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Sustainability of bioethanol production from wheat with recycled residues as evaluated by Emergy assessment

F. Coppola [a], S. Bastianoni [a], H. Østergård [b,*]

[a] Dept. of Chemistry, University of Siena, via Moro 2, 53100 Siena, Italy

[b] Risø National Laboratory for Sustainable Energy, Technological University of Denmark – DTU, P.O. Box 49, 4000 Roskilde, Denmark

ARTICLE INFO

Article history:
Received 15 August 2008
Received in revised form
11 July 2009
Accepted 10 August 2009
Published online 13 September 2009

Keywords:
1st generation bioethanol
2nd generation bioethanol
ELR
Biorefinery
Starch
Grain
Transformity
IBUS
Soil fertility
Organic fertilizer

ABSTRACT

An Emergy assessment study of 24 bioethanol production scenarios was carried out for the comparison of bioethanol production using winter wheat grains and/or straw as feedstock and conversion technologies based on starch (1st generation) and/or lignocellulose (2nd generation). An integrated biomass utilization system (IBUS) was used for combining the two kinds of feedstock. The crop was cultivated under four combinations of Danish soil conditions (sand or sandy loam) and crop managements (organic or conventional). For each of the production processes, two scenarios, with or without recycling of residues, were considered. Material and energy flows were assessed to evaluate the bioethanol yield, the production efficiency in terms of Emergy used compared to energy produced (transformity), and the environmental load (ELR) in terms of use of non-renewable resources. These three indicators varied among the four feedstock production scenarios to the same extent as among the three different industrial production scenarios and in each case the efficiency was lower and the use of non-renewables higher for the non-recycling system. The system most efficient for production of bioethanol (lowest transformity) and with the lowest environmental load (ELR) was bioethanol produced from grains cultivated in the organic sandy loam scenario; systems with the highest transformity and ELR were bioethanol production based on straw from conventional cultivation and without recycling of residues. The IBUS concept obtained the best bioethanol production efficiency for each cultivation system but its consumption of non-renewable resources was not optimal.

1. Introduction

In Europe, the transport sector accounts for around 30% of the total energy consumption and increasing focus on biofuels is an evident trend of the last years; an expert group formed by The EU Commission has estimated that there is a great potential for biofuels production (from the actual 2% of the total amount of used fuels, to the target of 25% in 2030) [1]. The estimations assumed a land use between 4 and 18% of the total EU agricultural land to produce biomass for energy purposes in order to replace the share of fossil sources required by the directive 2003/30/CE [2]. From this point of view a coordinated strategy for biofuel production, particularly in the transport sector is needed; in fact, it is expected that around 80% of the increase of CO_2 emissions between 1990 and 2010 will be attributable to this sector [1]. Therefore, sustainable technologies to produce biofuels from different kinds of biomass resources are needed and to assess the sustainability, a number of methodologies should be considered. In addition to technical and economic analyses (e.g. [3]), it is also important to carry out an assessment of the longer-term sustainability in terms of consumption of resources.

* *Corresponding author*. Tel.: +45 4677 4111.
E-mail addresses: coppola12@unisi.it (F. Coppola), bastianoni@unisi.it (S. Bastianoni), haqs@risoe.dtu.dk (H. Østergård).
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doi:10.1016/j.biombioe.2009.08.003

Biofuels may be characterized as the well-established 1st generation (G1) biofuels from starch and sugars and the developing 2nd generation biofuels (G2) from lignocellulosic material. An annual growth rate is expected for liquid biofuels around 6.3% between 2005 and 2030 and the bioethanol will be the largest share of them [4]. Application of G1 and G2 bioethanol production technology depends on the feedstock entering the production process; G1 feedstock come from starch, wheat or maize (wet or dry milling), and from sugars, in sugar cane and sugar beet [5], while G2 products come from lignocellulosic material in wood, straw and municipal waste [6]. In 2003, about 61% of the world's bioethanol was derived from sugar crops: sugar cane (Brazil), sugar beet (France) and molasses. The remaining 39% was produced from grains, predominantly maize (USA) [7]. The G1 bioethanol industry is characterized by large plants and maize-based bioethanol plants have reached capacities over the last ten years from about 75,000 $m^3\,y^{-1}$ up to the largest plant with a capacity of 600,000–700,000 $m^3\,y^{-1}$, located in Jilin, China [7].

Lignocellulosic material has a more complex structure than starch; this means that more expensive methods are required to transform the different kinds of sugar (C6 and C5 sugars) in G2 bioethanol production technologies. Today, lignocellulosic processing is well advanced, and the EU has three demonstration plants, in Sweden, Spain and Denmark (Table 1) [6].

One way to reduce the cost of bioethanol production is through integration and co-production with other industrial biorefinery plants ''refining'' carbon from biomass into, e.g. biofuel, fertilizer, fodder, heat and power; this is the new concept of integrated biorefineries built near existing power plants in order to maximize the energy efficiency of the entire production process. An example is the facility for G2 bioethanol production expected to be established in 2009 near the Asnæs power plant in Kalundborg, Denmark [8]. It is estimated that this plant will use a certain amount of solid biofuel (lignin) coming from the industrial process converting straw to bioethanol.

The aim of this paper is to compare first end second-generation bioethanol productions by means of an Emergy based approach, including the agricultural phase (production of wheat grain and straw feedstock in different Danish growing systems) and the industrial phase (starch and lignocellulosic material processes). The Emergy methodology introduced by Odum [9–11] is a way of sustainability assessment based on estimating the exploitation of natural resources and the amount of basic (solar) energy directly or indirectly required to produce them. Emergy has already been used in a few studies in order to evaluate G1 bioethanol production [12–16] but G2 bioethanol production has not been analyzed with an Emergy approach.

2. Methods

2.1. Emergy evaluation

Emergy represents the total amount of available energy, here solar energy, directly or indirectly required to make a product or to support a process; the Emergy of a product is therefore related to the way it is produced and it is expressed in solar Emergy joule (sej). All process inputs (i), including energy of different types and energy inherent in materials and services, are converted into Emergy by means of a conversion factor called transformity (Tr, Emergy per unit energy, $sej\,J^{-1}$ or $sej\,g^{-1}$) and the Emergy flow for a product (Em, sej) is calculated as

$$\mathrm{Em} = \sum_i \mathrm{Tr}_i E_i \quad (1)$$

where E_i is the available input (lower heating value (J) or weight (g)).

