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Energy and eMergy evaluation of bioethanol production from wheat in Henan Province, China

Xiaobin Dong [a], Sergio Ulgiati [b], Maochao Yan [c,d], Xinshi Zhang [a], Wangsheng Gao [c,*]

[a] State Key Laboratory of Earth Surface Processes and Resource Ecology, College of Resources Science and Technology, Beijing Normal University, Beijing 100875, China
[b] Department of Sciences for the Environment, Parthenope University of Napoli, Napoli 80133, Italy
[c] College of Agronomy and Biotechnology, China Agriculture University, Beijing 10094, China
[d] Institute of Geographical Sciences and Natural Resource Research, CAS, Beijing 100101, China

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ABSTRACT

Ethanol production from wheat has become an emerging economic activity in Henan Province due to the establishment in 2001 of the National Program for Alcohol Production. The program aimed at facing the unfolding world energy crisis in the near future and increasing China's energy security. Instead, in spite of claims for "green energy", such an activity is likely to generate great environmental damage and social problems. Moreover, the international market prices for raw materials (especially cereals) and fossil oil are putting this activity under siege. This research presents an energy and eMergy analysis of a typical wheat plantation/alcohol distillery system, in the Henan Province. Comparison is drawn with bioethanol production in Italy, based on corn from intensive, industrialized agriculture. Energy and eMergy indices of ethanol production from wheat and corn in the two agro-industrial systems are respectively as follows: output/input energy ratio, 1.09 (wheat) and 1.19 (corn); transformity of bioethanol, 2.77×105 and 1.89×105 seJ/J; renewability, 20% and 11%; eMergy yield ratio, 1.24 and 1.14; environmental loading ratio, 4.05 and 7.84; and finally eMergy sustainability index, 0.31 and 0.15. Results show that bioethanol from food crops is not a sustainable source of fuel.

1. Introduction

Large-scale wheat production for food has been responsible of several negative environmental impacts, such as destruction of native forests, loss of rural production diversity and the release of effluents into water bodies. Nowadays, due to the need for feeding an increasing population, a fraction of which is also shifting to a higher standard of living (e.g. eating meat instead of cereals, and so placing a huge demand on cereals for livestock feed), the environmental load is aggravated by a set of additional problems such as soil erosion, pollution of soils and aquifers due to pesticides and run-off of fertilizers, air pollution resulting from the straw burning process during wheat harvesting, further destruction of biodiversity due to intensive cropping, displacement of small and medium agricultural farms, human exodus from rural areas, etc. Increased soil exploitation needed for bioethanol to become a profitable activity is likely to make these problems even worse. In order to make a reliable and comprehensive analysis of ethanol production, the above-mentioned problems should be taken into proper account.

Fuels from biomass have been proposed in the last years as substitutes for fossil fuels, in order to meet future shortages, increase a country's energy security and offset the increasing price of fossil fuels. Although the scientific literature on biofuel production techniques is abundant, comprehensive evaluations of large-scale biofuel production as an alternative to fossil energy depletion were few and controversial. The complexity of the assessments involved and the ideological biases in the research of both opponents and proponents of biofuel production made it difficult to weigh the contrasting information found in the literature. Moreover, the validity of extrapolating results obtained at the level of an individual biofuel plant or farm to entire societies or ecosystems has rarely been addressed explicitly. Hoogwijk et al. (2003), after performing a thorough review of a large number of studies for biofuel production from cereals, sugar and oil seed crops as well as cellulosics worldwide, reach the conclusion that "it is therefore not "a given" that biomass for energy can become available at a large-scale". Berndes et al. (2003), based on the same set of data, conclude that "The question how an expanding bioenergy sector would interact with other land uses, such as food production, biodiversity, soil and nature conservation, and carbon sequestration has been insufficiently analyzed... It is therefore difficult to establish to what extent bioenergy is an attractive option for climate change mitigation in the energy sector".

* Corresponding author. Tel./fax: +86 10 62731436.
E-mail address: wshgao@cau.edu.cn (W. Gao).

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The context changed abruptly in the last 2 years. Price of cereals increased all over the world, due to increased price of fossil fuels, increased demand for food by an increasing population and increased use of cereals as animal feedstock. Moreover, the Kyoto Protocol-driven attention of governments to the environmental problems generated by CO_2 emissions translated into increased implementation of biofuel production programs (everywhere, but mainly in the United States, Brazil, European Union and Canada), thus affecting scarcity of cereals for food and feed. The previously isolated critical voices towards biofuel production (Pimentel et al., 1981, 1988; Pimentel, 1991; Giampietro et al., 1997; Ulgiati, 2001) found a larger audience and gave rise to a much deeper evaluation of pros and cons of such a business and its consequences on world agriculture, land management and food supply.

The United Nations General Assembly discussed the topic of the right to food, based on an alarming report submitted on August 2007 by the Special UN Rapporteur on the right to food, Jean Zigler (United Nations, 2007). In his report, "the Special Rapporteur is gravely concerned that biofuels will bring hunger in their wake. The sudden, ill-conceived, rush to convert food—such as maize, wheat, sugar and palm oil—into fuels is a recipe for disaster. There are serious risks of creating a battle between food and fuel that will leave the poor and hungry in developing countries at the mercy of rapidly rising prices for food, land and water. If agro-industrial methods are pursued to turn food into fuel, then there are risks that unemployment and violations of the right to food may result, unless specific measures are put in place to ensure that biofuels contribute to the development of small-scale peasant and family farming." The report also highlights that "there has been little production and investment in what are known as 'second-generation' cellulose-based fuels which could convert non-food crops and agricultural wastes (for example, the fibrous stalks of wheat) for production".

Finally, the Alternative Energy Working Group of the International Forum on Globalization (IFG, 2007) analyzes the feasibility of biomass fuels from a variety of substrates and the social, environmental and economic consequences of such a strategy, and concludes that governments are putting "a policy priority on an energy source with little if any net energy return, which contributes to climate change rather than alleviating the problem, and which contributes to several other serious environmental problems…It is also having a devastating impact on traditional farm communities and indigenous peoples around the world. None of this unfortunate transition would be possible without massive government subsidies". The IFG Report makes "the important distinction between large-scale and small-scale, locally operated and owned biofuels activities which can be relatively benign in their impacts and useful in local economic situations…Focus is on the large-scale, industrial biofuel operations, run by global mega-agriculture corporations that bulldoze local economies and food systems…"

Within the framework of such a changing context, the purpose of our study is therefore to assess the viability and sustainability of a biofuel option based on food crops for China, by investigating the ethanol agro-industry in Henan Province. In so doing, it is possible to provide insight into the present and future performance and suitability of biofuel production activities. We perform in this paper an energy and eMergy evaluation of ethanol production from wheat and compare our findings with results about ethanol production from corn in Italy, in order to shed light on both thermodynamic and environmental performance of such a process. Reference is also made to published literature about other food crops suitable for conversion to biofuels (sugarcane, sunflower, soybeans). Instead, our study does not deal with biofuel production from lignocellulose (from either non-food crops or residues) because it does not compete directly with food production. For the same reason we do not deal with biogas production from agricultural, industrial or urban wastes, although biogas could become—and in some countries already is—an important bioenergy source.

2. Material and methods

2.1. Embodied energy method

The commercial energy invested into the whole chain of processes that lead from extraction and processing of raw materials and resources to the final product (bioethanol) via crop production, harvesting, transport and conversion is calculated by firstly performing an inventory of all input energy and matter flows to the agricultural and industrial processes. Input flows are then multiplied by suitable conversion coefficients which express the unit energy demand "embodied" in each flow. Such coefficients are available in published embodied energy and life cycle assessment literature (cited in the footnotes of our tables). The embodied energy assigned to each input flow (i.e. the commercial energy used up to make that flow) is calculated according to the following equation:

$$E = \sum f_i \times c_i, \quad i = 1, \ldots, n \tag{1}$$

where E is the embodied energy, f_i the ith input flow of matter or energy and c_i the embodied energy coefficient of the ith flow (from literature or calculated in this work).

