A thermodynamic perspective on technologies in the Anthropocene: analyzing environmental sustainability

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Chapter 3

Is bioethanol a sustainable energy source? An energy-, exergy-, and emergy-based thermodynamic system analysis

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Abstract

Biofuels are widely seen as substitutes for fossil fuels to offset the imminent decline of oil production and to mitigate the emergent increase in greenhouse gas emissions. This view is, however based on too simple an analysis, focusing on only one piece in the whole mosaic of the complex biofuel techno-system, and such partial approaches may easily lead to ideological bias based on political preference. This study defines the whole biofuel techno-system at three scales, *i.e.*, the foreground production (A), the background industrial network (B, including A), and the supporting Earth biosphere (C, including B). The thermodynamic concepts of energy, exergy and emergy measure various flows at these three scales, *viz.*, primary resources, energy and materials products, and labor and services. Our approach resolves the confusion about scale and metric: direct energy demand and direct exergy demand apply at scale A; cumulative energy demand and cumulative exergy demand apply at scale B; and energy is applied at scale C, where it is named emergy, while exergy also can be applied at scale C. This last option was not examined in the present study.

The environmental performance of the system was assessed using a number of sustainability indicators, including resource consumption, input renewability, physical benefit, and system efficiency, using ethanol from corn stover in the US as a technology case. Results were compared with available literature values for typical biofuel alternatives. We also investigated the influence of methodological choices on the outcomes, based on contribution analysis, as well as the sensitivity of the outcomes to emergy intensity. The results indicate that the techno-system is not only supported by commercial energy and materials products, but also substantially by solar radiation and the labor and services invested. The bioethanol techno-system contributes to the overall supply of energy/exergy resources, although in a less efficient way than the process by which the Earth system produces fossil fuels.

Our results show that bioethanol cannot be simply regarded as a renewable energy resource. Furthermore, the method chosen for the thermodynamic analysis results in different outcomes in terms of ranking the contributions by various flows. Consequently, energy analysis, exergy analysis, and emergy analysis jointly provide comprehensive indications of the energy-related sustainability of the biofuel techno-system. This thermodynamic analysis can provide theoretical support for decision-making on sustainability issues.

Nomenclature

E	Energy [J]
Ex	Exergy [J]
Em	Emergy [seJ]

Greek letters

α	Input renewability
ε	Energy/exergy efficiency
ϱ	Resource intensity

Subscripts

e	Energy
ex	Exergy
em	Emergy
pro	Product or service
agr	Agriculture
ind	Industry

3.1 Introduction

Our concerns about greenhouse gas (GHG) emissions, energy security, and rural development are motivating the development of biofuel technology (Ragauskas *et al.*, 2006; Hill *et al.*, 2006; Srinivasan, 2009). The use of biofuel, *e.g.*, bioethanol, for transportation is already being promoted as a national policy, for instance in the United States (Energy Independence and Security Act, 2007) and in Europe (Directive 2003/30/EC, 2003). The global biofuel production totaled 78 billion litres in 2008 (Bacovsky *et al.*, 2009) and provided 1.8% of total transport fuels in 2007 (Bringezu *et al.*, 2009). There is, however, ongoing debate on the extent to which biofuel could be regarded as a "sustainable energy source" (Thamsiriroj *et al.*, 2010; Niven, 2005; Escobar *et al.*, 2009) and what biofuel technology would be preferable (Campell *et al.*, 2009; Howarth and Bringezu, 2009). However, the pertinent analysis only includes a small part of the whole complex biofuel techno-system, and this lack of comprehensiveness may easily lead to ideological bias and political preference.

It has been noted that biofuel technology, like any other materials technology, inherently represents a transformation of energy and materials and their transfer to different places. The science of thermodynamics, which has formulated laws on the conversion of energy and matter, is a suitable approach to analyze the behaviour of techno-systems like that for biofuel (Guan *et al.*, 2007; Sorguven and Özilgen, 2010; Farrell *et al.*, 2006; Dewulf *et al.*, 2005). The thermodynamic analysis in this study is based on energy analysis (EA), exergy analysis (ExA), and emergy analysis (EmA), using the example case of corn stover as a cellulosic biomass used as feedstock for bioethanol production, and referring to the US as the main producer, to address that how biofuel techno-system can best be analyzed to assess its sustainability as an energy source. Results were compared with literature values, to allow them to be generalized to a broader set of typical biofuel alternatives.

3.2 Materials and methods

3.2.1 System boundary

The principle of system definition is that it should include all relevant processes. A diagram of the techno-system we investigated is shown in Figure 3.1. All relevant processes are drawn with flows mainly from left to right. Flows of energy carriers (referred to below as energy without further specification) and non-energetic materials (referred to below as materials without further specification) are indicated. The system at the broadest scale is thermodynamically speaking a closed (though non-isolated) system with energy flows, *i.e.*, incoming solar radiation and outgoing earth radiation, across the system boundary.

The three scales of the system, labeled A, B and C, can be basically defined for the various types of thermodynamic analysis conducted in this study. Scale A includes the foreground production processes, mainly the agricultural production of energy crops from seeds (process A1) and the industrial conversion of energy crop into biofuel (process A2). At scale A, the direct inputs of the foreground production are energy and materials products (EMP) and primary resources, as is also shown in detail in Figure 3.2. Scale B also includes all energy and materials conversion processes that are needed to manufacture, transport and supply the inputs to scale A. It is defined by tracing back the direct EMP inputs of scale A to primary resources, *viz.*, primary renewable resources (RRs) and primary non-renewable resources (NRRs). Scale C principally includes the biospheric processes that provide the primary resources, and the related socioeconomic processes that provide the societal resources, *viz.*, labor and services (LS), for all the industrial processes occurring at scale B.

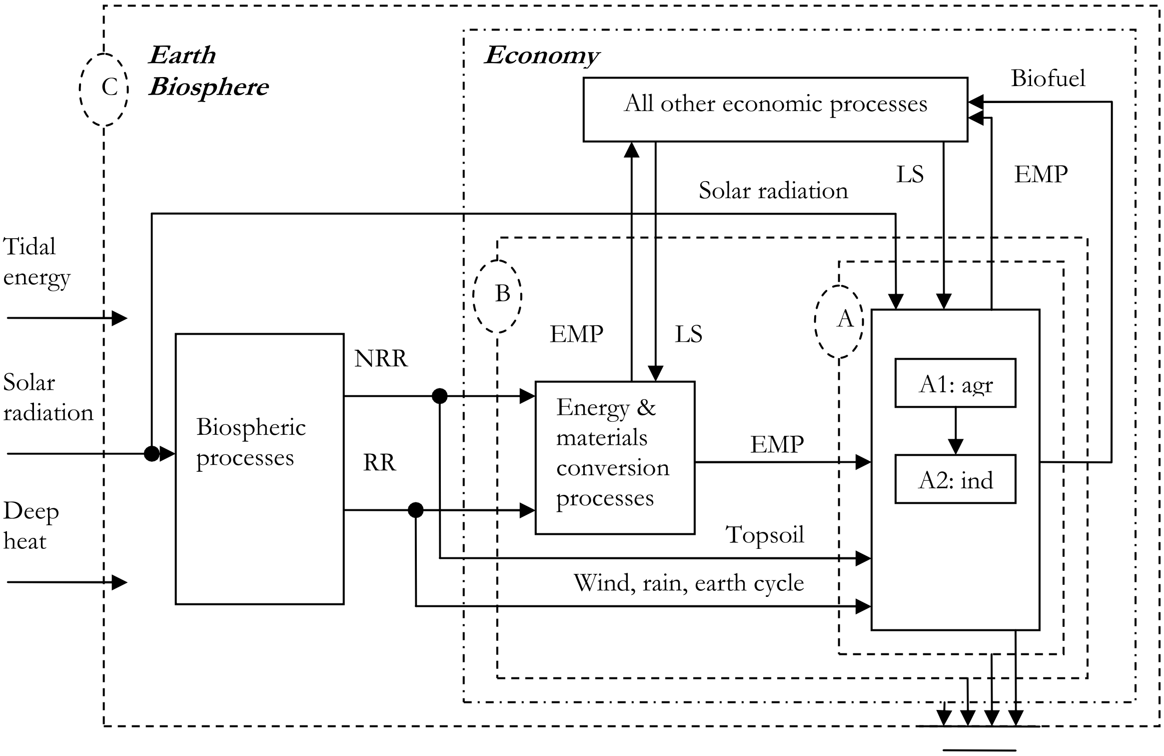

Figure 3.1 The diagram of biofuel techno-system showing various scales for thermodynamic system analysis. Level A: the foreground production; Level B: the background industrial network; Level C: the supporting Earth biosphere. RR: renewable resources; NRR: non-renewable resources; EMP: energy and material products; and LS: labor and service.