A higher transformity of a product or process means that more Emergy is needed to produce a unit amount of output. This can be deduced from another basic equation:

$$\mathrm{Tr}_o = \frac{\mathrm{Em}}{E_o} \quad (2)$$

where E_o is the energy of the output (measured) and Tr_o is the transformity of the output (calculated). The circularity of Equations (1) and (2) is avoided since, by definition, the transformity of solar energy is 1 $sej\,J^{-1}$. A global Emergy flow base of 15.83×10^{24} $sej\,y^{-1}$ has been assumed; therefore, all transformities calculated from the previously used 9.44×10^{24} $sej\,y^{-1}$ standard have been multiplied by 1.68.

The Emergy flow for each product or process is calculated by converting all its inputs into the solar equivalent energy needed to create those energy flows by multiplying each flow by its transformity. These values are summed and the result indicates the total amount of resources (renewable and non-renewable) that have been necessary in order to obtain the product or process (Equation (1)).

Three indices were used for the sustainability evaluation: bioethanol yield per hectare, transformity of bioethanol produced, and Environmental Loading Ratio (ELR) being the ratio between the non-renewable Emergy flow and the renewable one. ELR is an index to measure the load on the

Table 1 – Demonstration plants in EU for G2 bioethanol production. From [6].

Plant operator	Location	Capacity ($t\,d^{-1}$)	Hydrolysis method	Raw material
Abengoa	Salamanca, Spain	30–40	Steam pretreatment + enzymes	Barley straw
Etek Etanolteknik	Örnsköldsvik, Sweden	2	Dilute sulphuric acid + enzymes	Softwood
Inbicon	Denmark	2.4–24	Hydrothermal treatment + enzymes	Wheat straw, house-hold waste etc.

environment; it is often high for a system using a high level of technology.

2.2. Bioethanol production systems

In this study we consider 24 scenarios for bioethanol production in Denmark: wheat feedstock is produced in four cultivation systems (agricultural phase) and grain and/or straw are processed to bioethanol in three different industrial phases. For each of these twelve combinations recycling of residues is either included or not included.

Flows of energy and matter are described by using an Energy System Diagram (Fig. 1) showing all resources contributing to the agricultural phase and the industrial phase respectively. These are i) renewables such as sun, rain, geothermal heat and wind, ii) local (within the system) non-renewables such as soil, water and iii) imported (from outside the system and usually non-renewables) such as fossil fuels, fertilizers, seeds and chemical additives and enzymes. Two other system components which take part in recycling of residues are a Combined Heat and Power plant (CHP) located in the neighborhood of the industrial plant and a pig farm located near the agricultural production system. These components are considered as 'black boxes' implying that the assessment does not take into account how they are composed or how they work, but only the amount of inputs and outputs. This is possible as their Emergy weight can be considered negligible since they are existing items in the system.

The three production processes considered are:

G1 bioethanol production (use of grain) (Fig. 1a). Starch from grain is converted to bioethanol in the industrial phase. The potential recycling includes i) wheat straw utilized for energy and steam production (50–70%) in the combined heat and power plant (CHP) to substitute coal input; ii) the remaining wheat straw (30–50%) is left in the field to enhance soil fertility and prevent loss of organic matter, and iii) a by-product from the industrial phase, DDGS (dried distillers grains with soluble), may be recycled as fodder for pigs and their slurry may be utilized to substitute chemical fertilizers.

G2 bioethanol production (use of straw) (Fig. 1b). Lignocellulosic material from straw is converted to bioethanol in the industrial phase. The potential recycling includes i) slurry produced by pigs feeding on the wheat grain produced substitute chemical fertilizers; ii) by-products from industrial phase (lignin solid biofuel) used for energy and steam production (in the CHP plant) to substitute coal input, and iii) by-products from industrial phase (straw molasses) used as fodder for pigs and successive utilization of their slurry to substitute chemical fertilizers.

G1 + G2 bioethanol production (integrated biomass utilization, grain plus straw) (Fig. 1c). The industrial phase is the combination of the two processes above. In this case, all agricultural products are included in the industrial phase and the residues from the industrial phase may be recycled as above.

The reference system for all three processes (G1, G2, and G1 + G2) was a pilot plant in Denmark, the Integrated Biomass Utilizations System (IBUS) [6,17–19], in which bioethanol is produced from both feedstocks.

Comparisons were made between the three processes in the four growing system scenarios with and without recycling of inputs, in order to asses the difference in the exploitation of natural resources, and the importance of recycling in terms of sustainability.

2.2.1. Wheat grain and straw production

The present Emergy assessment compares winter wheat production conducted under conventional and organic management practices in two Danish locations with slightly different climatic conditions; site I: sandy soil in south of Jutland (N55° 3', E9° 2') and site II: sandy loam soil in east of Zealand (N55° 6', E12°7'). All calculations are made for 1 ha and 1 year. The organic and conventional management practices differ in this study mainly by the choice of fertilizer (pig slurry and chemical fertilizer, respectively) and use of fungicides and herbicides (conventional) versus mechanical weeding (organic). Data for inputs, field operations and yields were obtained from farmers' advisory manuals [20,21], norms for direct and indirect energy consumption from a Danish study [22] and global radiation and evapotranspiration from site-specific information ([23,24], respectively).

In the analyses, soil fertility is expressed by soil organic matter (SOM). Soil erosion removes an amount of SOM each year. In some scenarios, a percentage of straw (30–50%) is left in the field and thus adding a quantity of organic carbon (C_{org}) to the soil every year; this leads to an increase and to an improvement of SOM. To simulate the amount of C_{org} added to the soil we used a simplified version of the C-TOOL model that simulates the amount of C_{org} in soil in a time interval of 100 years [25]. This model provided data for the different cultivation scenarios by changing the input parameters: % of straw left, soil type and type of fertilizer.

The amount of slurry produced from feeding pigs with grain, DDGS or straw molasses (all feedback in the different processes) were found from tabulated average values of N, P and K elements in slurry output based on the SFU (Scandinavian Fodder Unit) intake per year [26]. The conversion of recycled inputs in SFU and estimation of potential output of slurry elements (N, P, K) were carried out to assess the share of chemical fertilizers replaceable per hectare per year in the different cultivation system scenarios (see Appendix A).

