligent decisions regarding future facilities. To make these decisions, policy makers will have to rely on suitable indicators. Yet, indicators may present many problems and be a source of misunderstandings, when used for policy. In fact, they usually highlight only one side of a process, so that wrong or insufficient strategies might be inferred. Data in Tables 3 and 4 may help clarify this issue, assuming that our figures represent the average behavior of other similar power plants (which they actually do, in the Italian situation).

4.1. Complementarity and synergy of approaches

Output/input energy ratios only offer a first Law picture. Maximizing the output energy flow versus the input flow allows a technical feasibility evaluation of the energy conversion process, with no clear reference to the quality of input and output flows. In Table 3, methane appears to offer a better performance than oil or carbon, while the hydroelectric plant shows the best ratio among all the facilities investigated, followed by the geothermal and the wind plants. Optimizing a plant based upon the second law of thermodynamics might be obtained by means of energy evaluation procedures, that are not dealt with in this paper (Refs. [1,22] among others). However, technical feasibility and optimization are not the only parameters that must be assessed for sustainable energy planning.

An environmentally sound policy does not necessarily need a very high return on energy investment, even if this is certainly desirable. Lower emissions of pollutants are also a necessary requisite. CO_2 emissions are believed by many to be a serious cause of global warming. If the CO_2 concern is to be accounted for, then, while the geothermal plant has high renewability, it still has a high CO_2 release, much more than the hydroelectric and wind plants and not very far from the values of fossil plants. Furthermore, a good equilibrium with the surrounding environment is not just a matter of emissions. It is also measured by the amount of the biosphere total productive processes are used. Processes in the biosphere (and human driven activities as well) are supported by flows of solar emergy (energy and resources measured in the same unit, seJ). As already pointed out, the flow of emergy supporting the production of 1 J of a given flow or storage has been called transformity. It is a measure of the required environmental support, also called 'ecological footprint' by other authors. Transformities in Table 4 show that wind and hydroelectric plants demand a very low environmental support, while the other plants require more than twice this amount. Additional information comes from the empower density, measuring the pressure of the emergy investment per unit of area. Again, wind and hydro cycles in comparison to alternatives show a lower pressure on land.

At this point of the analysis, a concerned policy maker might decide to address incentives and financial investments towards renewable hydroelectric and wind technologies. If he had to choose only among fossil cycles, then he could favor methane, as this cycle shows the best energy ratio, the lowest CO_2 emissions, and the lowest demand for environmental support among the fossil plants.

However, it is possible to move one or two steps further ahead, and complete our evaluation by means of an emergy-based measure of sustainability. We have already emphasized that the EIS offers an aggregated measure of yield and environmental loading, which may be a very useful complement to the previously discussed parameters. As already pointed out, the wind plant offers a very high EIS value, even in comparison with the hydroelectric and geothermal plants. We would therefore be able to assign to wind technology some kind of advantages, to reward its longer term sustainability.

An overall view of all these parameters might be a very satisfactory basis for energy policy and decision making regarding investments. Facilities showing an acceptable return on the energy investment after the application of energy and energy optimization procedures should be checked for environmental sustainability (carbon dioxide release, demand for environmental support, land as limiting factor). Finally, a global measure of economic and environmental compatibility would easily complement for best planning.

4.2. Renewable sources to power plants

The major renewable inputs to the fossil fuel plants are oxygen for combustion and water and air for cooling, which account for less than 10% of required inputs. These are necessary inputs to the generation systems for: (i) without environmental cooling plant efficiency would rapidly decline and eventually plants would cease to operate; (ii) furthermore, without atmospheric oxygen no combustion occurs. Oxygen supply is a vital input, but does not appear to be a limiting factor. However, recognizing oxygen as a driving force is useful to calculate the correct values of emergy-based parameters and indicators in order to rank their thermodynamic position within the biosphere hierarchy.

As the environment's capacity to absorb heat is limited each plant represents a load on the environment. Therefore the density of power plants can never exceed the ability of the environment to absorb generated heat. A sustainable pattern of power plant siting must balance the generation of heat and the environment's ability to recycle it.

In the so-called renewable power plants, the use of environment is in the form of direct conversion of the energy in wind, elevated water, and deep hot water, to electricity. As might be expected, the renewable portions of the wind, geothermal, and hydroelectric plants are quite high (86.61, 69.67 and 68.84%, respectively). The high emergy yields derived from these renewable sources, provide more to the economy per unit of investment, but unfortunately there are a very limited number of sites where these power generation systems can be located in Italy. The hydroelectric production in Italy only covers 10–12% of the total electric production, and no other suitable sites are easily available [9]. It is also estimated, that if all areas that are suitable for wind generation of electricity in Italy (wind speed within acceptable range, easy access, lack of constraints due to aesthetic concerns, etc.) were capitalized upon, only about 6000 MW of power could be generated. This would represent about 11% of current national electric installed power, while less than 0.5% is presently covered by wind generators.

4.3. Emergy indices

In this paper, we have suggested the use of several indices based on emergy evaluations of processes and economies to evaluate their net contributions and their relative sustainability for the future, to complement the existing energy and monetary indicators. Like any index these are relative measures that require comparison between differing situations and processes so that perspective is gained.