Summing up the embodied energy values of all input flows we calculate the total energy invested into the process, i.e. the total energy cost of producing bioethanol through energy cropping.

2.2. The eMergy synthesis method

Primary energy and material resources do not come from nothing. They are provided by nature through biosphere cycles powered by solar, geothermal and gravitational energies. Calculating the work performed by nature in order to provide the resources that we extract, process and use within our economic systems provides a measure of their "donor-side" quality, i.e. a measure of their cost from the point of view of biosphere, and—as a consequence—a measure of their renewability and sustainability from an environmental point of view. eMergy is defined as "the total available energy (exergy) of one kind (usually solar) directly and indirectly used up to drive a process and generate a product or a product flow" (Odum, 1988, 1996). Geothermal and gravitational energies are converted into solar equivalents by means of conversion coefficients that take into account the complex interactions among biosphere processes, so that the total eMergy accounts for direct solar radiation as well as solar equivalent geothermal and gravitational energy flows (Odum, 2000a). Its unit is "solar equivalent joule" (seJ). The solar eMergy required to make one unit of product is named "solar transformity" (seJ/J) when the product is measured in joule and "specific eMergy" (seJ/g) when the product is measured in grams.

The eMergy assigned to each input flow is calculated according to the following equation:

$$Em = \sum f_i \times tr_i, \quad i = 1, \ldots, n \tag{2}$$

where Em is the solar eMergy, f_i the ith input flow of matter or energy and tr_i the transformity of the ith flow (from literature or calculated in this work).

Summing up the emergies of all input flows we can calculate the total eMergy invested into the process, i.e. the total biosphere work (and environmental support) to bioethanol production. Total eMergy contributions to the geobiosphere are about 15.83 E24 seJ/yr based on a re-evaluation and subsequent recalculation of energy contributions done in the year 2000 (Odum, 2000a). Prior to that date, the total eMergy contribution to the geobiosphere that was used in calculating transformities and other unit eMergy values was 9.44×10^{24} seJ/yr. The increase in the global eMergy reference base to 15.83×10^{24} seJ/yr changes all the unit eMergy values which directly and indirectly were derived from the value of global annual empower. Thus, unit eMergy values calculated prior to that year are multiplied by 1.68 (the ratio of 15.83/9.44). Updated values are, in general, referred to as the "new eMergy baseline".

The eMergy method is also known as "eMergy synthesis". "Synthesis is the act of combining elements into coherent wholes. Rather than dissect and break apart systems and build understanding from the pieces upward, eMergy synthesis strives for understanding by grasping the wholeness of systems" (Brown and Ulgiati, 2004). By evaluating complex systems using eMergy methods, the major inputs from the human economy and those coming "free" from the environment can be integrated and used to analyze questions of public policy and environmental management holistically. A full explanation of concepts, principles and applications of eMergy can be found in "Environmental Accounting" by H.T. Odum (1996) as well as in Brown and Ulgiati (2004). A short description of the method is also provided in Appendix A.

The study of energy alternatives in terms of eMergy has a history of more than 20 years. Pioneering work was done by Odum (1971, 1975, 1976, 1977, 1980, 1996, 2000b), Kemp et al. (1977), Brown et al. (1993), Odum et al. (1981), Odum and Odum (1985, 2001), Tonon et al. (2006) and Brown and Ulgiati (2002), among others. Huang and Odum (1991), Lan and Odum (1993, 1994), Lan et al. (1998), Yan and Odum (1998, 2001), Dong and Gao (2003), Li and Lu (2005) and other researchers provided further investigation of case studies in China and interesting insights into the potentialities of the method.

3. The investigated system

The factory studied is located in Nanyang city of Henan Province. The total fixed capital investments were US$$1\times10^7$ in the year 2001. The plant is able to process, on a yearly basis, 7.18×10^5 ton of wheat, obtained from about 167,000 ha of plantation lands. The milling capacity of the plant is about 2000 ton of wheat/day. The average production ratio is 0.28 ton alcohol/ton of wheat, according to Li and Lu (2005). The average productivity of wheat in the area is 4300 kg/ha, so that alcohol productivity per ha is around 1.20 ton/ha. The alcohol produced is concentrated up to 99.5%. The total alcohol production could therefore reach 2×10^5 ton/yr. By-products such as filter cake and vinasse are used as fertilizers, in order to decrease the need for fossil-based chemical fertilizers. Table 1 provides a picture of the technical performance of the wheat to ethanol conversion process, with main conversion and economic parameters. Due to the large variety of water sources used (ground water, river water, stored rain water) as well as due to the variety of irrigation regimes of wheat production (depending on season and wheat cultivar), water was not accounted for in our tables. Moreover, sometimes irrigation is not used, due to sufficient rainfall (620 mm/yr or more), or is very limited. Accounting for water—when needed—would further decrease the output/input energy ratio of the final product and, in some cases, might even make it lower than one, indicating water as a limiting factor to the feasibility of bioethanol from wheat. In this regard, the evaluation should be performed case by case.

Table 1
Technical and economic parameters of ethanol production from 1 ha wheat land (Li and Lu, 2005)

Item	Amount required or produced
Wheat productivity	4.301 ton/ha
Conversion factor	0.2785 ton alcohol/ton wheat
Alcohol productivity	1.20 ton/ha[a]
Water for industrial ethanol production	20 ton/ha[b]
Electricity	396 kWh/ha[c]
Average fixed capital (FC) needed on yearly basis per ha	$6/ha[d]
Average chemicals	60 kg/ha[e]
Transportation of wheat to plant	2700 MJ/ha[f]

[a] 4.301 ton/ha × 0.2785 ton alcohol/ton wheat.
[b] 1 ton alcohol production requires 20 ton water in the factory.
[c] 1 ton alcohol production requires 330 kWh electricity.
[d] Total FC (including plant and machinery) is $$10^7$, the capacity of alcohol production is 2×10^5 ton/yr, therefore $5 are invested per ton of alcohol produced.
[e] 1 ton alcohol production requires 50 kg chemicals (see Table 2).
[f] The average distance from wheat field to the plant is 204 km, the truck carries 8 ton wheat and uses 35 L fuel/100 km, the energy content of fuel is 4.45 MJ/L, therefore transportation of 1 ton of wheat requires 627 MJ fuel (truck runs one way empty and one way full load).

Data about Italian bioethanol from corn refer to Giampietro and Ulgiati (2005), who also accounted for an energy credit due to the use of distillation residues as animal feedstock. Such an indirect energy saving increased by 26% the output/input energy ratio of bioethanol produced. Due to the concerns of these authors about the actual applicability of such a credit and in order to make the two studies comparable, we subtracted the energy credit from Giampietro and Ulgiati's results, therefore slightly decreasing the energy ratio calculated in the Italian case.

4. Results

The ethanol production process includes wheat cropping, transport to factory, wheat to alcohol conversion, mixture with gasoline and finally delivery to the gas station. The systems diagram of the process is shown in Fig. 1. Systems diagrams not only identify the main steps of the linear production chain, but also show all main input flows to each step as well as feedback flows, degraded resource flows and money flows, if any. In so doing, a clear overview of the process is gained, for better understanding and comprehensive evaluation. Once the diagram is drawn for the whole system as well as, if needed, for the individual steps, each flow can be identified and listed in a table (Tables 2–5) in support to the calculation procedure. Data of a typical wheat cropping and ethanol production process were obtained from farmers and plant operators. Raw data are converted to energy and eMergy flows, as described in Sections 2.1 and 2.2. Flows are grouped according to their characteristics: locally renewable input, locally nonrenewable input, materials and services from economy, and products. Finally, energy and eMergy-based performance indicators (see Appendix A) are calculated in order to evaluate the bioethanol production process in terms of its global-scale demand for energy and environmental support.