To clarify abbreviations in the text and tables, LO and SO refer to organic management systems in loamy (sandy loam) or sandy soil, respectively, while LC and SC refer to loamy (sandy loam) conventional and sandy conventional, respectively.

2.2.2. Bioethanol industrial production

Comparing different processes of feedstock conversion into bioethanol required a set of representative data for both G1 and G2 bioethanol production technologies (from starch and lignocellulose, respectively) as applied alone or combined in the G1 + G2 scenario (IBUS concept, straw and grain used together for bioethanol production). Data used were mainly from Danish systems [5,17–19].

2.2.3. Transportation

Transport of feedstock and residues was taken into account as follows:

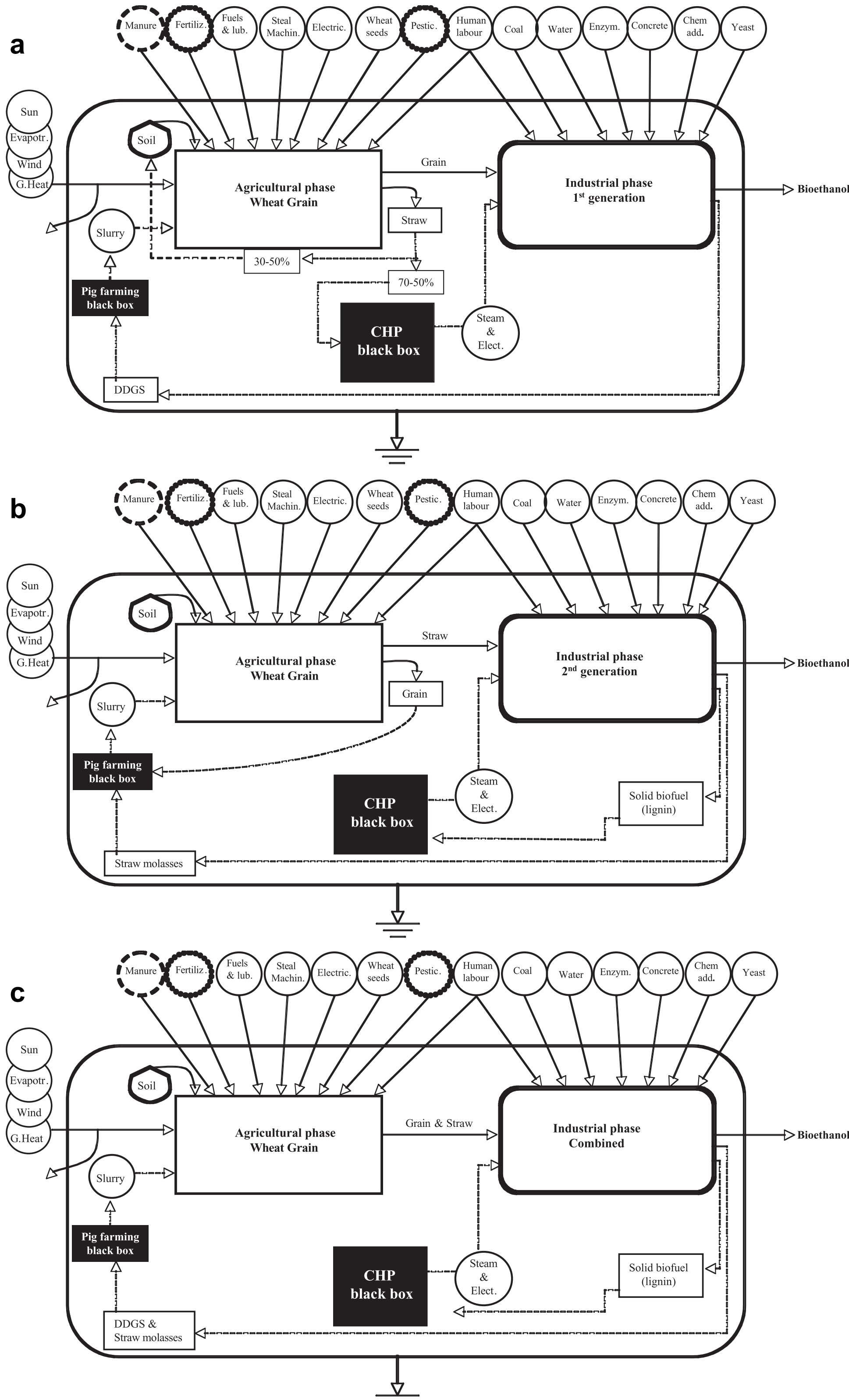

Fig. 1 – Energy System Diagram of 1st generation, G1 (Fig. 1a), 2nd generation, G2 (Fig. 1b) and G1 + G2 (Fig. 1c) bioethanol production, with recycled inputs. In the no recycled scenarios, for each system the flows with dashed lines are not considered. Circles indicate input: full-drawn line (both managements), dashed line (organic), dotted line (conventional). Arrows indicate material flows: full-drawn line (all cases), dashed line (recycling).

G1 process: grain to the bioethanol facility, DDGS from the bioethanol facility to the pig farm, straw from fields to the CHP plant (the share to substitute coal for steam and electricity used up in the bioethanol conversion process).
G2 process: straw to the bioethanol facility, straw molasses from the bioethanol facility to the pig farm.

Other transports were not taken into account (grain fodder from the field to the pig farm, and lignin from the bioethanol facility to the CHP plant) due to the assumptions about location of the different facilities.

Energy needed for transportation (from diesel fuel) was calculated as 770 J kg^{-1} km^{-1} of biomass transported [27]. The average distance between the agricultural facilities and the industrial facilities is assumed to be 90 km (one-way) [17].

2.2.4. *Black boxes: combined heat and power plant and pig farming*

The pig farms were not included in the accounting. In Denmark there is an annual production of about 20.8 million fattening pigs [28] so pig farms are considered as an existing subsystem in the wheat growing areas. The recycled by-product and residues (grain, DDGS, straw molasses) usable as feed for pigs are free in Emergy terms. The only input to take into account is the fuel (diesel) used to transport the feed from the bioethanol facility to the pig farm.