From past experience, we believe that EYR's less than about 5 are indicative of secondary energy sources (not primary energy sources) and primary materials like cement and steel. Primary energy sources usually have EYR's greater than 5. Further, processes that yield products with EYR's less than 2 probably do not contribute enough to be considered an energy source, and act more as consumer products or transformation steps than actual energy sources.

We are just beginning to explore the relative scale of ELR. Again from past experience, it appears that low ratios (around 2) are indicative of relatively low environmental impacts (or processes that use a large area of a local environment to 'dilute impacts'). ELR's greater than 10 are indicative of relatively concentrated environmental impact, and those between 3 and 10 might be considered moderate. Extremely high ELR's might result from the investment, in a relatively small local environment, of very concentrated inputs derived from nonrenewable energies.

The EIS is a relatively new index. As a relative measure, EIS's of less than 1 appear to be indicative of products or processes that are not sustainable in the long run and those with ratios greater than one indicative of products and processes that are sustainable contributions to the economy. Medium run sustainability seems to be characterized by EIS's between 1.0 and 5.0, while processes and products with long range sustainability have EIS's accordingly greater.

Finally, it is worth emphasizing that, despite the fact that these six power plants are different in technology and size, most of the indices and indicators are surprisingly similar within the two groups of renewable and nonrenewable plants. For instance, the transformities of the wind and hydro plants are identical. The same occurs with the Percent renewable values of the geothermal and hydro plants, while those of the fossil plants are not very different. Other similarities can be easily found among the fossil plants, despite the fact that they are driven by three different fuels. In conclusion, very tiny differences are shown by plants within each group, while the two groups differ very significantly from each other. This outcome was more or less expected, but the fact that it can be quantitatively assessed to this extent is a very significant result of the approach.

5. Summary and conclusions

Evaluation of the net contributions to the economy that are made by energy sources should account for all energy inputs including environmental services for which there is a finite capacity. Also, each input must be evaluated according to its quality, i.e. the convergence of environmental work to provide it. The inclusion of many different forms of energy in net yield evaluations requires that they be expressed in the same or equivalent energy form so that they may be combined and compared on an equivalent basis. Emergy evaluation generates equivalency in units of emergy. In this study data from six different Italian electric power plants were evaluated using emergy accounting, as a complementary approach to other more widely used methodologies.

Calculated emergy indices of thermodynamic efficiencies indicated that wind generation and hydroelectric power plants have the highest EYR, while the oil fired power plant was the lowest. A calculated index of environmental loading indicated quantitatively that electricity generated using wind, geothermal, and hydro power plants had the lowest environmental impact, while fossil fired plants the highest, as might be expected. Finally, an emergy-based index of sustainability indicated that the wind and hydroelectric plants had the highest-over-all aggregated (economic and ecological) sustainability, followed by geothermal electricity.

We must be aware that economies are unlikely to stop using these thermal conversion plants for electricity generation in the near term future. The use of emergy-based indicators to monitor changes of performance and technological improvements in some or in all of the steps of the conversion processes could be an additional policy tool. Coupled with other evaluation indicators the emergy-based indicators would form the basis for a qualitative and quantitative assessment of electricity production pathways, in order to determine use and appropriate investments.

Policy decisions concerning energy use and investments in energy technology require that decision-makers have the ability to compare wholistically net yields, environmental impacts, and sustainability. First law energy evaluations offer a tool to assess the thermal energy cost of the produced electricity, while second law energy evaluations may offer an appropriate tool for performance optimization at the local scale of the plant. However, in the larger scale of energy planning, it is not enough to evaluate energy in its thermal equivalents, and compare the outputs to inputs to make decisions concerning energy use and investments. Since all energy sources have environmental impacts and require free environmental services, the contributions of the environment must be included. Without such their inclusion, energy decisions consider only a portion of the real costs, and cannot realistically compare the net benefits of sources; much less compare them on the basis of sustainability.

Acknowledgements

This research was supported by a research contract from Italian ENEA, National Agency for New Technology, Energy and the Environment, that the authors gratefully acknowledge. Data on power plants have been provided by: (i) the 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), whose collaboration the authors gratefully acknowledge. The authors also acknowledge valuable scientific comments from contract supervisor Corrado Giannantoni (ENEA). Data, suggestions, and support also came from: (i) ENEL (the National Electric Company), through Franco Luccioli, Roberto Iachetta, Giancarlo Passaleva, Aldo Linari, Franco Paulet, Mauro Maxia, Gianfranco Andreoli, Franco Rancati, Guido Giraldi, Sergio Santoni, Gianmaria La Porta, Ezio Vidoli, Fabrizio Fiorani, Carlo Menichelli, Emo Sartini, Giovanni Salvietti, Franco Capuozzi; (ii) ENEA, through Luciano Barra and Aldo Li Causi; (iii) Riva Calzoni S.p.A. (Bologna), through Mario Rosnati, Guido Baldi and Dario Command; (iv) AEM (Azienda Energetica Municipalizzata, Torino), through Angelo Quaglia and his engineering and technical staff; (v) AGIP-Eurosolare, through Daniele Margadonna; and (vi) Paolo Frankl and Andrea Masini (University of Roma ‘La Sapienza’, Italy). The opinions expressed by the authors of this paper do not necessarily match the opinions and the energy policy of the above cited persons and Companies.

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