Table 2 lists the main matter and energy input flows to wheat cropping. Embodied energy of such flows is calculated according to Eq. (1). The total energy invested directly and indirectly into the agricultural step is equal to 2.38×10^4 MJ/ha. About 5.5 kJ are needed per gram of grain produced, which translates into an

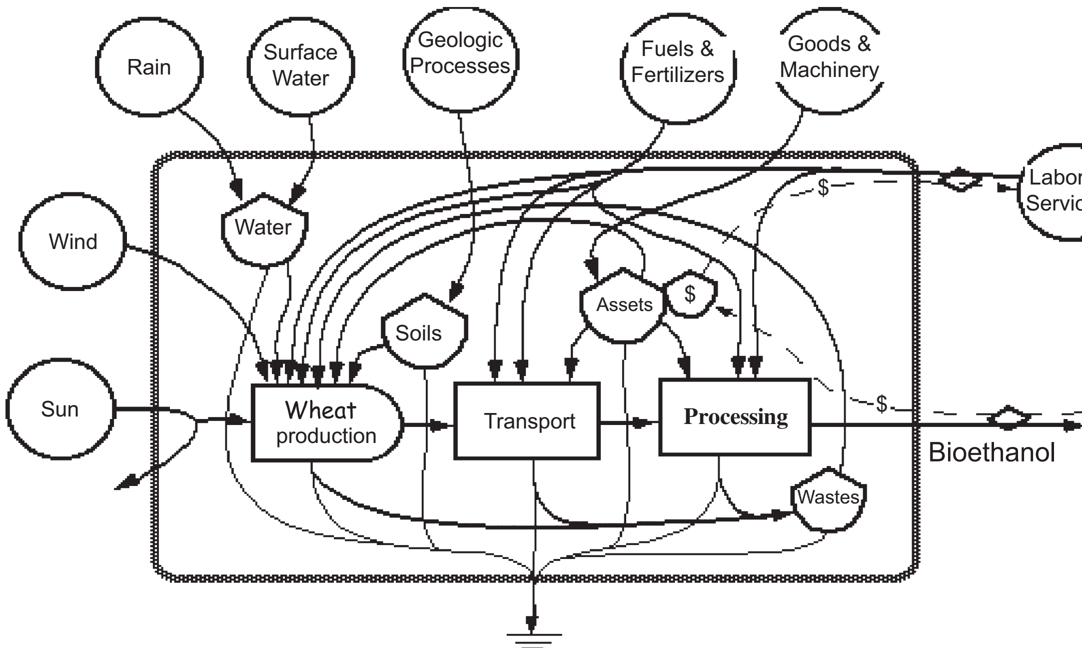

Fig. 1. Energy systems diagram of bioethanol production from wheat (after Brown and Ulgiati, 2004) showing the main inputs to and steps of the process. Dashed lines show the inflow of money from bioethanol sale and the outflow of money for the purchase of goods and services.

Table 2
Energy analysis of wheat production in China (1 ha; reference years: 2002–2004)

Item	Raw amount	Unit	Energy equivalent (J/unit)	Ref. of energy equivalents	Energy flows (J/ha/yr)	% of total energy use
Seeds[a]	1.25E+05	g/ha/yr	5.53E+03	This work	6.91E+08	2.90
Nitrogen fertilizer, N[b]	1.80E+05	g/ha/yr	7.33E+04	Ulgiati (2001)	1.32E+10	55.40
Phosphate fertilizer, P_2O_5[c]	7.50E+04	g/ha/yr	1.34E+04	Ulgiati (2001)	1.00E+09	4.22
Potash fertilizer, K_2O[d]	6.00E+04	g/ha/yr	9.21E+03	Ulgiati (2001)	5.53E+08	2.32
Herbicides[e]	1.11E+04	g/ha/yr	5.99E+04	Ulgiati (2001)	6.66E+08	2.80
Steel for agricultural machinery[f]	7.30E+03	g/ha/yr	8.00E+04	Ulgiati (2001)	5.84E+08	2.45
Fuel for machinery (diesel)[g]	1.38E+05	g/ha/yr	5.15E+04	Ulgiati (2001)	7.12E+09	29.90
Wheat harvested[h]	4.30E+06	g/ha/yr				
Total energy invested[i]		J/ha/yr			2.38E+10	100.00
Energy equivalent of wheat		J/g	5.53E+03	This work		
Output/input energy of wheat production		J/J	2.496	This work		

[a] Seeds used, 125 kg/ha/yr (Xiong and Zhang, 1996).
[b] Nitrogen (N), 1.80E+05 g/ha/yr (Chen and Zhang, 2006).
[c] Phosphate (P_2O_5), 7.50E+04 g/ha/yr (Chen and Zhang, 2006).
[d] Potash (K_2O), 6.00E+04 g/ha/yr (Chen and Zhang, 2006).
[e] Herbicides, 1.11E+04 g/ha/yr (Feng et al., 2002).
[f] Equipment and machinery. Total machinery weight: 7300 kg, mainly steel, allocated to 100 ha farmland for 10 years = 7.30E+03 g/ha/yr (personal on-field investigation of the authors).
[g] Fuel for machinery = 138.2 kg/ha/yr (Li and Lu, 2005).
[h] Wheat harvested, 4.30E+03 kg/ha/yr (Li and Lu, 2005).
[i] Energy content of wheat, 1.38E+04 J/g (Pimentel (1980).

output/input energy ratio of 2.5 for wheat grain. Such a low energy return on investment indicates that the agricultural step is already affected by an energy problem, namely the large amounts of nitrogen fertilizer, accounting for 55% of the total energy input, and diesel fuel, accounting for about 30%. If wheat is to be used as a suitable substrate for bioenergy production, nitrogen fertilizer and diesel fuel must be decreased, not to become the energy constraints to the next steps of the process. Table 3 shows the same calculation procedure applied to the energy and matter inflows to the industrial step, converted into embodied energy amounts. The total, global-scale energy invested into the whole agro-industrial process is 3.28×10^4 MJ/ha, translating into a production energy cost of 27.4 kJ/g bioethanol (5 times higher than production of wheat) and a final energy ratio of 1.09 (i.e. 1.09 J are obtained in the form of bioethanol by investing 1 J of input flow mix).