Since the CHP plant is more resource demanding than the pig farms, an approximate Emergy calculation was made to support that it can be considered as a black box, i.e. not included in the final accounting (Appendix B). The recycled by-products and residues (straw, lignin) going to the CHP in the different scenarios to substitute coal are free in Emergy terms. The only input to take into account is the transport (MJ of diesel) necessary to carry the biomass feedstock from fields to the CHP.

Table 2 – Emergy per unit (transformity values) for all inputs used in the Emergy assessment.

	Emergy per unit (sej J^{-1} or sej g^{-1})	References
Inputs agricultural phase (units)		
Solar radiation (J)	1	[29]
Rain (evapotranspiration) (g)	1.51E+05	[29]
Wind (J)	2.52E+03	[29]
Geothermal heat (J)	1.20E+04	[29]
Soil erosion (J)	1.24E+05	[29]
N Fertilizers (g)	2.41E+10	[30]
K Fertilizers (g)	1.74E+09	[30]
P Fertilizers (g)	2.02E+10	[30]
Manure (g)	2.13E+08	[31]
Pesticide (g)	1.85E+09	[32]
Seeds (g)	1.20E+09[a] and 1.45E+09[b]	Our calculations
Lime (g)	1.65E+09	[30]
Diesel oil (J)	1.10E+05	[32]
Lubricants (J)	1.10E+05	[32]
Steel machinary (g)	1.13E+10	[29]
Human labour (J)	1.24E+07	[29]
Electricity (J)	2.00E+05	[30]
Inputs industrial phase		
Conversion plant (steal) (g)	1.13E+10	[29]
Concrete (g)	1.81E+09	[33]
Coal (electricity+steam generation) (J)	3.98E+04	[34]
Human labour (J)	1.24E+07	[29]
Water (g)	1.25E+06	[30]
Enzymes[c] (J fossil oil)	5.40E+04	[34]
Chemicals[d] (g)	3.80E+08	[30]
Yeast (J fossil oil)	5.40E+04	[34]

a Conventional management.
b Organic management.
c Enzymes: Cellulase, A-amylase, AMG, Protease.
d Chemicals: Sulphuric acid, Sodium Hydroxide, Ammonia Water, Urea, Calcium Chloride.

3. Results

For each of the 24 scenarios (Fig. 1), Emergy flows for the agricultural and industrial phases, respectively, were calculated using published or calculated transformity values for all the inputs (Table 2). Transformity values of winter wheat seeds were calculated as average of the values for transformity of grain in the actual systems. For organic fertilizer (pig slurry) a published transformity value for cattle manure produced in an intensive stable system was used. For enzymes and yeast, no transformity value has been published so we used the energy consumed to produce them (J fossil oil) and multiplied by the transformity of fossil oil (sej J^{-1}).

3.1. *Agricultural phase*

Calculations of all inputs (J or g) and the associated Emergy flows expressed per hectare and per year for the agricultural phase are summarized in Table 3 (details for LC in Appendix A). Most inputs are common to all combinations of bioethanol technology and recycling concept except the input of fertilizer (organic or chemical) and the loss of soil organic matter (soil erosion). These inputs are to different extent substituted by the recycled by-products or residues: i) DDGS, straw molasses and grain as fodder for pigs and converted into pig slurry used in the agricultural phase to substitute fertilizers, ii) straw left in the field as an increasing source of organic matter against soil erosion.

In general, in the four growing systems the three most important contributions to the Emergy flow are fertilizers (more than 50%), lime application and evapotranspiration. Among the renewables, the Emergy flow of evapotranspiration is the biggest, and among the non-renewables, N fertilizers and manure are the most important, followed by lime, diesel, seeds, P and K fertilizers and electricity. All other inputs are two orders of magnitude lower than that of the fertilizers.

The largest differences between the two sites in Emergy flow terms are the evapotranspiration (calculated from 420 mm in the loamy soil and 480 mm in the sandy soil) and the difference in soil erosion (calculated from 110 g m^{-2} y^{-1}

Table 3 – Inputs and Emergy flows for the agricultural phase; in the upper part are inputs common for the different industrial scenarios and in the lower part soil erosion, fertilizers (N, P, K) and manure (as recycled inputs) are considered for each scenario. Emergy flow is obtained by multiplying the amount in J or g by the respective transformities (sej J^{-1}) or (sej g^{-1}) reported in Table 2.