As regards the foreground production processes, the agricultural production of corn grain and stover (A1) was calculated mainly on the basis of the average situation in the US, with a corn grain yield of 8687 kg/ha/yr (12% moisture content) and a harvested stover yield of 5210 kg/ha/yr (15% moisture content). However, the industrial conversion of stover to ethanol (A2) was limited to the individual plants in the State of Iowa, where 1 kg of ethanol (99.5% by mass) was produced from 3.97 kg of stover, which means an ethanol yield of 1312 kg/ha/yr, with 1.23 kWh electricity co-produced for process use. A description of foreground production processes in detail can be found in the Swiss Centre of Life Cycle Inventories (2009), Luo *et al.* (2009), and a report by NERL (Aden *et al.*, 2002). However, due to lack of process details, transportation of corn stover from the farmland to the bio-refinery plants is left out of consideration in the study.

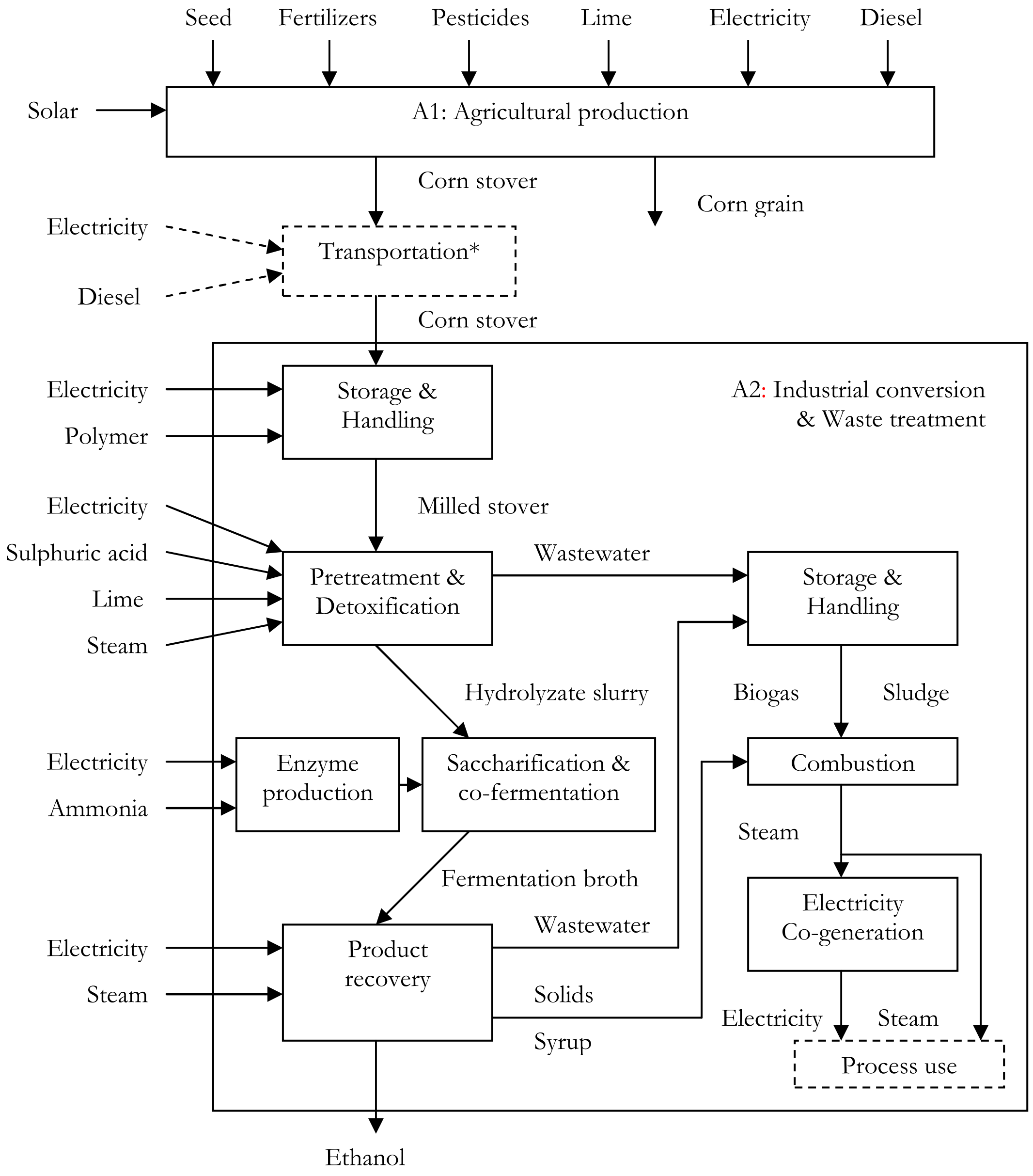

Figure 3.2 Detailed diagram of scale level A of the biofuel techno-system. Nomenclature for the diagram can be found in (Aden *et al.*, 2002). *Due to lack of process details and data, transportation of corn stover from the farmland to the bio-refinery plants is left out of consideration in the study.

3.2.2 Data sources

Data used in this study were obtained from various sources. Agricultural data and data on energy and materials conversion processes were obtained from the ecoinvent database v2.1 (Swiss Centre of Life Cycle Inventories, 2009) and Luo *et al.* (2009). Data on the industrial conversion and waste treatment were collected from a report by NERL (Aden *et al.*, 2002). Data on direct solar irradiation and other RRs were obtained from the NASA atmospheric science database (NASA, 2009), the Climatology Report by the Iowa Agricultural Department (Iowa Agricultural Department, 2008) and the Department of Commerce National Climatic Database (US DOC, 2009). Data gaps were partially filled by making various assumptions and referring to some trivial literature as noted below. Raw data were converted into flows of energy, exergy and emergy; see Appendix Table S3.1, S3.2, and S3.3.

3.2.3 Energy analysis (EA)

Various types of measurement methods are used in energy analysis (EA) to determine the direct and indirect energy inputs that a system uses to deliver a product or service (IFIAS, 1978). Energy demand can be evaluated on the basis of different valuation concepts; a discussion of the pros and cons of these concepts can be found in Frischknecht *et al.* (1998). In the present study, the direct energy demand (DED) was defined so as to account for the direct energy inputs (primary energy resources and energy products) to the foreground production processes (scale A). The indirect energy inputs which are needed to deliver the inputs as materials products can also be traced back to primary energy resources, allowing us to define the cumulative energy demand (CED) in the industrial network (scale B). CED, in this respect, extends DED so as to include the indirect energy inputs as well. Furthermore, the net energy value (NEV) can be defined by deducting CED_{EMP} from the energy contained in the products (E_{pro}) which was measured as their lower heating value in this study.

3.2.4 Exergy analysis (ExA)

Exergy is defined as the maximum amount of work which can be obtained from a flow of energy or materials when it is brought into equilibrium with the reference environment (for a commented history of the concept, see Sciubba and Wall (2007)). It has the same unit as energy, *viz.*, Joules. This study adopted the reference environment proposed by Szargut *et al.* (1988, 2005) with the natural environment subsystem by Gaggioli and Petit (1977). Exergy is consumed in all real processes in proportion to the entropy being produced. Exergy analysis (ExA) can measure exergy loss or exergy destruction and is being used in various fields, including industrial and engineering models, economics, environmental impact assessment, systems ecology, and societal systems. A comprehensive review of the use of ExA can be found in Dewulf *et al.* (2008).