The agricultural phase uses 72% of total energy investment to the whole bioethanol process. Nitrogen fertilizer accounts for 40% of total energy used, while agricultural and transportation fuel account for about 32%. Process electricity is 13% of total energy input. A sensitivity analysis performed by gradually assuming a variation of the nitrogen inflow by $\pm10\%$, $\pm20\%$, …, $\pm50\%$, shows that the energy ratio of wheat changes accordingly, up to a maximum of $\pm28\%$. A similar test performed for the fuel input shows variations of the energy ratio up to a maximum of $\pm15\%$. If a simultaneous 20% decrease of nitrogen and fuel inputs was

Table 3
Energy analysis of ethanol production from wheat (industrial phase)

Item	Raw amount	Unit	Energy equivalent (J/unit)	Ref. of energy equivalents	Energy flows (J/ha/yr)	% of total energy use
Wheat from agricultural phase[a]	4.30E+06	g/ha/yr	5.53E+03	This work	2.38E+10	72.47
Water for alcohol production[b]	2.40E+07	g/ha/yr	5.99E+00	After Boustead and Hancock (1979)	1.43E+08	0.44
Sulfuric acid[c]	5.29E+04	g/ha/yr	6.28E+03	After Boustead and Hancock (1979)	3.32E+08	1.01
C_6H_6[d]	3.00E+03	g/ha/yr	5.15E+04	Ulgiati (2001)	1.54E+08	0.47
Sodium hydroxide[e]	2.00E+03	g/ha/yr	6.28E+03	After Boustead and Hancock (1979)	1.26E+07	0.04
Lubricants[f]	2.00E+03	g/ha/yr	8.37E+04	After Boustead and Hancock (1979)	1.67E+08	0.51
Electricity[g]	1.42E+09	J/ha/yr	3.00E+00	After Boustead and Hancock (1979)	4.27E+09	13.01
Equipment (assumed mainly steel and iron)[h]	7.80E+03	g/ha/yr	8.00E+04	After Boustead and Hancock (1979)	6.24E+08	1.90
Fuel for transportation (diesel)[i]	6.48E+04	g/ha/yr	5.15E+04	After Boustead and Hancock (1979)	3.34E+09	10.16
Mass of ethanol produced[j]	1.20E+06	g/ha/yr		This work		
Total energy investment		J/ha/yr		This work	3.28E+10	100.00
Energy equivalent of ethanol		J/g	2.74E+04	This work		
Output/input energy ratio			1.09	This work		

[a] Wheat used, 4.30E+06 g/ha/yr (Li and Lu, 2005).

[b] Process water: production of 1 ton of ethanol from wheat requires 20 ton water and 3.59 ton of wheat according to Li et al. (2007). Water used = 23.96 ton water needed = 2.40E+07 g/ha/yr.

[c,d,e] Chemicals: 1 ton of ethanol from wheat requires 50 kg of chemicals (44.16 kg sulfuric acid, 2.5 kg C_6H_6, 1.67 kg sodium hydroxide and 1.67 kg lubricants). Therefore, sulfuric acid used, 5.29E+04 g H_2SO_4/ha/yr, after Li et al. (2007); C_6H_6 used, 3.00E+03 g C_6H_6/ha/yr, after Li et al. (2007); sodium hydroxide used, 2.00E+03 g NaOH/ha/yr, after Li et al. (2007).

[f] Lube oils used, 2.00E+03 g lube/ha/yr, after Li et al. (2007).

[g] Electricity: Total used = 1.42E+09 J/ha/yr, after Li et al. (2007).

[h] Equipment (mainly steel and iron): equipment allocated yearly to 1 ha ethanol production: 7.8 kg/ha/yr. Estimate includes processing machinery 0.44 kg/ha/yr, washing machinery 0.41 kg/ha/yr; boiler 1.5 kg/ha/yr, distillery stainless steel 0.37 kg/ha/yr; distillery steel 1.95 kg/ha/yr, other 3.03 kg/ha/yr. (personal on-field investigation of the authors) = 7.80E+03 g/ha/yr.

[i] Transport: average distance from wheat production site to factory, 204 km; average distance from factory to market place, 50 km; transport truck maximum load, 8 ton/trip; consumption of diesel, 0.35 L/km; total mass of diesel for transport of produced ethanol, 6.48E+04 g/ha/yr.

[j] Ethanol produced: 1.2 ton EtOH/ha = 1.20E+06 g/ha/yr, after Li et al. (2007); HHV of ethanol, 2.98E+04 J/g, after Wyman et al. (1993, p. 870); total energy of ethanol produced, 3.57E+10 J/ha/yr.

obtained by means of optimized cropping techniques, it would translate into a global increase of the energy ratio of wheat up to a value 3.0 as well as into a corresponding 14% increase of the energy ratio of bioethanol, from 1.09 to 1.24.

A similar calculation procedure, as described in Section 2.2 and based on the same set of input data, is used for the eMergy analysis and synthesis evaluation. Environmental data (solar radiation, wind, rain, deep heat, topsoil used up) plus labor and services are also accounted for according to the definition of eMergy. Tables 4 and 5, in which raw input are multiplied by suitable transformities to yield eMergy flows, show the eMergy calculation results. According to Ulgiati et al. (2005), eMergy flows are split into their renewable and nonrenewable fractions (e.g. solar radiation is completely renewable; diesel fuel is considered completely nonrenewable; labor and services—two flows supported by the economic system—are 26% renewable in China and only 6% renewable in Italy, according to the share of renewables driving these economic systems). Transformities (seJ/J) and specific emergies (seJ/g) of wheat and bioethanol are calculated in Tables 4 and 5, with and without accounting for the eMergy content of labor and services. Thanks to the splitting into renewable and nonrenewable components of each eMergy flow, we were able to calculate the renewable component of the final products (wheat and bioethanol) as respectively 22% and 20%, shedding light into the renewability claims of such products.

eMergy-based performance indicators (eMergy yield ratio (EYR), environmental loading ratio (ELR), eMergy sustainability index (ESI)) are sentitive to a different extent to the characteristics of input flows (see Appendix A). While transformities are sensitive to the biosphere-scale efficiency, the EYR is only sensitive to the alternative "local-imported"; the ELR—and, consequently, the ESI—are instead strongly dependent on the "renewable–nonrenewable" alternative of input flows. We therefore calculated each index according to the formulas indicated in Table 6, where the renewable and nonrenewable components are properly accounted for, as suggested by Ulgiati et al. (2005).

Fig. 2 shows the so-called "eMergy signature" of the whole process, i.e. a bar diagram indicating the relative size of the different categories of input flows. Such a clear picture of the process indicates what the actual driving forces of the final products are. Results from embodied energy analysis indicated nitrogen fertilizer, fuel and electricity as the main input to the process, based on the heat content of each input, as previously discussed. Instead, as Brown and Ulgiati (2004) clearly indicate, complex systems are not only driven by heat supply, but also by a mix of environmental services, fuels, minerals, goods, labor, information, all items with characteristics other than heat content. Fig. 2 indicates services (a measure of the indirect labor invested to make and supply goods and resources) as the largest eMergy input (slightly less than 30%) while energy (fuels and electricity) is the second largest input in eMergy terms, totalling a little less than 15%. Nitrogen fertilizer ranks third around 11%. Other input flows such as herbicides and process chemicals, even if supplied in smaller amounts, are not negligible in eMergy terms, due to their higher transformity. Finally, several flows always disregarded in embodied energy analyses, such as rain, topsoil used up and direct labor each account for about 9% of total eMergy investment.

Table 4
Emergy analysis of wheat production (1 ha; reference years: 2002–2004)