Inputs	SO		SC		LO		LC	
	Amount (J or g)	Emergy flow (10^{13} sej $ha^{-1} y^{-1}$)	Amount (J or g)	Emergy flow (10^{13} sej $ha^{-1} y^{-1}$)	Amount (J or g)	Emergy flow (10^{13} sej $ha^{-1} y^{-1}$)	Amount (J or g)	Emergy flow (10^{13} sej $ha^{-1} y^{-1}$)
All scenarios								
Solar radiation (J)	3.67E+13	3.67	3.67E+13	3.67	3.73E+13	3.73	3.73E+13	3.73
Evapotranspiration (g)	4.80E+09	72.48	4.80E+09	72.48	4.20E+09	63.42	4.20E+09	63.42
Wind (J)	4.53E+10	11.41	4.53E+10	11.41	4.53E+10	11.41	4.53E+10	11.41
Geothermal heat (J)	2.21E+10	26.49	2.21E+10	26.49	2.21E+10	26.49	2.21E+10	26.49
Pesticide (g)	0	0	1.38E+03	0.26	0	0	1.38E+03	0.26
Seeds (g)	2.00E+05	29.40	1.70E+05	20.39	2.00E+05	29.00	1.70E+05	20.40
Lime (g)	5.00E+05	82.50	5.00E+05	82.50	5.00E+05	82.50	5.00E+05	82.50
Diesel oil (J)	3.24E+09	35.63	2.59E+09	28.50	3.42E+09	37.57	2.89E+09	31.80
Lubricants (J)	3.00E+08	3.30	2.40E+08	2.64	3.17E+08	3.48	2.68E+08	2.95
Steel machinary (g)	2.41E+03	2.72	1.98E+03	2.24	2.41E+03	2.72	1.98E+03	2.24
Human labour (J)	3.40E+06	4.22	2.88E+06	3.57	3.40E+06	4.22	2.88E+06	3.57
Electricity (J)	5.55E+08	11.10	7.20E+08	14.40	8.10E+08	16.20	1.20E+09	24.00
Recycled inputs G1								
Soil erosion (J)	7.46E+08	9.25	7.46E+08	9.25	5.14E+08	6.38	0	0
N Fertilizers (g)	–	–	1.22E+05	294.30	–	–	1.18E+05	283.99
K Fertilizers (g)	–	–	5.85E+04	10.18	–	–	5.09E+04	8.85
P Fertilizers (g)	–	–	1.23E+04	24.79	–	–	1.21E+04	24.48
Manure (g)	1.09E+07	232.12	–	–	9.22E+06	196.40	–	–
Recycled inputs G2								
Soil erosion (J)	7.46E+08	9.25	7.46E+08	9.25	5.14E+08	6.38	5.14E+08	6.38
N Fertilizers (g)	–	–	5.35E+04	129.05	–	–	5.49E+03	13.23
K Fertilizers (g)	–	–	3.13E+04	5.45	–	–	6.28E+03	1.09
P Fertilizers (g)	–	–	1.05E+03	2.13	–	–	0	0.00
Manure (g)	3.63E+06	77.41	–	–	0.00E+00	0.00	–	–
Recycled inputs (G1 + G2)								
Soil erosion (J)	7.46E+08	9.25	7.46E+08	9.25	5.14E+08	6.38	5.14E+08	6.38
N Fertilizers (g)	–	–	1.16E+05	278.46	–	–	1.09E+05	262.19
K Fertilizers (g)	–	–	5.59E+04	9.73	–	–	4.73E+04	8.23
P Fertilizers (g)	–	–	1.12E+04	22.62	–	–	1.06E+04	21.49
Manure (g)	1.03E+07	219.33	–	–	8.42E+06	179.32	–	–
No recycled inputs (G1 + G2)								
Soil erosion (J)	7.46E+08	9.25	7.46E+08	9.25	5.14E+08	6.38	5.14E+08	6.38
N Fertilizers (g)	–	–	1.51E+05	363.91	–	–	1.66E+05	400.06
K Fertilizers (g)	–	–	7.00E+04	12.18	–	–	7.00E+04	12.18
P Fertilizers (g)	–	–	1.70E+04	34.34	–	–	2.00E+04	40.40
Manure (g)	1.40E+07	298.20	–	–	1.40E+07	298.20	–	–

on sandy soil and 45 g $m^{-2} y^{-1}$ on loamy soil). The soil erosion interacts with the recycling of straw: In one scenario (LC and G1) the percentage of straw left in the field (50%) releases enough C_{org} to enhance soil organic matter (SOM) to the same extent as what is lost every year by erosion; from an Emergy point of view, the value of soil erosion is, therefore, in this case equal to zero. In the other cases the balance is negative implying that SOM is lost by soil erosion.

The largest difference in terms of Emergy flows between the two crop management systems is due to the use of chemical fertilizers in the conventional management and pig manure (slurry) in the organic one. At first it is seen that recycling of residues decreases the resource use (Emergy flow) in all systems. With recycling, the lowest input is needed in the G2 bioethanol production (use of straw to bioethanol, use of grain and straw molasses as fodder for pigs leading to a production of slurry that substitute fertilizers); in the LO scenario manure input is even zero because the recycled input from pig manure covers all what is needed and in the LC system P fertilizer input is zero because it is substituted by the content of P in the slurry. Also N and K fertilizer inputs are considerably lower than in the other scenarios.

Other differences between management systems of importance in Emergy terms are the different resources needed for seeds (organic seed production is more resource consuming than conventional according to the actual

Table 4 – Inputs and Emergy flows for the industrial phase. Common values for recycled and no recycled input scenarios, except for coal and transport given in the lower part.