Just as in EA, the direct exergy demand (DExD) is defined at scale A. The cumulative exergy demand (CExD), which is similar to the cumulative exergy consumption (CExC) defined by Szargut (2005) and the cumulative exergy extracted from the natural environment (CEENE) as defined by Dewulf *et al.* (2007), is defined at scale B. The net exergy value (NExV) is then obtained by deducting $CExD_{EMP}$ from the exergy content of products (Ex_{pro}).

3.2.5 Emergy analysis (EmA)

Emergy is defined as the total amount of available energy of one form that was originally used up, directly and indirectly, in the work of making a product or service (Odum, 1996). Emergy theory considers solar energy to be the primary source feeding all processes occurring at scale C. Hence the unit of emergy, although representing energy and thus being measured in Joules, is named solar emergy Joules (seJ). Emergy analysis (EmA) categorizes the inflows of a system used to deliver a product or service into locally renewable (RR, solar, rain, wind, earth cycle, *etc.*), locally non-renewable (NRR, topsoil, *etc.*), and purchased (F, energy and materials products, labor, service, *etc.*). The total emergy driving the system can be determined by adding up the emergy of all inflows, and is assigned to the product or service delivered (for details about the emergy algebra, see Odum (1996) and Brown and Herendeen (1996). After all the flows of interest have been quantified, a set of indicators can be developed for policy making, by assessing the environmental performance of the system itself (Brown and Ulgiati, 1997).

3.2.6 Synthesis of sustainability indicators

An energy source is environmentally sustainable when it consumes few natural resources, especially non-renewable resources, contribute to the overall energy supply chain, and is produced with high efficiency. On the basis of a thermodynamic analysis of the biofuel techno-system, the environmental sustainability of the system can be assessed against a range of indicators, *viz.*, resource consumption, input renewability, physical profit, and system efficiency. Table 3.1 below summarizes the various thermodynamic quantities of sustainability indicators for EA, ExA, and EmA at the three scales.

Table 3.1 Indicators for different types of thermodynamic system analysis

Quantity	Definition	Scale	Indication	Unit
DED	Total energy of the direct inputs	A	Resource consumption	J
DExD	Total exergy of the direct inputs	A	Resource consumption	J
CED	Total energy of the used primary resources	B	Resource consumption	J
CExD	Total exergy of the used primary resources	B	Resource consumption	J
$\mathrm{Em}_{\mathrm{pro}}$	Total solar energy used for a product or service	C	Resource consumption	seJ
α_{e}	$\alpha_{\mathrm{e}} = \mathrm{E}_{\mathrm{RR}}/\mathrm{DED}$	A	Input renewability	-
α_{ex}	$\alpha_{\mathrm{ex}} = \mathrm{Ex}_{\mathrm{RR}}/\mathrm{DExD}$	A	Input renewability	-
α_{em}	$\alpha_{\mathrm{em}} = \mathrm{Em}_{\mathrm{RR}}/\mathrm{Em}_{\mathrm{pro}}$	C	Input renewability	-
NEV	$\mathrm{NEV} = \mathrm{E}_{\mathrm{pro}} - \mathrm{CED}_{\mathrm{EMP}}$	B	Physical profit	J
NExV	$\mathrm{NExV} = \mathrm{Ex}_{\mathrm{pro}} - \mathrm{CExD}_{\mathrm{EMP}}$	B	Physical profit	J
ε_{e}	$\varepsilon_{\mathrm{e}} = \mathrm{E}_{\mathrm{pro}}/\mathrm{DExD}$	A	System efficiency	-
$\varepsilon_{\mathrm{ex}}$	$\varepsilon_{\mathrm{ex}} = \mathrm{Ex}_{\mathrm{pro}}/\mathrm{DExD}$	A	System efficiency	-
$\varrho_{\mathrm{e}}^{-1}$	$\varrho_{\mathrm{e}} = \mathrm{CED}/\mathrm{E}_{\mathrm{pro}}$	B	System efficiency	-
$\varrho_{\mathrm{ex}}^{-1}$	$\varrho_{\mathrm{ex}} = \mathrm{CExD}/\mathrm{Ex}_{\mathrm{pro}}$	B	System efficiency	-
$\varrho_{\mathrm{em}}^{-1}$	$\varrho_{\mathrm{em}} = \mathrm{Em}_{\mathrm{pro}}/\mathrm{E}_{\mathrm{pro}}$	C	System efficiency	-

3.3 Results and discussion

3.3.1 Resource consumption

Figure 3.3 represents the flows of primary resources, EMP, final product and co-products of the system on the basis of 1 kg of ethanol, in terms of EA and ExA. The balance between the inflows and outflows can be completed by taking wastes, exhausted heat, and irreversible exergy destruction into account. It is clear that RR, mainly solar radiation, dominates the resource consumption of process A1, both at scale A and at scale B. This corresponds with the nature of cropping, *i.e.*, the process of photosynthesis.

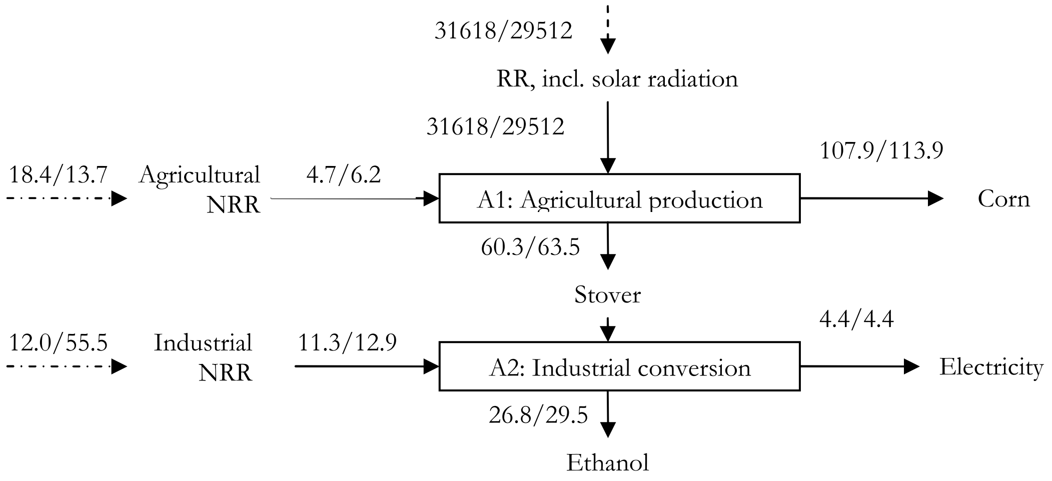

Figure 3.3 Energy/exergy flows diagram of the ethanol techno-system, in MJ/kg EtOH. Figures at dashed lines are the shares of CED/CExD. Figures at solid lines are the shares of DED/DExD and the energy/exergy of products.

Table 3.2 summarizes the results of resource consumption in terms of EA and ExA. At scale A, apart from solar radiation, the direct energy required to deliver 1 kg of ethanol is 15.98 MJ. At scale B, the CED due to EMP inputs related to process A1 that is required to finally produce 1 kg of ethanol turns out to be 18.39 MJ, 74.5% of which consists of indirect inputs such as primary energy for the production of corn seeds, chemicals, and farm machinery. Whilst related to process A2, most of the CED (94.3%) consists of the direct inputs of electricity and steam into the process, while a much lower amount of energy is used to deliver materials products.

Table 3.2 Resource consumption in EA and ExA of the ethanol techno-system

Resource consumption	Process A1		Process A2	Techno-system
(MJ/kg EtOH)	EMP	Solar [a]		EMP
DED	4.68	3.16E+04	11.30	15.98
DExD	6.15	2.95E+04	12.91	19.06
CED	18.39	3.16E+04	12.03	30.42
CExD	13.67	2.95E+04	55.47	69.14

[a] The solar energy used for electricity production and oil refinery in the supply chain of EMP is lower by several orders of magnitude than the insolation energy for cropping.

The DExD value corresponds to a direct consumption of 19.1 MJ exergy of NRRs, mainly as EMP, to produce 1 kg of ethanol. By comparison, Dewulf *et al.* (2005) found that for the corn-to-ethanol system it takes 6.39 MJ exergy of this kind to produce 1 kg of ethanol. Both exergy values are less than the exergy content of the ethanol (29.5 MJ/kg) that these two techno-systems deliver. This is because stover and corn store a certain fraction of solar exergy in their chemical structures through the process of photosynthesis. Though the fraction may be small, the stored solar exergy is generally larger than the exergy of EMP invested in the agricultural production system.