Item	Raw amount	Unit	Transformity (seJ/unit)	Ref. of transf.	Emergy flows (seJ/ha/yr)	Percent of total eMergy use	Renewable fraction	Nonrenewable fraction
Local renewable resources								
Solar radiation[a]	4.93E+13	J/ha/yr	1	After Odum (1996)	4.93E+13			
Rain (chemical potential)[b]	3.06E+10	J/ha/yr	3.06E+04	After Odum (1996)	9.36E+14			
Deep heat[c]	5.46E+10	J/ha/yr	1.02E+04	After Odum (1996)	5.55E+14			
Total renewables					*9.36E+14*	*11.93%*	9.36E+14	
Local nonrenewable resources								
Soil loss (organic matter)[d]	7.83E+09	J/ha/yr	1.24E+05	After Brown and Arding (1991)	9.71E+14	12.37%		9.71E+14
Total local resources (renewables+nonrenewables)			1.91E+15	24.30%	9.36E+14	9.71E+14		
Resources from outside								
Seeds[e]	1.73E+06	J/ha/yr	7.91E+04	This work	1.37E+11	0.00%	1.63E+10	1.20E+11
Fertilizers[f]								
Nitrogen, N[g]	1.80E+05	g/ha/yr	6.38E+09	After Odum (1996)	1.15E+15	14.64%		1.15E+15
Phosphate, P_2O_5[h]	7.50E+04	g/ha/yr	6.55E+09	After Odum (1996)	4.91E+14	6.26%		4.91E+14
Potash, K_2O[i]	6.00E+04	g/ha/yr	1.85E+09	After Odum (1996)	1.11E+14	1.41%		1.11E+14
Herbicides[j]	1.11E+04	g/ha/yr	2.49E+10	After Brown and Arding (1991)	2.76E+14	3.52%		2.76E+14
Steel for agricultural machinery[k]	7.30E+03	g/ha/yr	1.13E+10	After Brown and Arding (1991)	8.22E+13	1.05%		8.22E+13
Fuel for machinery (diesel)[l]	6.14E+09	J/ha/yr	1.11E+05	After Odum (1996)	6.81E+14	8.68%		6.81E+14
Total materials					2.79E+15	35.56%	1.63E+10	2.79E+15
Labor and services[m]								
Management and labor[n]	4.07E+01	$/ha/yr	1.18E+13	UFL (2007)	4.81E+14	6.12%	1.25E+14	3.56E+14
Miscellaneous services[o]	1.92E+02	$/ha/yr	1.18E+13	UFL (2007)	2.27E+15	28.91%	5.90E+14	1.68E+15
Cost of machinery, assets[p]	3.40E+01	$/ha/yr	1.18E+13	UFL (2007)	4.01E+14	5.10%	1.04E+14	2.96E+14
Total L and S	2.67E+02	$/ha/yr	1.18E+13	UFL (2007)	3.15E+15	40.14%	8.19E+14	2.33E+15
Wheat harvested[q]	4.30E+06	g/ha/yr						
Total emergy, without L and S		seJ/yr			4.70E+15	59.86%		
Total emergy, U, with L and S		seJ/yr			7.85E+15	100.00%		
Transformity of wheat, without L and S		seJ/J	7.91E+04					
Specific eMergy of wheat, without L and S		seJ/g	1.09E+09				%R	%N
Transformity of wheat, with L and S		seJ/J	1.32E+05				22.37%	77.63%
Specific eMergy of wheat, with L and S		seJ/g	1.82E+09				22.37%	77.63%

[a] Solar radiation, 4.93E+13 J/ha/yr (Cheng, 1990).
[b] Rain = (area, 1 ha) (rainfall, 0.62 m) (10,000 m^2/ha) (1E+6 g/m^3) (4.94 J/g) = 3.06E+10 J/ha/yr (Cheng, 1990).
[c] Deep heat, 5.46E+10 J/ha/yr, http://www.chinamining.com.cn/report/default.asp?V_DOC_ID=1370. (last accessed December 2007).
[d] Organic matter in topsoil used up = (soil loss, 800 g/m^2) (10,000 m^2/ha) (OM content, 4.33%) (5.4 kcal/g) (4186 J/kcal) = 7.83E+09 J/ha/yr.
[e] Energy of seeds = (125 kg/ha) (1.64E4 kJ/kg) = 1.73E+06 J/ha/yr.
[f] Nitrogen (N), 1.80E+05 g/ha/yr (Chen and Zhang, 2006).
[g] Phosphate (P_2O_5), 7.50E+04 g/ha/yr (Chen and Zhang, 2006).
[h] Potash (K_2O), 6.00E+04 g/ha/yr (Chen and Zhang, 2006).
[i] Herbicides, 1.11E+04 g/ha/yr (Feng et al., 2002).
[j] Equipments and machinery: total machinery weight: 7300 kg, mainly steel, allocated to 100 ha farmland for 10 years = 7.30E+03 g/ha/yr (personal on-field investigation of the authors).
[l] Fuel for machinery (diesel) = 138.2 kg/ha/yr (Li and Lu, 2005). Higher heating value of diesel = 4.45E+07 J/kg (Boustead and Hancock, 1979). Total energy of diesel fuel, 6.14E+09 J/ha/yr.
[m] Management and labor, 300 RMB/ha/yr; cost of planting, harvesting, driving machinery, average data for investigated area, equivalent to $41/ha/yr.
[n] Miscellaneous services (measured as total cost of purchased items), 1416 RMB/ha/yr; average price in Chinese fertilizer market is 4 RMB/kg N, K_2O and P_2O_5. Miscellaneous goods add up further 156 RMB = $192/ha/yr.
[o] Yearly cost of machinery and assets, 250 RMB/ha/yr; total cost of machinery and related equipment is 150,000 RMB allocated to 100 ha over 10 years; assets with life span of 30 years cost 300,000 RMB equivalent to $34/ha/yr.
[p] Total L and S: $267/ha/yr.
[q] Wheat harvested, 4.30E+03 kg/ha/yr (Li and Lu, 2005). Energy content of wheat, 1.38E+04 J/g, Pimentel (1980). Total energy of wheat, 5.94E+10 J/ha/yr.

5. Discussion

Table 6 shows the main results of energy and eMergy evaluation. Results can be discussed by comparing:

(a) the findings from energy and eMergy methods, as such;
(b) the values of indicators in the different steps of grain and bioethanol production;
(c) the performance of the investigated system (the Chinese process) with a previously investigated or a different one (e.g., the Italian process);
(d) the performance of the investigated system over time, depending on data availability.

We will not be able, unfortunately, to perform the latter evaluation (point d) due to lack of a reliable historical data set and

Table 5
Emergy analysis of ethanol production from wheat (industrial phase)

Item	Raw amount	Unit	Transformity (seJ/unit)	References of transformities	Emergy flows (seJ/ha/yr)	Percent of total eMergy use	Renewable fraction	Nonrenewable fraction
Wheat from agric. phase, without L and S[a]	4.30E+06	g/ha/yr	1.09E+09	This work	4.70E+15	47.43%	0.00E+00	4.70E+15
Wheat from agric. phase, with L and S[a]	4.30E+06	g/ha/yr	1.82E+09	This work	7.85E+15		1.76E+15	6.09E+15
Water for alcohol production[b]	1.18E+08	J/ha/yr	6.89E+04	After Brown and Arding (1991)	8.15E+12	0.08%	4.08E+12	4.08E+12
Sulfuric acid[c]	5.29E+04	g/ha/yr	6.38E+09	After Odum (1996)	3.38E+14	3.41%		3.38E+14
C_6H_6[d]	3.00E+03	g/ha/yr	6.38E+09	After Odum (1996)	1.91E+13	0.19%		1.91E+13
Sodium hydroxide[e]	2.00E+03	g/ha/yr	6.38E+09	After Odum (1996)	1.28E+13	0.13%		1.28E+13
Lubricants[f]	2.00E+03	g/ha/yr	7.98E+09	After Odum (1996), modif	1.60E+13	0.16%		1.60E+13
Electricity[g]	1.42E+09	J/ha/yr	3.36E+05	After Odum (1996)	4.78E+14	4.83%		4.78E+14
Equipment (assumed mainly steel and iron)[h]	7.80E+03	g/ha/yr	1.13E+10	After Brown and Arding (1991)	8.78E+13	0.89%		8.78E+13
Fuel for transportation (diesel)[i]	2.88E+09	J/ha/yr	1.11E+05	After Odum (1996)	3.19E+14	3.22%		3.19E+14
Management and labor[j]	36.00	$/ha/yr	1.18E+13	UFL (2007)	4.25E+14	4.29%	1.10E+14	3.14E+14
Miscellaneous services[k]	24.00	$/ha/yr	1.18E+13	UFL (2007)	2.83E+14	2.86%	7.36E+13	2.10E+14
Cost of machinery, assets[l]	6.00	$/ha/yr	1.18E+13	UFL (2007)	7.08E+13	0.71%	1.84E+13	5.24E+13
Ethanol produced[m]	3.57E+10	J/ha/yr						
Total eMergy, without L and S		seJ/yr			5.98E+15	60.34%	4.08E+12	5.97E+15
Total eMergy, with L and S		seJ/yr			9.91E+15	100.00%	1.96E+15	7.94E+15
Transformity of ethanol, without L and S		seJ/J	1.67E+05					
Specific eMergy of ethanol, without L and S		seJ/g	4.98E+09				%R	%N
Transformity of ethanol, with L and S		seJ/J	2.77E+05				19.8%	80.2%
Specific eMergy of ethanol, with L and S		seJ/g	8.26E+09				19.8%	80.2%

[a] Wheat used, with and without accounting for production labor and services, from Table 4.