	SO		SC		LO		LC	
	Amount (J or g)	Emergy flow (10^{13} sej $ha^{-1} y^{-1}$)	Amount (J or g)	Emergy flow (10^{13} sej $ha^{-1} y^{-1}$)	Amount (J or g)	Emergy flow (10^{13} sej $ha^{-1} y^{-1}$)	Amount (J or g)	Emergy flow (10^{13} sej $ha^{-1} y^{-1}$)
G1 recycled inputs								
Conv. plant (steal) (g)	5.23E+04	59.10	5.23E+04	59.10	5.23E+04	59.10	5.23E+04	59.10
Conv. plant (concrete) (g)	9.30E+04	16.83	9.30E+04	16.83	9.30E+04	16.83	9.30E+04	16.83
Coal (elect.+steam gen.) (J)	0	0	0	0	0	0	0	0
Human labour (J)	2.18E+05	0.27	2.84E+05	0.35	3.35E+05	0.42	4.72E+05	0.59
Water (g)	1.10E+05	0.01	1.43E+05	0.02	1.69E+05	0.02	2.38E+05	0.03
Enzymes (A-amylase) (J oil)	8.32E+06	0.04	1.08E+07	0.06	1.28E+07	0.07	1.80E+07	0.10
Enzymes (AMG) (J oil)	1.66E+07	0.09	2.16E+07	0.12	2.56E+07	0.14	3.60E+07	0.19
Enzymes (Protease) (J oil)	7.62E+06	0.04	9.89E+06	0.05	1.17E+07	0.06	1.65E+07	0.09
Sulphuric acid (g)	2.75E+04	1.04	3.56E+04	1.35	4.23E+04	1.61	5.94E+04	2.26
Phosphorous acid (g)	6.37E+03	0.24	8.27E+03	0.31	9.82E+03	0.37	1.38E+04	0.52
Sodium hydroxide (g)	3.96E+03	0.15	5.13E+03	0.19	6.09E+03	0.23	8.55E+03	0.32
Ammonia water (g)	1.32E+04	0.50	1.71E+04	0.65	2.03E+04	0.77	2.85E+04	1.08
Urea (g)	6.37E+03	0.24	8.27E+03	0.31	9.82E+03	0.37	1.38E+04	0.52
Calcium chloride (g)	1.32E+03	0.05	1.71E+03	0.06	2.03E+03	0.08	2.85E+03	0.11
Yeast (J oil)	1.28E+08	0.69	1.67E+08	0.90	1.98E+08	1.07	2.78E+08	1.50
Straw transport (J)	1.31E+08	1.44	1.70E+08	1.87	2.02E+08	2.22	2.83E+08	3.12
Grain transport (J)	5.13E+08	5.64	6.65E+08	7.32	7.90E+08	8.69	1.11E+09	12.20
DDGS transport (J)	1.83E+08	2.01	2.37E+08	2.61	2.81E+08	3.09	3.95E+08	4.34
G2 recycled inputs								
Conv. plant (steal) (g)	5.23E+04	59.10	5.23E+04	59.10	5.23E+04	59.10	5.23E+04	59.10
Conv. plant (concrete) (g)	9.30E+04	16.83	9.30E+04	16.83	9.30E+04	16.83	9.30E+04	16.83
Coal (elect.+steam gen.) (J)	0	0	0	0	0	0	0	0
Human labour (J)	8.87E+04	0.11	1.35E+05	0.17	1.18E+05	0.15	1.86E+05	0.23
Water (g)	6.24E+04	0.01	9.50E+04	0.01	8.32E+04	0.01	1.31E+05	0.02
Enzymes (Cellulase) (J oil)	1.46E+07	0.08	2.22E+07	0.12	1.95E+07	0.11	3.06E+07	0.17
Sulphuric acid (g)	1.53E+04	0.58	2.34E+04	0.89	2.04E+04	0.78	3.21E+04	1.22
Phosphorous acid (g)	3.57E+03	0.14	5.44E+03	0.21	4.76E+03	0.18	7.48E+03	0.28
Sodium hydroxide (g)	2.31E+03	0.09	5.13E+03	0.19	3.08E+03	0.12	4.84E+03	0.18
Ammonia water (g)	7.35E+03	0.28	1.12E+04	0.43	9.80E+03	0.37	1.54E+04	0.59
Urea (g)	3.57E+03	0.14	5.44E+03	0.21	4.76E+03	0.18	7.48E+03	0.28
Calcium chloride (g)	7.35E+02	0.03	1.12E+03	0.43	9.80E+02	0.04	1.54E+03	0.06
Yeast (J oil)	2.65E+08	1.43	4.04E+08	2.18	3.54E+08	1.91	5.56E+08	3.00
Straw transport (J)	2.91E+08	3.20	4.44E+08	4.88	3.88E+08	4.27	6.10E+08	6.71
Straw molasses (J)	3.90E+07	0.43	5.94E+07	0.65	5.20E+07	0.57	8.17E+07	0.90
(G1 + G2) recycled inputs[a]								
Coal (elect.+steam gen.) (J)	9.43E+09	37.53	1.13E+10	44.91	1.54E+10	61.26	2.07E+10	82.25
Grain transport (J)	5.13E+08	5.64	6.65E+08	7.32	7.90E+08	8.69	1.11E+09	12.20
DDGS transport (J)	1.83E+08	2.01	2.37E+08	2.61	2.81E+08	3.09	3.95E+08	4.34
Straw transport (J)	2.91E+08	3.20	4.44E+08	4.88	3.88E+08	4.27	6.10E+08	6.71
Straw molasses transport (J)	3.90E+07	0.43	5.94E+07	0.65	5.20E+07	0.57	8.17E+07	0.90
G1 no recycled inputs								
Coal (elect.+steam gen.) (J)	1.36E+10	54.19	1.77E+10	70.30	2.10E+10	83.48	2.94E+10	117.17
Grain transport (J)	5.13E+08	5.64	6.65E+08	7.32	7.90E+08	8.69	1.11E+09	12.20
G2 no recycled inputs								
Coal (elect.+steam gen.) (J)	1.05E+10	41.84	1.60E+10	63.76	1.40E+10	55.79	2.20E+10	87.67
Straw transport (J)	2.91E+08	3.20	4.44E+08	4.88	3.88E+08	4.27	6.10E+08	6.71
(G1 + G2) no recycled inputs[a]								
Coal (elect.+steam gen.) (J)	2.41E+10	96.03	3.37E+10	134.06	3.50E+10	139.27	5.15E+10	204.84
Grain transport (J)	5.13E+08	5.64	6.65E+08	7.32	7.90E+08	8.69	1.11E+09	12.20
Straw transport (J)	2.91E+08	3.20	4.44E+08	4.88	3.88E+08	4.27	6.10E+08	6.71

a Inputs for the G1 + G2 industrial phase is considered as the sum of G1 and G2 process inputs, except for coal. Here electricity and steam are needed to produce bioethanol, and diesel fuel to transport the straw to the CHP plant.

numbers) and the different use of fossil fuels (diesel and lubricants) with more field operations in the organic management and bigger machinery and more diesel needed to spread slurry than chemical fertilizer.

Finally, electricity input varies in the four systems increasing from SO to SC to LO to LC due to an increasing quantity of grain to dry.

3.2. Industrial phase

In the industrial phase (summarized in Table 4, details for loamy conventional, LC, in Appendix A) some inputs differ between G1 and G2 technologies and inputs for the combined system (G1 + G2) are calculated as the sum of the two. In case of no recycling of residues, coal input increases whereas energy inputs for transportation decreases as less material is moved around. The highest Emergy flow is due to the conversion plant (steel and concrete); one order of magnitude less is the diesel used for transport of different by-products and residues (straw, grain, DDGS, straw molasses) and sum of additives used in the processes.

The largest difference in Emergy terms between G1 and G2 technologies is due to the different quantity of yeast used (20 $kg\,t^{-1}$ of straw in the G2 compared to about 6 $kg\,t^{-1}$ of grain in G1), of sulphuric acid used, and of transportation. As the G1 + G2 production system needs the summed inputs from the two technologies there is an increase in the Emergy flow accounting for the conversion plant. Further, additional coal is needed for electricity and steam production since the lignin from the bioethanol facility is not enough to sustain the total energy requirement to treat both grain and straw.

3.3. Bioethanol production

The full process from the feedstock to the bioethanol product is evaluated by the three indicators: yield, transformity and environmental load ratio (ELR). The yield of grain and of bioethanol about doubled among cultivation systems from SO to SC to LO to LC and the straw production increased similarly except that it was higher in SC than in LO (Table 5). The total Emergy flow for producing bioethanol varied between 3.57×10^{15} and 11.06×10^{15} $sej\,ha^{-1}\,y^{-1}$ always higher under conventional than organic management when other factors are equal and lowest in the G2 process with recycling because of the highest amount of recycled inputs that enter in the production system avoiding the use of external resources.