The $CExD_{EMP}$ translates into an exergy intensity for ethanol of $\varrho_{ex} = 2.34\ MJ_{EMP}/MJ_{pro.}$ In the year 2007, bioethanol production in the US was 0.6 EJ[1] (Howarth and Bringezu, 2009). This corresponds to a $CExD_{EMP}$ of 1.4 EJ, which is already of the order of magnitude of 1% of the global anthropogenic exergy consumption (13 TW, *i.e.*, 378 EJ, (Szargut, 2003)). This suggests a considerable impact of the regional application of the biofuel techno-system in the US on the Earth.

The emergy flows diagram of the techno-system is shown in Figure 3.4. It shows an Em_{pro} of 9.82 E+12 seJ, which means that 9.82 E+12 J of solar energy is used directly and indirectly to deliver 1 kg of ethanol at scale C. The emergy inputs of local RRs, local NRRs and purchased inflows account for 12.0%, 5.2%, and 82.8%, respectively, of the emergy resource consumption of the ethanol techno-system.

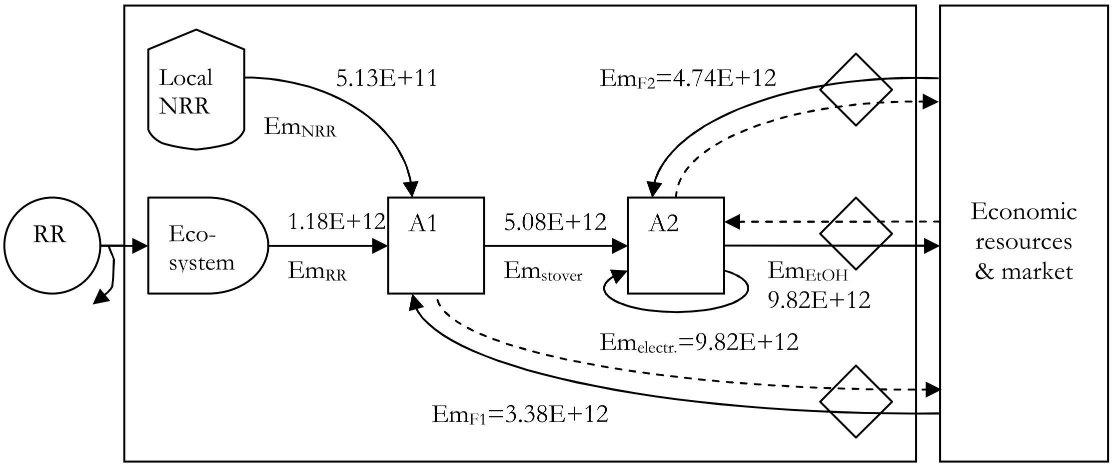

Figure 3.4 Emergy flows diagram of the ethanol techno-system, in seJ/kg EtOH

3.3.2 Input renewability

Table 3.3 summarizes the results in terms of input renewability of the techno-system. It shows that, similar to Table 3.2, the renewable resources, mainly solar radiation, account for no less than 99.9% of the direct energy/exergy inputs both for process A1 and for the techno-system. The agricultural production and the stover-to-ethanol techno-system are thus highly renewable-based. The final product (ethanol), the coproduct (corn), and the intermediate product (stover) can therefore be regarded as renewable resources for further application in the economy from an energy/exergy viewpoint. However, the α_{em} of 12.0% resulting from EmA does not support this conclusion. Other available research findings show even lower emergy-based renewability, *i.e.*, 5.36% for ethanol produced from corn in Italy (Ulgiati, 2001) and 9.45% for ethanol produced from wheat in China (Dong *et al.*, 2008). All three studies indicate that, in terms of emergy, the product ethanol cannot be regarded as a renewable energy source.

Table 3.3 Input renewability of the ethanol techno-system

Renewability	Process A1	Process A2	Techno-system
α_e	> 99.9%	84.2%	99.9%
α_{ex}	> 99.9%	83.1%	99.9%
α_{em}	n.a.	n.a.	12.0%

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[1] The cited value is based on the HHV of ethanol, so the exergy value is approximately the same.

3.3.3 Physical profit

Table 3.4 summarizes the results in terms of physical profit from the techno-system. Both NEV and NExV are positive, which indicates that the ethanol techno-system contributes to the overall supply of energy/exergy resources that can be readily utilized to meet human needs. If the credits of co-products are not taken into account, EA yields a negative NEV (-3.62 MJ/kg EtOH). This is similar to the results by Pimental *et al.* (2005) and Patzek (2004), who studied corn as the feedstock for ethanol production.

Table 3.4 Physical profit of the ethanol techno-system

	EMP	Products			Physical profit
		Ethanol	Corn	Electricity	(MJ/kg EtOH)
EA	30.42	26.80	107.97	4.43	108.78
ExA	69.15	29.50	113.88	4.43	78.66

3.3.4 System efficiency

Table 3.5 summarizes the results in terms of energy/exergy efficiency and energy/exergy/emergy intensity of the techno-system. It shows that the techno-system is more efficient in terms of exergy than in terms of energy required to deliver the products. The energy/exergy efficiencies of process A1 and the overall techno-system are all very low (<1%), indicating that the techno-system is not efficient in terms of delivering energy/exergy into the products. This is mainly due to the nature of agriculture, *i.e.*, the process of photosynthesis, which inherently has limited efficiency and operation time.

Table 3.5 System efficiency of the ethanol techno-system

Efficiency	Process A1	Process A2	Techno-system
ε_{e}	0.53%	43.6%	0.44%
ε_{ex}	0.60%	44.3%	0.50%
ϱ_{e}^{-1}	0.53%	0.27%	0.44%
ϱ_{ex}^{-1}	0.60%	0.32%	0.50%
ϱ_{em}^{-1}	n.a.	n.a.	2.73E-06

The exergy intensity translates into a cumulative degree of thermodynamic perfection (CDP) of 0.005, which is much lower than the range of CDP for conventional EMP technologies (0.05 – 0.84); for instance, diesel production has a CDP of 0.835. Besides, the emergy intensities of bioethanol (2,95E+05 seJ/J (Ulgiati, 2001) – 3,66E+05 seJ/J) and biodiesel (average value 4.51E+05 seJ/J) (Ulgiati *et al.*, 1997) are much higher than those of fossil fuels (coal, crude oil, and natural gas, 6.67E+04 seJ/J – 8.89E+04 seJ/J), indicating that the biospheric processes of producing fossil fuels have been more efficient than the human dominated processes of cropping for biofuels. This is mainly because large amounts of fossil fuels and fossil-derived fertilizers and chemicals are usually used in agricultural production and industrial conversion[2].

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[2] In the specific case under consideration, however, most of the electricity and steam used in the bio-refinery were produced from lignin and wastes by waste treatment, so actually only a small amount of fossil fuels was used for the industrial conversion.

3.3.5 Contribution analysis

Various inflows were taken into account and weighted by their respective conversion factors, *viz.*, exergy-to-energy ratios, CDP, and emergy intensities; see Appendix Table S3.2 and S3.3.

Since only four energy inflows, *viz.*, solar radiation, diesel, electricity, and steam, are taken into account in EA, process A1 and process A2 as different sub-processes, rather than as different inflows, to investigate their contributions to energy use. Solar radiation is explicitly left out of consideration, since it dominates CED for up to 99.9% as shown in Table 3.3. A pertinent energy signature is presented in Figure 3.5[3]. In process A1, a large amount of natural gas is used for steam reforming in the production of ammonia, which is then used in the production of nitrogen fertilizer. In process A2, a large amount of steam (5.33 MJ/kg EtOH) is used to maintain a high temperature condition for stover prehydrolysis and to prepare the boiler feed water. And the production of enzyme uses a large amount of electricity (2.59 MJ/kg EtOH) to pump air into the fermentor to ensure aerobic conditions. Figure 3.5 shows that fertilizer use, pretreatment and detoxification, and enzyme production are the three largest contributors to the energy use.