[b] Process water: production of 1 ton of ethanol from wheat requires 20 ton water and 3.59 ton of wheat according to Li et al. (2007). Water used = 23.96 ton water = 2.40E+07 g/ha/yr. Gibbs energy of fresh water, relative to sea water, 4.94 J/g (Odum, 1996). Total Gibbs energy of water used 1.18E+08 J/ha/yr.

[c,d,e] Chemicals: 1 ton of ethanol from wheat requires 50 kg of chemicals (44.16 kg sulfuric acid, 2.5 kg C_6H_6, 1.67 kg sodium hydroxide and 1.67 kg lubricants). Therefore, sulfuric acid used, 5.29E+04 g H_2SO_4/ha/yr after Li et al. (2007); C_6H_6 used, 3.00E+03 g C_6H_6/ha/yr after Li et al. (2007); sodium hydroxide used, 2.00E+03 g NaOH/ha/yr after Li et al. (2007).

[f] Lube oils used, 2.00E+03 g lube/ha/yr after Li et al. (2007).

[g] Electricity: total used = 1.42E+09 J/ha/yr after Li et al. (2007).

[h] Equipment (mainly steel and iron): equipment allocated yearly to 1 ha ethanol production: 7.8 kg/ha/yr. Estimate includes: processing machinery 0.44 kg/ha/yr, washing machinery 0.41 kg/ha/yr; boiler 1.5 kg/ha/yr, distillery stainless steel 0.37 kg/ha/yr; distillery steel 1.95 kg/ha/yr, other 3.03 kg/ha/yr = 7.80E+03 g/ha/yr.

[i] Fuel for transport (diesel): average distance from wheat production site to factory, 204 km. Average distance from factory to market place, 50 km. Transport truck maximum load, 8 ton/trip. Consumption of diesel, 0.35 L/km. Total mass of diesel for transport of produced ethanol, 6.48E+04 g/ha/yr. Higher heating value of diesel = 4.45E+07 J/kg (Boustead and Hancock, 1979). Total energy of diesel fuel, 2.88E+09 J/ha/yr.

[j] Labor and services (total): management and labor unit cost, $30.00/ton ethanol. Total management and labor cost, $36.00/ha/yr.

[k] Miscellaneous services unit cost, $20.00/ton ethanol. Total cost of miscellaneous services, $24.00/ha/yr.

[l] Total investment for machinery and assets, $1.00E+07 (lifetime of investment: 10 years). Total ethanol production potential, 2.00E+05 ton (whole project). Total investment cost allocated to product, $6.00/ha/yr.

[m] Ethanol produced: 1.2 ton EtOH/ha = 1.20E+06 g/ha/yr after Li et al. (2007). HHV of ethanol, 2.98E+04 J/g after Wyman et al. (1993, p. 870). Total energy of ethanol produced, 3.57E+10 J/ha/yr.

therefore will not account—in the present paper—for the impact of technological improvement, decreased soil fertility, different climate, etc., all factors likely to affect the overall performance over time. This was not, however, the goal of the present investigation.

Results of eMergy accounting differ from results of embodied energy analysis in that all input flows are accounted for within the eMergy procedure, not only commercial energy flows of fossil fuels and fossil-equivalent energies. Transformities and specific emergies are calculated in such a way that they also take into account (a) free environmental services (solar radiation, rain, wind, deep heat), (b) locally available, slowly renewable flows (topsoil, ground water) and finally (c) labor, human services and information (know-how, education) from the economic system. Instead, environmental services and unmonied input flows are not included in embodied energy evaluations. As a consequence of the way eMergy figures are defined and calculated, they do not refer to the actual energy content of each flow, but instead to the environmental work performed by nature in order to make and supply that flow or product. This is, indeed, a measure of how important is a flow from a donor-side perspective and how difficult is to replace it, when used up.

It is important to highlight that the yield per hectare of wheat production in the Chinese case is about 60% of corn production

Table 6
Energy and emergy performance indicators of wheat and ethanol production in China, compared with corn and ethanol in Italy

	Units	Wheat	Corn
Energy and mass flows			
Total commercial energy invested for grain production	J/ha/yr	2.38E+10	2.92E+10
Total commercial energy invested for bioethanol production	J/ha/yr	3.28E+10	4.92E+10
Grain produced	g/ha/yr	4.30E+06	7.60E+06
Ethanol produced	g/ha/yr	1.20E+06	1.96E+06
Energy content of bioethanol produced	J/ha/yr	3.57E+10	5.84E+10
Net energy yield of bioethanol (energy of ethanol−energy invested)	J/ha/yr	2.89E+09	9.15E+09
Emergy flows			
Locally renewable inputs, R_1 (without double counting), agricultural phase	seJ/ha/yr	9.36E+14	9.35E+14
Locally nonrenewable inputs, N	seJ/ha/yr	9.71E+14	4.01E+14
% renewable of purchased inputs to agricultural phase, $\%R\_F_1$, without services	seJ/ha/yr	1.63E+10	4.68E+13
% nonrenewable of purchased inputs to agricultural phase, $\% N\_F_1$, without services	seJ/ha/yr	2.79E+15	3.21E+15
% renewable of labor and services related to agricultural phase, $\% R\_S_1$	seJ/ha/yr	8.19E+14	1.97E+14
% nonrenewable of labor and services related to agricultural phase, $\%N\_S_1$	seJ/ha/yr	2.33E+15	3.09E+15
Total eMergy inputs to agricultural phase, $Y_1 = (R_1+N+\%R\_F_1+\%N\_F_1+\%R\_S_1+\%N\_S_1)$	seJ/ha/yr	7.85E+15	7.88E+15
% renewable of purchased inputs to industrial phase, $\%R\_F_2$, without services	seJ/ha/yr	4.08E+12	2.14E+12
% nonrenewable of purchased inputs to industrial phase, $\%N\_F_2$, without services	seJ/ha/yr	1.28E+15	2.05E+15
% renewable of labor and services related to industrial phase, $\%R\_S_2$	seJ/ha/yr	2.02E+14	6.49E+13
% nonrenewable of labor and services related to industrial phase, $\%N\_S_2$	seJ/ha/yr	5.76E+14	1.02E+15
Total eMergy inputs to industrial phase, $Y_2 = (\%R\_F_2+\%N\_F_2+\%R\_S_2+\%N\_S_2)$	seJ/ha/yr	2.06E+15	3.14E+15
Total eMergy input to process, $Y = (Y_1+Y_2)$	seJ/ha/yr	9.91E+15	1.10E+16
Grain production			
Energy cost of grain	J/g	5.53E+03	3.84E+03
Output/input energy ratio of grain		2.50	3.82
Transformity of grain, with labor and services	seJ/J	1.32E+05	9.92E+04
Transformity of grain without labor and services	seJ/J	7.91E+04	6.96E+04
Specific eMergy of grain with labor and services	seJ/g	1.82E+09	1.45E+09
Specific eMergy of grain without labor and services	seJ/g	1.09E+09	1.02E+09
Emergy yield ratio of grain $= Y_1/(\%R\_F_1+\%N\_F_1+\%R\_S_1+\%N\_S_1)$ (with L and S)		1.32	1.20
ELR of grain $= (N+\%N\_F_1+\%N\_S_1)/(R_1+\%R\_F_1+\%R\_S_1)$ (with L and S)		3.47	5.68
Empower density of grain (Y_1/area) (with L and S)	seJ/m^2	7.85E+11	7.88E+11
EYR/ELR of grain		0.38	0.21
Ethanol production			
Energy cost of ethanol	J/g	2.74E+04	2.51E+04
Output/input energy ratio		1.09	1.19
Transformity of ethanol, with labor and services	seJ/J	2.77E+05	1.89E+05
Transformity of ethanol, without labor and services	seJ/J	1.67E+05	1.24E+05
Specific eMergy of ethanol, with labor and services	seJ/g	8.26E+09	5.46E+09
Specific eMergy of ethanol, without labor and services	seJ/g	4.98E+09	3.56E+09
EYR of bioethanol $= Y/(\%R\_F_1+\%N\_F_1+\%R\_S_1+\%N\_S_1+\%R\_F_2+\%N\_F_2+\%R\_S_2+\%N\_S_2)$ (with L and S)		1.24	1.14
ELR of bioethanol $= (N+\%N\_F_1+\%N\_S_1+\%N\_F_2+\%N\_S_2)/(R_1+\%R\_F_1+\%R\_S_1+\%R\_F_2+\%R\_S_2)$ (with L and S)		4.05	7.84
% Renewable = 1/(1+ELR) (with L and S)		19.81%	11.31%
Empower density = (Y/area) (with L and S)	seJ/m^2	9.91E+11	1.10E+12
EYR/ELR (with L and S)		0.31	0.15