In all scenarios, the transformity increased from grain to straw to bioethanol (Table 5). Further, they all increased when the production process was without recycling and they decreased from SO to LC reflecting an increase in the efficiency per hectare of the four different cultivation systems for grain and bioethanol.

Comparing the G1 and G2 technologies, G1 bioethanol production is the most efficient (lower transformity). This is due to the fact, that the transformity is per unit of product; even if the production of grain and straw are equal to or more efficient in the G2 than in the G1 scenarios, the amount of grain available from 1 hectare for the G1 bioethanol production is higher than the amount of straw from the same area for the G2 bioethanol production and also the conversion efficiency is larger for the G1 process being 0.297 for G1 and 0.213 for G2. Finally, the G1 + G2 scenarios show the lowest transformity values of bioethanol production and, in all cases, the absence of recycling increases the transformity (Table 5).

The ELR values (Fig. 2) are higher for the conventional management than for the organic one (in both soils). Differences among the ELR values are due to the amount of recycled inputs that enter into the crop production system and the industrial processes, avoiding the use of external resources (as chemical fertilizers, manure, coal) as well as the reduction of the soil erosion. The increase in ELR value for the G1 + G2 industrial phase is due to the fact that the sum of the inputs for both G1 and G2 processes are needed (grain plus straw) and that an additional amount of coal is necessary since the lignin is not enough for processing both grain and straw.

The most sustainable scenario in terms of Emergy evaluation is the one with low transformity and low ELR, to indicate high efficiency and renewability (Fig. 2). The system most efficient for production of bioethanol (lowest transformity) and with the lowest environmental load (ELR) was bioethanol produced from grains cultivated in the LO scenario (Fig. 2); systems with the highest transformity and ELR were bioethanol production based on straw from conventional cultivation and without recycling of residues (Fig. 2). The IBUS concept (G1 + G2 process with recycling) obtained the best bioethanol production efficiency for each cultivation system but it had a higher consumption of non-renewable resources.

4. Discussion

The aim of an Emergy evaluation is to weight the exploitation of natural resources (renewable and non-renewable) used up in a process or in producing a product. In this study especially the trade-offs between resource use per unit bioethanol produced (transformity) and environmental load due to use of non-renewable resources (ELR) were analyzed. Among all growing systems, the loamy organic crop management (LO) turned out, in most scenarios, to be the best to produce bioethanol, because of the best compromise in yield, transformity and ELR values (Fig. 2).

Emergy assessment of the G1 technology to produce bioethanol from sugar cane (Florida, Brazil, Louisiana) and from grapes (Italy) was carried out by Bastianoni et al. [12] whereas Ulgiati [16] studied maize as feedstock (Table 6). Their transformities, omitting grapes, are in the range from 1.56 to 2.35×10^5 $sej\,J^{-1}$ i.e. exactly as as our transformity values of G1 bioethanol (1.07–2.43 $\times 10^5$ $sej\,J^{-1}$) and of the same order of magnitude as for the technologies including G2 processes (1.47–5.87 $\times 10^5$ $sej\,J^{-1}$). The same is the case for the ELR values, except for grapes and our G1 + G2 process (recycling and non-recycling) related to the LC growing system.

Given that the society demands bioethanol from wheat crops, the best choice of process based on the present technologies, will be the G1 + G2 solution integrating both feedstocks. This solution gives in all scenarios the highest

Table 5 – Outputs and transformities for products and by-products from different scenarios.

	SO		SC		LO		LC	
	Amount (t)	Transformity (10^5 sej J^{-1})	Amount (t)	Transformity (10^5 sej J^{-1})	Amount (t)	Transformity (10^5 sej J^{-1})	Amount (t)	Transformity (10^5 sej J^{-1})
G1 recycled inputs								
Grain	3.70	0.99	4.80	0.88	5.70	0.59	8.00	0.51
Straw	2.10	1.69	3.20	1.29	2.80	1.17	4.40	0.91
Bioethanol	1.10	2.04	1.43	1.80	1.69	1.25	2.38	1.07
Total emergy flow bioethanol production (10^{15} sej ha^{-1} y^{-1})	**5.99**		**6.89**		**5.66**		**6.78**	
G2 recycled inputs								
Grain	3.70	0.68	4.80	0.59	5.70	0.34	8.00	0.25
Straw	2.10	1.17	3.20	0.87	2.80	0.68	4.40	0.44
Bioethanol	0.45	3.66	0.68	2.67	0.60	2.24	0.94	1.47
Total emergy flow bioethanol production (10^{15} sej ha^{-1} y^{-1})	**4.37**		**4.85**		**3.57**		**3.68**	
(G1 + G2) recycled inputs								
Grain	3.70	1.00	4.80	0.85	5.70	0.57	8.00	0.50
Straw	2.10	1.72	3.20	1.24	2.80	1.12	4.40	0.88
Bioethanol	1.55	1.76	2.11	1.41	2.29	1.13	3.31	0.94
Total emergy flow bioethanol production (10^{15} sej ha^{-1} y^{-1})	**7.27**		**7.95**		**6.91**		**8.28**	
G1 no recycled inputs								
Grain	3.70	1.11	4.80	1.00	5.70	0.72	8.00	0.64
Straw	2.10	1.90	3.20	1.46	2.80	1.42	4.40	1.13
Bioethanol	1.10	2.43	1.43	2.18	1.69	1.65	2.38	1.46
Total emergy flow bioethanol production (10^{15} sej ha^{-1} y^{-1})	**7.14**		**8.31**		**7.44**		**9.29**	
G2 no recycled inputs								
Grain	3.70	1.11	4.80	1.00	5.70	0.72	8.00	0.64
Straw	2.10	1.90	3.20	1.46	2.80	1.42	4.40	1.13
Bioethanol	0.45	5.87	0.68	4.52	0.60	4.46	0.94	3.57
Total emergy flow bioethanol production (10^{15} sej ha^{-1} y^{-1})	**7.00**		**8.22**		**7.11**		**8.93**	
(G1 + G2) no recycled inputs								
Grain	3.70	1.00	4.80	0.85	5.70	0.57	8.00	0.50
Straw	2.10	1.72	3.20	1.24	2.80	1.12	4.40	0.88
Bioethanol	1.55	2.03	2.11	1.74	2.29	1.45	3.31	1.25
Total emergy flow bioethanol production (10^{15} sej ha^{-1} y^{-1})	8.40		9.80		8.84		11.06	

bioethanol yield per hectare and in addition a good compromise between process efficiency and use of non-renewable resources. From the G1 + G2 process animal feed can be recycled to produce slurry to substitute fertilizer and from the lignocellulosic material solid biofuel can be produced which to some extend can substitute for the coal needed for the G1 process. In this way, the G1 + G2 process is more sustainable from the point of view of nutrient substances recycled to the soil through the animal feed (straw molasses and DDGS fodder) using the pig slurry as fertilizer. However the G1 + G2 process is penalized by the highest ELR value, mainly a result of the need for coal to run the G1 process in this situation.