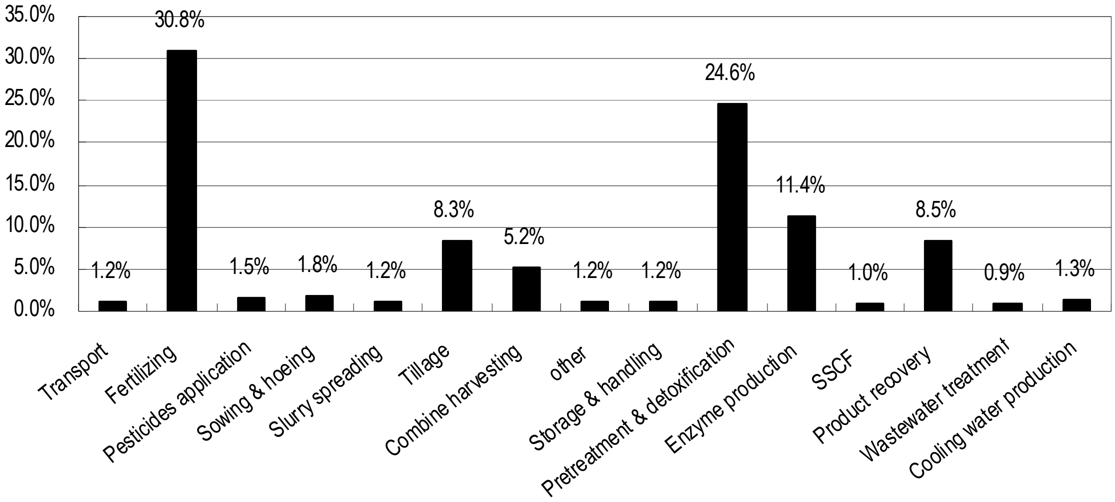

Figure 3.5 Energy signature of the ethanol techno-system

Similarly, an exergy signature can be drawn, as shown in Figure 3.6, and an emergy signature in Figure 3.7. These obviously present different outcomes of contribution analysis. They also indicate that ExA and EmA take different inflows into account at scale B and scale C.

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[3] Figure 3.5 was drawn after Luo *et al.* (2009), who presented a so-called energy products-to-gate analysis. So compared to the CED in our study, the energy conversion processes were actually left out of consideration.

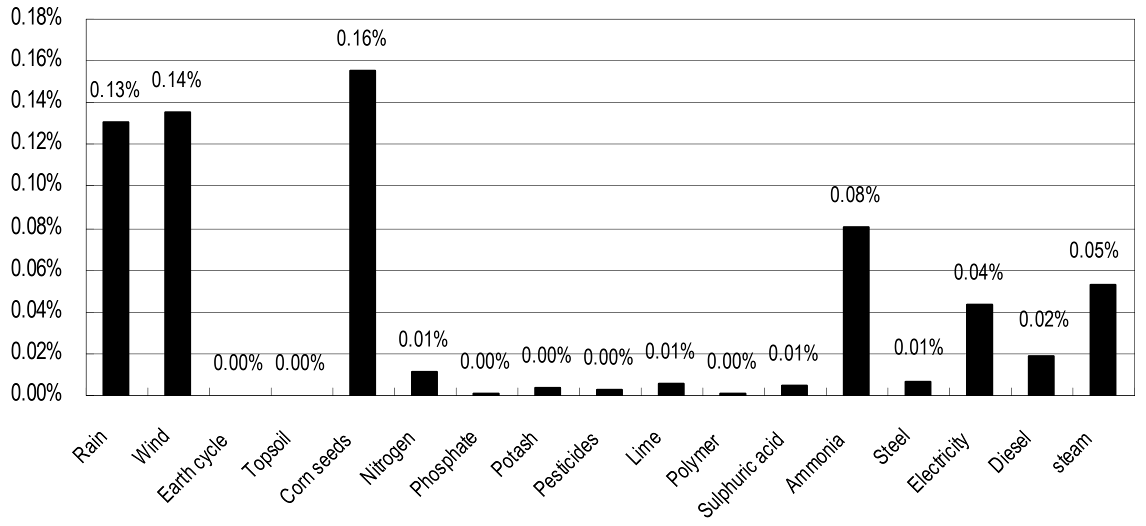

Figure 3.6 Exergy signature of the ethanol techno-system

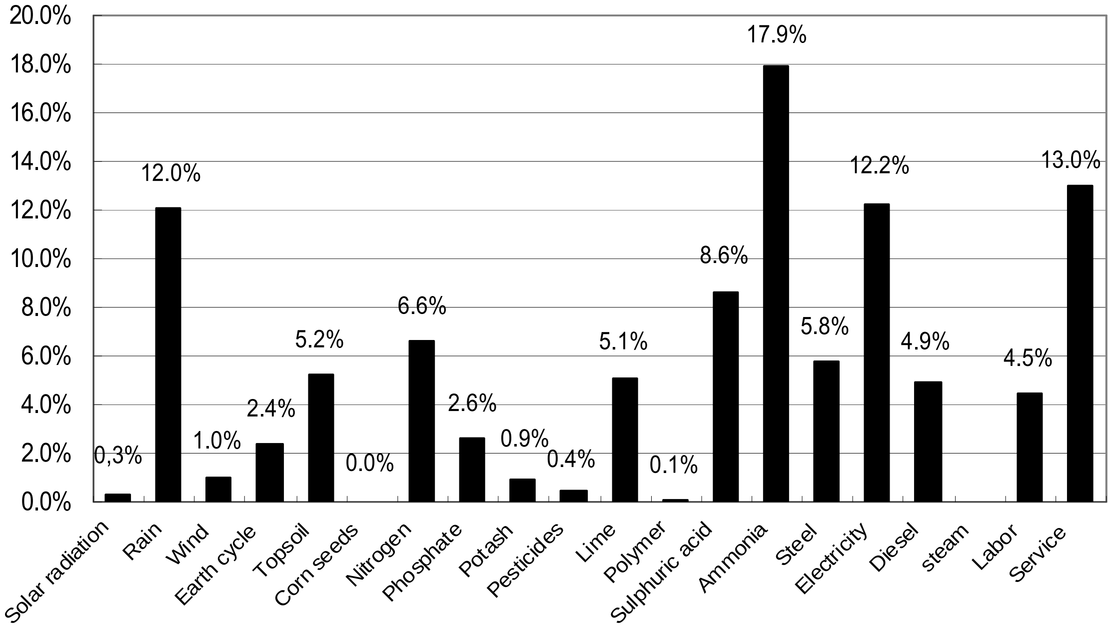

Figure 3.7 Emergy signature of the ethanol techno-system

3.3.6 Sensitivity analysis of EmA

Emergy intensity, which is equivalent to the concept of transformity used in Odum (1996) and Brown and Herendeen (1996), is a crucial concept in EmA. The emergy intensity of a product is case-specific in terms of the spatial and temporal frames and the pathway by which the product is delivered. Primary resources (RRs and NRRs) from the biosphere, which undergo natural selection and evolution and are presumed to result from long trial and error processes (Fath, 2004; Jørgensen and Svirezhev, 2004), have a range of emergy intensities, and a global average value is explicitly chosen in practice. For many manufactured products, *e.g.* electricity, steel, *etc.*, the emergy intensity varies case by case, since a product is technologically specific. This section investigates the consequences of different choices for the emergy intensity.

Table 3.6 Sensitivity to emergy intensity of emergy analysis

Emergy intensity, in seJ/J	Grid elect	Coproduced elect	Ethanol
Scenario 1[a]	2.68E+05	2.22E+06	3.66E+05
Scenario 2[b]	2.68E+05	3.27E+07	5.39E+06

[a] Scenario 1: coproduced electricity by A2 enters the national grid and the process electricity in A2 is purchased from the economy

[b] Scenario 2: coproduced electricity is reused as process energy in A2

Table 3.6 presents the outcomes in terms of emergy intensities for two scenarios that differ in the source of process electricity used in process A2. Since the difference in percentage is significant, a correspondingly different result of the contribution analysis by EmA can be expected. Despite the case study on process A2 reported by NREL (Aden, 2002), where almost all of the co-produced electricity was reused as process energy (*i.e.*, the same as in Scenario 2), when investigating future large scale applications of the bioethanol techno-system, it is more likely that the process electricity will be purchased from the national economy. This is why our analysis based on Scenario 1 was conducted as described above, in order to assess the consequences of the promotion of bioethanol technology at national level in the US. The main cause of the difference shown in Table 3.6 is undeniably the fact that Scenarios 1 and 2 model different systems, *viz.*, process A2 and the background main economy.