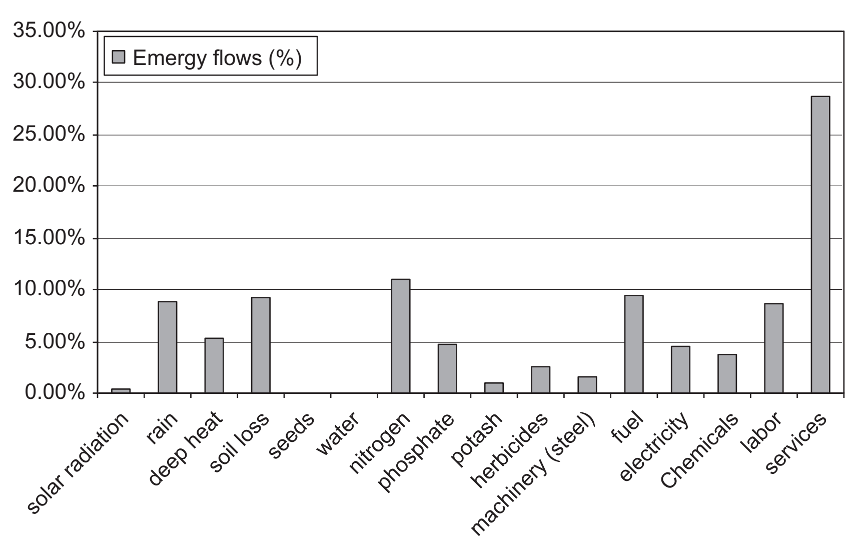

Fig. 2. Emergy signature of the wheat to bioethanol conversion process, indicating the percentage of each eMergy input to the process, including environmental services, soil loss as well as direct and indirect labor.

yield in Italy. This is not because of a less productive agricultural system, but simply because of the intrinsic different yield of the two crops. As a consequence, the output/input energy ratio is lower for wheat (2.50) than for corn (3.82): the latter captures more solar energy via photosynthesis and its energy return on energy investment is larger. The energy return drops respectively by 43% and 31% after conversion to bioethanol, becoming 1.09 and 1.19. This means that 1 J invested only generates a tiny amount of additional bioenergy, as a consequence of both the low capture of solar energy and of the huge conversion energy costs (and losses). It also means that the real net energy provided is about 10% for wheat bioethanol and 20% from corn bioethanol. Such a result translates into the need of respectively 10 and 5 ha cropped in order to have 1 ha actually providing a 100% net amount of biofuel, a mission impossible in countries characterized by scarcity of arable land compared to food demand.

The picture—still providing a net yield, although small—becomes even worse when the eMergy analysis and synthesis approach comes into play. In fact, when all costs (environmental services, energy, materials and labor) are accounted for and converted into solar equivalent units, we obtain a transformity of 1.32×10^5 seJ/J for bioethanol from wheat, much higher than that from corn in Italy (9.92×10^4 seJ/J). These values, compared to the transformity of fossil fuels (see for example the diesel used in the process, 1.11×10^5 seJ/J, Table 4), show that bioethanol in the investigated cases demands a similar or higher amount of environmental support than fossil fuels (coal, 6.71×10^4 seJ/J; natural gas, 8.05×10^4 seJ/J; crude oil, 9.07×10^4 seJ/J; Odum, 1996, updated according to the new eMergy baseline). Since transformities are efficiency measures on the space and time scales of the biosphere, this result simply means that—strange though it may appear—nature's work in making fossil fuels has been more efficient than our work of cropping and converting cereals. The EYR, a measure of the process ability to exploit the locally available resources is very low (1.24 for wheat ethanol and 1.14 for corn ethanol). The problem here is that, from the point of view of exploitation of local resources, the EYR of extraction of mineral and fossil resources is much higher (from 3 to 7, according to Odum, 1996). This means that cropping for fuel provides an eMergy return—and a contribution to the economy—even lower than mining or extracting nonrenewable resources, if available in the country. Therefore, the assumed advantage of cropping for fuel is not a real one, due to the low exploitation of local resources (imported nonrenewable resources are simply converted into biofuel). This would be, however, only part of the picture, from the point of view of the alternative "local-imported".

The ELR, an indicator of the loading of the process on the local ecosystems as well as a measure of the percent renewable fraction of the product (see Appendix A, point 4), is 4.05 for bioethanol from wheat and twice that much for bioethanol from corn. These figures respectively translate into 20% and 11% renewable fractions for these biofuels. In other terms, bioethanol is not renewable, in that it is produced by investing large amounts of nonrenewable resources. The figure is more favorable for the Chinese case than for the Italian case, due to the splitting of input flows into renewable and nonrenewable fractions, described in Section 4. Since ELR is sensitive to the renewable characteristics of input flows, the still larger renewable fractions of input flows in the Chinese case (see Tables 4 and 5) determine a slightly more sustainable result. Such a performance is confirmed by the ESI, an aggregated measure of reliance on local resources and environmental loading. ESI is 0.31 for wheat bioethanol and 0.15 for corn bioethanol. The problem with ELR and ESI is that the absolute values obtained for bioethanol are worse than those calculated for several different land uses, such as wind electricity (Brown and Ulgiati, 2004), cattle raising (Rotolo et al., 2007), cropping for food (Odum, 1996; Brandt-Williams, 2002), forestry and wood production (Brown and Bardi, 2001; Tilley and Swank, 2003), among many others.