3.3.7 Additional discussion

As shown in Figures 3.6 and 3.7, different methods of thermodynamic analysis take different resource inflows into account. Table 3.7 summarizes the importance of four categories of emergy inflows in ethanol production from stover in the US, corn in Italy (Ulgiati, 2001) and wheat in China (Dong, 2008). Emergy inflows such as local RRs and NRRs from the biosphere account for 17.2%, 7.7%, and 19.2% of total emery consumption in ethanol production from stover, corn, and wheat, respectively, while emergy associated with labor and service from the economy contribute 17.5%, 22.3%, and 39.7%, respectively. These three categories of inflows are not taken into account in many other types of energy analysis; neither is the category of purchased labor and service in ExA. However, their importance, despite the fact that they are only being shown from an emergy viewpoint here, indicates that the complex bioethanol system may be more accurately depicted if their necessary contribution to support the system is not disregarded.

Table 3.7 Breakdown of main emergy inflow categories of ethanol production from stover, corn, and wheat

	Stover	Corn	Wheat
local RRs	12.0%	5.4%	9.4%
local NRRs	5.2%	2.3%	9.8%
purchased products, F_{EMP}	65.3%	70.0%	41.1%
purchased L & S, F_{LS}	17.5%	22.3%	39.7%

Table 3.5 also shows that the emergy intensity is about 1600 times higher than the energy intensity, *i.e.*, the unit cumulative primary energy input. This is not surprising when the necessary environmental support for the earth cycles and processes providing primary resources and ecological services is taken into account. Since process A2 is partly supported by its self-produced electricity and steam, we have mainly considered process A1, *i.e.*, the agricultural production. As shown in Table 3.2, it has a CED of 18.4 MJ/kg EtOH, *i.e.*, 18.4 MJ of primary energy, which is mainly fossil fuels, to deliver 1 kg of ethanol for the process A1. Given that the emergy intensity of the fossil fuels is about 8.00E+04 seJ/J, the above CED translates into an emergy intensity of about 1.5E+12, which is of the same order of magnitude as the result of the EmA. This shows an approximate link between CED and emergy consumption.

3.4 Conclusions and comments

This study used three types of thermodynamic system analysis, *viz.*, energy analysis (EA), exergy analysis (ExA), and emergy analysis (EmA), which can be regarded as a linear sequence of increasingly abstract types of analysis (Brown, 1996; Jørgensen and Svirezhev, 2004; Nilsson, 1997; Gattie *et al.*, 2007). The study shows that there is not really a one dimensional linear sequence, but rather basically two separate dimensions: scale and metric. The scale dimension identifies three archetypal choices: the foreground production process (A); A plus the supply chain (B); and finally B plus the biospheric processes (C). The metric dimension distinguishes two options: energy as such and energy insofar as it can be used for work with respect to a reference environment, *i.e.*, exergy. Given that EA and ExA can be performed at scales A and B, and that EmA is an analysis at scale C on the basis of the energy definition, we can now map the field as shown in Table 3.8.

Table 3.8 The place of EA, ExA and EmA in the two-dimensional diagram of scale and metric. Notice that ExA at scale C, although conceivable, has not been investigated in the present study.

Metric	Scale A	Scale B	Scale C
Energy	EA	Cumulative EA	EmA
Exergy	ExA	Cumulative ExA	–

The two-dimensional thermodynamic system analysis is proposed to depict the complex biofuel techno-system by measuring the flows and describing the processes. The environmental performance of the system can consequently be assessed against several sustainability indicators, *viz.*, resource consumption, input renewability, physical profit, and system efficiency. Conclusions can be drawn on the basis of both the case study of the stover to ethanol techno-system and the comparison with available literature results:

- Solar radiation dominates the resource consumption from an energy/exergy viewpoint, and the labor and service invested also contribute substantially to the bioethanol techno-system.
- The regional production of bioethanol in the US has considerable implications at a global scale in terms of exergy consumption.
- A straightforward conclusion on whether biofuels are renewable resources cannot be drawn for the bioethanol case investigated here, as this depends on the thermodynamic metric and scale level chosen.
- The bioethanol techno-system contributes to the overall supply of energy/exergy resources that can be readily utilized for human society.

- The bioethanol techno-system is not efficient in terms of delivering energy/exergy into the products. Also, the human-dominated processes of cropping for biofuels are less efficient than the biospheric processes of producing fossil fuels, from an emergy point of view.
- The contributions made to the bioethanol techno-system by different inflows can be investigated by the three methods of thermodynamic analysis. Each selected method has its own specific outcome.
- The choice of emergy intensity of manufactured products has a large influence on the outcomes in terms of sensitivity in EmA.

The methodology of thermodynamic system analysis developed in this study can be readily applied to other biofuel feed-stocks and other advanced biofuel techno-systems, *e.g.*, Sorguven and Özilgen (2010) and Hertwich and Zhang (2009), as well as to any other energy and materials based systems. Nevertheless, since the three methods of thermodynamic analysis are based on different theoretical assumptions and cover different flows and processes, the interrelationships among these three methods need to be investigated further and framed more consistently to offer more comparable results. Broader sustainability indicators like GHG emissions (De Souza *et al.*, 2010), biodiversity (Groom *et al.*, 2007), land and water requirements (Gopalakrishnan *et al.*, 2009; Rathmann *et al.*, 2010), and air and water pollution (Williams *et al.*, 2009) might be linked to some thermodynamic indicators to tackle the complex biofuel issue according to our different concerns. The present study, however, only supports sustainability decision making by offering information about the performance of the biofuel techno-system in the new two-dimensional scale-and-metric framework developed here.

Appendix

Table S3.1 Energy data based on Luo *et al.* (2009) and the calculation of CED

Agriculture				
			Energy **kJ/kg EtOH**	
Primary energy for energy conversion				
	electricity production	oil refinery		
Coal	2608,00	265,19	2873,19	
Uranium	1415,32	126,74	1542,06	
Natural gas	475,66	357,04	832,70	
Crude oil	290,08	8485,55	8775,63	
Hydropower	221,00	21,05	242,05	
Wind	38,20	3,31	41,51	
Biomass	25,80	3,01	28,81	
Solar	0,50	0,04	0,54	
	5074,56	9261,93	**14336,49**	
Primary energy for materials conversion				
Natural gas			4037,60	
Coal			14,89	
			4052,49	
		CED_{agr}	**18388,98**	
		=	**24126,34**	MJ/ha/yr
Biorefinery				
Electricity			4216,95	
Steam			7167,69	
Diesel			20,61	
Light fuel oil			12,87	
Heave fuel oil			253,28	
Natural gas			224,54	
Hard coal			135,11	
		CED_{ind}	**12031,05**	
		=	**15784,74**	MJ/ha/yr
		CED	30420,03	kJ/kg EtOH
		=	39911,08	MJ/ha/yr
		LHV	26,8	MJ/kg EtOH
		=	21,2	MJ/L EtOH
		NEV=	LHV-CED	
		=	(3,62)	MJ/kg EtOH

Table S3.2 Raw inflow data and the calculation of DED, DExD, and CExD

Agricultural production

Note	**Flow item**	**Unit**	**Raw amount**	**DED MJ/ha/yr**	**Spec. Ex MJ/kg**	**Ex/E**	**DExD MJ/ha/yr**	**CDP**	**CExD MJ/ha/yr**
Input									
1	solar	MJ/ha/yr	4,15E+07	4,15E+07		0,933	3,87E+07	1	3,87E+07
2	rain (chemical potential)	MJ/ha/yr	5,09E+04			1	5,09E+04	1	5,09E+04
3	wind	MJ/ha/yr	5,27E+04			1	5,27E+04	1	5,27E+04
4	earth cycle	MJ/ha/yr	3,00E+04						n.a.[a]
5	topsoil	MJ/ha/yr	5,43E+03						n.a.
						DExD$_{\text{agr.RR}}$	**3,87E+07**	**CExD$_{\text{agr.RR}}$**	**3,87E+07**
6	N-fertilizer as N	kg/ha/yr	1,34E+02		3,68E+00		4,93E+02	0,112	4,40E+03
7	P-fertilizer as P_2O_5	kg/ha/yr	5,08E+01		2,91E+00		1,48E+02	0,387	3,82E+02
8	K-fertilizer as K_2O	kg/ha/yr	6,25E+01		3,43E+00		2,14E+02	0,14	1,53E+03
9	lime	kg/ha/yr	2,64E+02		1,97E+00		5,20E+02	0,361	1,44E+03
10	pesticides	kg/ha/yr	2,33E+00		2,40E+01		5,59E+01	0,053	1,05E+03
11	corn seeds	kg/ha/yr	1,87E+02		1,72E+01		3,22E+03	0,053	6,07E+04
12	electricity	MJ/ha/yr	4,36E+02	4,36E+02		1	4,36E+02	0,35	1,25E+03
13	diesel	MJ/ha/yr	5,71E+03	5,71E+03		1,07	6,11E+03	0,835	7,31E+03
14	steel	kg/ha/yr	1,36E+01		7,04E+00		9,57E+01	0,17	5,63E+02
15	labor	J	1,16E+08						n.a.
16	service	USD	6,27E+02						n.a.
			DED$_{\text{agr.NRR}}$	**6,14E+03**		**DExD$_{\text{agr.NRR}}$**	**8,07E+03**	**CExD$_{\text{agr.NRR}}$**	**1,79E+04**
Output									
17	stover	kg/ha/yr	5,21E+03		1,60E+01		**8,34E+04**		
18	corn	kg/ha/yr	8,69E+03		1,72E+01		**1,49E+05**		

[a] n.a.= not available

Table S3.2 Raw inflow data and the calculation of DED, DExD, and CExD

Industrial Conversion

Note	**Flow item**	**Unit**	**Raw amount**	**DED MJ/ha/yr**	**Spec. Ex MJ/kg**	**Ex/E**	**DExD MJ/ha/yr**	**CDP**	**CExD MJ/ha/yr**
Input									
19	stover	kg/ha/yr	5,21E+03		1,60E+01				
20	polymer	kg/ha/yr	1,48E+00		2,29E+01		3,40E+01	0,15	2,27E+02
21	sulphuric acid	kg/ha/yr	1,75E+02		1,67E+00		2,92E+02	0,15	1,95E+03
22	lime	kg/ha/yr	1,27E+02		1,97E+00		2,51E+02	0,361	6,95E+02
23	ammonia	kg/ha/yr	3,63E+02		1,98E+01		7,18E+03	0,229	3,14E+04
24	electricity	MJ/ha/yr	5,46E+03	5,46E+03		1	5,46E+03	0,35	1,56E+04
25	steam	MJ/ha/yr	9,41E+03	9,41E+03		0,356	3,35E+03	0,161	2,08E+04
26	steel	kg/ha/yr	5,23E+01		7,04E+00		3,68E+02	0,17	2,17E+03
27	labor	yrs	2,00E-03						n.a.
28	service	USD	2,39E+02						n.a.
			DED_{ind}	**1,49E+04**		**$DExD_{ind}$**	**1,69E+04**	**$CExD_{ind}$**	**7,28E+04**
Output									
29	ethanol	kg/ha/yr	1,31E+03		2,95E+01		3,87E+04		
		MJ/ha/yr	3,52E+04						
30	electricity	MJ/ha/yr	5,81E+03			1	5,81E+03		
			DED_{NRR}	**2,10E+04**		**$DExD_{NRR}$**	**2,50E+04**	**$CExD_{NRR}$**	**1,80E+07**
	Exergy content of EtOH =		29,52MJ/kg						

Table S3.3 Raw inflow data and the calculation of emergy value, *i.e.*, emergy analysis table (/ha/yr)

Note	Flow item	Unit	Quantity /ha/yr	Emergy intensity seJ/unit	Ref.[a]	Solar emergy seJ/ha/yr	Percent. %
Agricultural production							
renewable inputs							
1	solar	J	4,15E+13	1,00E+00	(1)	4,15E+13	0,3
2	Rain (chemical potential)	J	5,09E+10	3,05E+04	(2)	1,55E+15	12,1
3	wind	J	5,27E+10	2,52E+03	(2)	1,33E+14	1,0
4	earth cycle	J	3,00E+10	1,02E+04	(2)	3,06E+14	2,4
Non-rewable inputs							
5	topsoil	J	5,43E+09	1,24E+05	(2)	6,73E+14	5,2
purchased inputs							
6	N-fertilizer	g	1,34E+05	6,37E+09	(2)	8,54E+14	6,6
7	P-fertilizer	g	5,08E+04	6,54E+09	(2)	3,32E+14	2,6
8	K-fertilizer	g	6,25E+04	1,84E+09	(2)	1,15E+14	0,9
9	lime	g	2,64E+05	1,68E+09	(2)	4,44E+14	3,4
10	pesticides	g	2,33E+03	2,48E+10	(3)	5,78E+13	0,4
11	corn seeds	g	1,87E+05	5,88E+04	(4)	1,10E+10	0,0
12	electricity	J	4,36E+08	2,68E+05	(2)	1,17E+14	0,9
13	diesel	J	5,71E+09	1,11E+05	(2)	6,33E+14	4,9
14	steel	g	1,36E+04	1,13E+10	(2)	1,54E+14	1,2
15	labor	J	1,16E+08	4,50E+06	(5)	5,22E+14	4,1
16	service	USD	6,27E+02	1,93E+12	(6)	1,21E+15	9,4
agricultural product and by-product							
17	stover	g	5,21E+06	1,28E+09	(7)	6,66E+15	51,7
18	corn	g	8,69E+06	7,67E+08	(7)	6,66E+15	51,7
Industrial Conversion							
19	stover	g	5,21E+06	1,28E+09	(7)	6,66E+15	51,7
20	polymer	g	1,48E+03	6,37E+09	(2)	9,44E+12	0,1
21	sulphuric acid	g	1,75E+05	6,37E+09	(2)	1,11E+15	8,6
22	lime	g	1,27E+05	1,68E+09	(2)	2,14E+14	1,7
23	ammonia	g	3,63E+05	6,37E+09	(2)	2,31E+15	17,9
24	electricity	J	5,46E+09	2,68E+05	(2)	1,46E+15	11,4
25	steam	J	9,41E+09	n.a.	(2)	n.a.	n.a.
26	steel	g	5,23E+04	1,13E+10	(2)	5,91E+14	4,6
27	labor	yrs	2,00E-03	2,69E+16	(4)	5,38E+13	0,4
28	service	USD	2,39E+02	1,93E+12	(6)	4,61E+14	3,6
industrial product and byproduct							
29	ethanol	g	1,31E+06	9,81E+09	(7)	1,29E+16	100,0
	ethanol, as joules	J	3,52E+10	3,66E+05	(7)	1,29E+16	100,0
30	electricity	J	5,81E+09	2,22E+06	(7)	1,29E+16	100,0

[a] The reference of emergy transformities: (1) By definition; (2) After Odum (1996); (3) After Brown and Arding (1991); (4) After Ulgiati (2001); (5) Brandt-Williams (2002); (6) UFL (2009); (7) This study.