It clearly appears that the donor-side perspective provided by the eMergy analysis and synthesis adds new insight to the understanding of the relation of a product with the surrounding environment. It is not just a matter of energy return upon investment, but much more a matter of quality of the resources invested (and therefore a matter of suitability of the investment). One joule of electricity is not the same thing as 1 J of solar radiation or 1 J of wood or organic matter in the soil. The quality of input flows, their being local or imported, their being renewable or nonrenewable, their larger or smaller demand for environmental support, make a product more or less valuable according to what driving forces were invested by nature to make it and for how much time. Something that requires a large environmental work will also be hardly replaced through the same environmental dynamics and therefore may not be the best resource base for an economic system to be sustainable. The same set of eMergy input flows, each characterized by a given transformity and quality, could be used to drive an alternative system or development strategy with much better results.

Finally, a doubt could arise about what extent the choice of crops could affect the results. Giampietro and Ulgiati (2005) investigated biodiesel from sunflower seeds and calculated an output/input energy ratio of about 1.4–1.5. Pimentel and Patzek (2005) investigated biodiesel from sunflower and soybean calculating respectively output/input energy ratios of 0.53 and 0.98, i.e. no net energy at all. In general, Brazilian sugarcane is the only food crop that provides bioethanol at energy ratios between 1.6 and 2.0 (Pimentel and Patzek, 2005) and maybe even slightly higher, but this occurs at the expenses of large environmental disruption and huge social problems (NAT, 2006) and is not, however, feasible worldwide at the same large scale and intensity as in Brazil. These results add to the above quoted Hoogwijk et al. (2003) and Berndes et al. (2003) and point out the difficult task of converting food crops to biofuel.

6. Conclusion

From a methodological point of view, we highlighted that both methods—energy and eMergy—provide important insight into the feasibility of an energy process such as biofuel production from food crops. Energy analysis identifies a prerequisite for an energy source to be feasible: more thermal energy must be obtained per unit of input invested, as it slightly happens in the investigated case studies. However, such a precondition is not sufficient for the process to be sustainable. The eMergy approach—thanks to its focus on donor-side value of process inputs—also accounts for the indirect environmental support to input flows different than thermal energy, but crucial for sustainability (e.g. soil erosion, rain, labor and services). In so doing, several hidden costs are unveiled and policy makers are provided with more comprehensive evaluation in support to informed choices and planning.

Concerning the subject of the study performed in this paper, i.e. the profitability and viability of bioethanol from wheat, the most pessimistic concerns about the process are confirmed. Bioethanol from wheat only provides a tiny amount of net energy, posing an impossible challenge on land availability. The process does not provide a sustainable product, because its demand for environmental support is huge and mainly based on the indirect support embodied in nonrenewable resources. The dependence of the process upon resources imported from outside the system is also large and therefore the process does not appear to be able to contribute to local self-sufficiency nor to the self-sufficiency at country level. We cannot exclude—based on this paper—that the biofuel option can provide a sustainable source of energy at the local scale of small farms or enterprises, specially in the presence of exceeding unused amounts of raw substrates. Nor do we exclude that improved processes based on cellulosic material can be developed and implemented, able to provide better energy and eMergy performances. The point made in this paper is that food-to-fuel conversion processes, similar to the investigated case studies of Henan Province and Italy, do not appear to be a sustainable and profitable option for China and the world.

The constraints are not simply of technological nature, but also based on the large-scale consequences of biofuel programs in terms of demand for land and environmental support. It appears that the energy profit of the process is so low as to be uneconomic. The calculated eMergy-based sustainability index is so small that the transformation process in unlikely to be sustainable. Until now, there is no evidence that a large-scale production of biofuels from food crops could be considered an ‘‘environmental-friendly’’ solution for world energy security.

Acknowledgment

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Appendix A

eMergy, transformity and eMergy-based indicators

eMergy is defined as ‘‘the total amount of available energy (exergy) *of one kind* (usually *solar*) that is directly or indirectly required to make a given product or to support a given flow’’ (Odum, 1996). Capital M in eMergy refers to the original terms ‘‘embodied energy’’ previously used and then abandoned in order to prevent misunderstandings about the underlying meaning. In some way, this concept of embodiment supports the idea that something has a value according to what was invested into making it. This way of accounting for required inputs over a hierarchy of levels might be called a ‘‘donor system of value’’, while exergy analysis and economic evaluation are ‘‘receiver systems of value’’, i.e. something has a value according to its usefulness to the end user. S*olar eMergy* was therefore suggested as a measure of the total environmental support to all kinds of processes in the biosphere. Flows that are not from solar source (like deep heat and gravitational potential) are expressed as solar equivalent energy by means of suitable transformation coefficients (Odum, 1996).

The amount of input eMergy of the solar kind dissipated per unit of output exergy is called *solar transformity*, a ‘‘quality’’ factor which functions as a measure of the intensity of biosphere support to the product under study. Values of transformities are available in the scientific literature on eMergy. The procedure for eMergy calculation is indicated in Section 2.2. A set of indices and ratios suitable for policymaking (Ulgiati et al., 1995; Ulgiati and Brown, 1998; Brown and Ulgiati, 1999, 2004) can also be calculated.

Brief explanation of selected eMergy indices

(1) Total eMergy use, $U = R+N+F$. It measures the renewable (R), nonrenewable (N) and imported (F) eMergy that converge to produce the yield Y. Since it is a measure of the eMergy cost of the yield, we can also say that U is the eMergy assigned to the yield Y or the environmental work supporting the yield Y.

(2) Transformity $= U$/output. It measures how much eMergy it takes to generate one unit of output, regardless of whether the input is renewable or not. The transformity is not sensitive to the renewable-versus-nonrenewable alternative. According to the way it is defined and calculated, the transformity measures the global conversion efficiency over the whole chain of processes leading from primary resources to the final product.

(3) eMergy yield ratio, EYR $= (R+N+F)/F$. It is a measure of the ability of a process to exploit and make available locally renewable and nonrenewable resources by investing outside resources. It provides a look at the process from the perspective of its ‘‘openness’’. The lowest possible value of the EYR is one, which indicates that the eMergy converging to generate the yield does not differ significantly from the eMergy invested from outside the system to drive the process. Processes with EYR equal to one or only slightly higher do not provide significant net eMergy to the economy and only transform resources that are already available from previous processes. In so doing they act as consumer processes more than creating new opportunities for system's growth. EYR is linked to the so-called eMergy investment ratio, EIR $= F/(N+R)$, by the following equation:

$$\mathrm{EYR} = (N+R+F)/F = 1+(N+R)/F$$
$$= 1+1/[F/(N+R)] = 1+1/\mathrm{EIR}$$

(4) Environmental loading ratio, ELR $= (N+F)/R$. It is designed to compare the amount of nonrenewable and purchased eMergy to the amount of locally renewable eMergy sources. In the absence of investments from outside, the renewable eMergy that is locally available is capable of driving local processes and maybe supporting an ecosystem within the constraints imposed by the environment and characterized by an ELR $= 0$. Instead, the nonrenewable and imported emergies drive a different site development, whose distance from the natural ecosystem can be indicated by the ELR value. In a way, the ELR is a measure of the possible disturbance to the local environmental dynamics, generated by the development driven from outside sources. The ELR is clearly able to make a difference between nonrenewable and renewable resources, thus complementing the information that is provided by the transformity. ELR is linked to the so-called renewability index (%Ren), by the equation

$$\%\mathrm{Ren} = R/(R+N+F) = 1/[(R+N+F)/R]$$
$$= 1/[1+(N+F)/R] = 1/(1+\mathrm{ELR})$$

(5) eMergy sustainability index, ESI $=$ EYR/ELR. If we combine the EYR (sensitive to the outside-versus-local eMergy alternative) and the ELR (sensitive to the nonrenewable-versus-renewable eMergy alternative), we generate an aggregated ‘‘sustainability’’ index based on both interaction with surrounding environment and renewability. This indicator is usefully applicable to measure changes in openness and loading occurring over time in both technological processes and economies.

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