Footnotes of EmA

Note	Flow Item	Raw amount	Unit	Ref.
Agricultural production				
1	solar			
	Radiation	3,85E+00	KWh/m^2/day	http://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi
	Albedo	1,80E-01		http://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi
	Conversion	3,60E+06	J/kWh	
		3,65E+02	day/yr	
	Cropped area	1,00E+04	m^2/ha	
	Insolation energy	4,15E+13	J/ha/yr	Iowa State, (Lat 42, Lon -93) ; State specified in NREL report
2	rain (chemical potential)			
	precipitation	4,36E+01	in/yr	http://www.iowaagriculture.gov/climatology.asp
	Conversion	2,54E+01	in/mm or in/(L/m^2)	
	Cropped area	1,00E+04	m^2/ha	
	water density	1,00E+00	kg/L	
	run-off coefficient	7,00E-02		Brandt-Williams, 2002
	Gibbs free energy of water	4,94E+03	J/kg	
	energy of rain	5,09E+10	J/ha/yr	
3	wind			
	velocity	1,15E+01	mile/h	http://cdo.ncdc.noaa.gov/cgi-bin/climatenormals/climatenormals.pl
	Conversion	1,61E+03	m/mile	
		3,60E+03	s/h	
		3,15E+07	s/yr	
	air density	1,23E+00	kg/m^3	
	drag coefficient	1,00E-03		Brandt-Williams, 2002
	Cropped area	1,00E+04	m^2/ha	
	energy of wind	5,27E+10	J/ha/yr	
4	earth cycle			
	heat flow through earth crust contributing to uplift replacing erosion, *i.e.*, deep heat			
	average flow per area	3,00E+06	J/m^2/yr	Odum, 1996
	Cropped area	1,00E+04	m^2/ha	
	earth cycle energy	3,00E+10	J/ha/yr	
5	topsoil			
	organic matter loss due to soil erosion	2,00E+04	kg/ha/yr	http://www.earth-policy.org/Books/Eco/EEch3_ss5.htm

	organic matter content in topsoil	4,00E-02		Pimentel *et al.*, 1995
	water content in organic matter	7,00E-01		estimation of average value
	energy content of dry organic matter	5,40E+03	kcal/kg	
	Conversion	4,19E+03	J/kcal	
	energy loss	5,43E+09	J/ha/yr	
6	nitrogen fertilizer as N			
	ammonia, liquid, at plant	8,44E+00	g/kg corn	ecoinvent
	ammonia, liquid, at plant, as N	6,95E+00	g/kg corn	
	urea as N	3,54E+00	g/kg corn	ecoinvent
	ammonia nitrate as N	4,89E+00	g/kg corn	ecoinvent
	total N-fertilizer	1,54E+01	g/kg corn	
	corn yield	8,69E+03	kg corn/ha/yr	
	N-fertilizer	1,34E+05	g/ha/yr	
7	phosphate fertilizer as P_2O_5			
	diammonium phosphate as P_2O_5	5,85E+00	g/kg corn	ecoinvent
	corn yield	8,69E+03	kg corn/ha/yr	
	P-fertilizer	5,08E+04	g/ha/yr	
8	potash fertilizer as K_2O			
	potassium chloride as K_2O	7,19E+00	g/kg corn	ecoinvent
	corn yield	8,69E+03	kg corn/ha/yr	
	K-fertilizer	6,25E+04	g/ha/yr	
9	lime			
	mass of limestone used	3,04E+01	g/kg corn	ecoinvent
	corn yield	8,69E+03	kg corn/ha/yr	
	total lime	2,64E+05	g/ha/yr	
10	pesticides			
	total pesticides	2,33E+00	kg/ha/yr	ecoinvent
11	corn seeds			
	maize seed IP, at regional store house	2,15E-02	kg/kg corn	ecoinvent
	corn yield	8,69E+03	kg corn/ha/yr	
	total seeds	1,87E+02	kg/ha/yr	
12	electricity			
	direct-used electricity per kg corn	3,32E+02	kJ/6,62kg corn	Luo, 2009
	corn yield	8,69E+03	kg corn/ha/yr	
	total direct-used electricity	4,36E+05	kJ/ha/yr	

13	diesel			
	direct-used diesel per kg corn	4,35E+03	kJ/6,62kg corn	Luo, 2009
	corn yield	8,69E+03	kg corn/ha/yr	
	total direct-used electricity	5,71E+06	kJ/ha/yr	
14	steel			
	steel for agri. machinery (10-yr life span)	1,36E+04	g/ha/yr	after Ulgiati, 2001
15	labor			
	Minnesota case	1,16E+08	J/ha/yr	Campbell, 2008
16	service			
	Minnesota case	6,27E+02	USD/ha/yr	Campbell, 2008
17	stover			
	stover yield	5,21E+06	g/ha/yr	Luo, 2009
18	corn			
	corn yield	8,69E+06	g/ha/yr	Luo, 2009
Industrial				
19	stover			
	the same as 17			
20	polymer			
	polymer per kg ethanol	1,13E+00	g/kg	Luo, 2009
	ethanol production	1,31E+03	kg/ha/yr	
	total polymer	1,48E+03	g/ha/yr	
21	sulphuric acid			
	sulphuric acid per kg ethanol	1,33E+02	g/kg	Luo, 2009
	ethanol production	1,31E+03	kg/ha/yr	
	total sulphuric acid	1,75E+05	g/ha/yr	
22	lime			
	lime per kg ethanol	9,70E+01	g/kg	Luo, 2009
	ethanol production	1,31E+03	kg/ha/yr	
	total lime	1,27E+05	g/ha/yr	
23	ammonia			
	ammonia per kg ethanol	2,76E+02	g/kg	Luo, 2009
	ethanol production	1,31E+03	kg/ha/yr	
	total ammonia	3,63E+05	g/ha/yr	
24	electricity			
	feedstock storage & handling	2,87E+02	kJ/kg ethanol	Luo, 2009

	pretreatment & hydrolyzate condition	2,52E+02	kJ/kg ethanol	Luo, 2009
	enzyme production	2,59E+03	kJ/kg ethanol	Luo, 2009
	SSCF	2,47E+02	kJ/kg ethanol	Luo, 2009
	product recovery	2,45E+02	kJ/kg ethanol	Luo, 2009
	wastewater treatment	2,14E+02	kJ/kg ethanol	Luo, 2009
	cooling water production	3,29E+02	kJ/kg ethanol	Luo, 2009
	total electricity per kg ethanol	4,16E+03	kJ/kg ethanol	
	ethanol production	1,31E+03	kg/ha/yr	
	total electricity	5,46E+06	kJ/ha/yr	
25	steam			
	pretreatment & hydrolyzate condition	5,33E+03	kJ/kg ethanol	Luo, 2009
	product recovery	1,84E+03	kJ/kg ethanol	Luo, 2009
	total steam per kg ethanol	7,17E+03	kJ/kg ethanol	
	ethanol production	1,31E+03	kg/ha/yr	
	total steam	9,41E+06	kJ/ha/yr	
26	steel			
	steel for agri. machinery (10-yr life span)	5,23E+04	g/ha/yr	after Ulgiati, 2001
27	labor			
	labor input	2,00E-03	work yrs/ha/yr	after Ulgiati, 2001
28	service			
	plants life span	2,00E+01	yr	NREL report
	ethanol production	6,93E+01	MM gal/yr	NREL report
	Conversion	3,79E+00	L/gal	
	ethanol density	7,89E+02	g/L	
	ethanol production per ha per yr	1,31E+06	g/ha/yr	
	equivalent cropped land area	1,58E+05	ha	
	total equipment cost	1,14E+02	MM USD	NREL report
	equipment cost per ha	3,60E+01	USD/ha/yr	
	total project investment (capital)	1,97E+02	MM USD	NREL report
	project investment (capital) per ha	6,26E+01	USD/ha/yr	
	non-feedstock raw materials	1,27E+01	MM USD/yr	NREL report
	non-feedstock raw materials per ha	8,05E+01	USD/ha/yr	
	waste disposal	2,00E+00	MM USD/yr	NREL report
	waste disposal per ha	1,27E+01	USD/ha/yr	
	fixed costs	7,50E+00	MM USD/yr	NREL report

	fixed costs per ha	4,75E+01	USD/ha/yr	
	capital and service per ha per yr	2,39E+02	USD/ha/yr	
29	ethanol			
	ethanol produced in grams	1,31E+06	g/ha/yr	NREL report
	energy content of ethanol	2,68E+04	J/g	
	ethanol produced in joules	3,52E+10	J/ha/yr	
30	electricity			
	electricity co-produced	5,81E+09	J/ha/yr	NREL report