As shown by the three indicators (yield, transformity, ELR), the Emergy evaluation can be seen as an additional tool to assess the feasibility of a process (as a supplement to other analyses e.g. economic, technological). The technology chosen for a specific scenario can be requested to have the best efficiency, or the lowest environmental impact or the best compromise of them (for example shifting from bottom to top and left to right in Fig. 2). As an Emergy evaluation is an ''energy based'' assessment it is also important to look at the energy balance of the systems under study. The integrated biomass utilization system (IBUS) (i.e. the G1 + G2 process with recycling) shows an output/input energy ratio about 2.05 as reported by Bentsen et al. in a study based on average Danish soil type and crop management

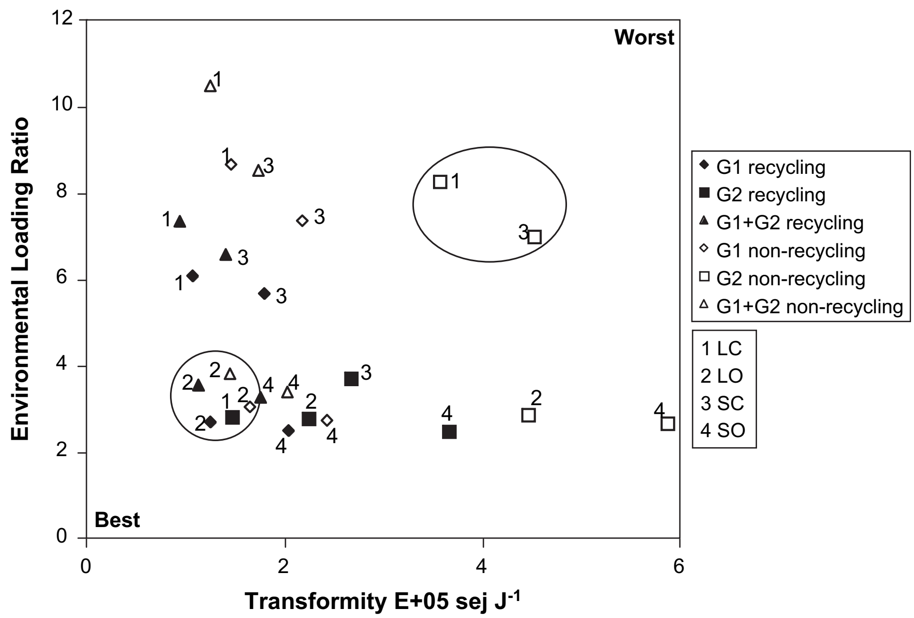

Fig. 2 – Relation between Environmental Loading Ratio (ELR) and transformity for the 24 studied scenarios. LO and SO refer to organic management systems in loamy (sandy loam) or sandy soil, respectively, while LC and SC refer to loamy (sandy loam) conventional and sandy conventional, respectively.

Table 6 – Transformity values according to the 15.83×10^{24} sej y^{-1} standard and Environmental Loading Ratios (ELRs) from other published Emergy assessments of G1 bioethanol production.

Transformity (10^5 sej J^{-1})	ELR	Feedstock	Authors
1.73	3.27	Sugar cane (Brasil)	Bastianoni et al. [12]
2.35	6.04	Sugar cane (Florida)	Bastianoni et al.[12]
1.56	1.57	Sugar cane (Louisiana)	Bastianoni et al. [12]
12.80	13.63	Grapes (Italy)	Bastianoni et al. [12]
1.80	–	Corn	Ulgiati [16]

[17]. This means that the IBUS production of bioethanol produces twice as much energy as has been used for cultivating and processing of the winter wheat crop.

The importance of recycled inputs in bioethanol production has also been analyzed by Farrell et al. combining results from six analyses of 1G bioethanol based on corn [35]. Omitting two studies ignoring recycling of by-products, the remaining studies showed a positive net energy yield of about 4–9 MJ l^{-1}. However, this metric was criticized for not being fully comparable between studies. Concerning the GHG emissions, they reported slightly lower values than for gasoline, but they concluded that this aspect of biofuel production is poorly understood, and that large-scale bioethanol production will require cellulosic technology.

5. Conclusions

Supply security in transportation fuels is needed (as much as decreasing GHG emissions). Bioethanol can show a great potential for these two purposes, if it is produced in a sustainable way. The variation found among the Emergy assessment of 24 scenarios for bioethanol production from Danish grown wheat feedstock can be summarized as follows:

- yield, transformity and ELR varied among the four feedstock production scenarios to the same extent as among the three different industrial production scenarios and in each case the efficiency was lower and the use of non-renewables higher for the non-recycling system;
- G1 bioethanol has a good efficiency i.e. a low value of transformity for bioethanol, but it has the problem of high value of the ELR indicator, i.e. a relatively large use of non-renewable resources, and it is in competition with food and feed;
- G2 bioethanol has a lower efficiency due to a lower yield of the final product but it shows a lower value of the ELR indicator and it is not in competition with food and feed;
- the G1 + G2 process (IBUS) shows the best efficiency in bioethanol production with the lowest transformity value in the final product, due to the use of integrated by-products recycled in the process. However, the ELR value is higher than for the two processes separately. As the yield is higher there is a reduction in land needed to produce a certain amount of bioethanol compared to G1 alone.

Concerning the four different growing system scenarios (Danish soil types and crop management) the Emergy assessment showed that the most suitable and sustainable biomass production is the loamy organic scenario because of the best compromise in bioethanol yield, transformity and ELR value. Similar transformity and ELR values were found as in other Emergy assessments of other feedstocks (maize and sugar cane) for bioethanol production. Finally, scenarios with recycling are most suitable to produce bioethanol in an efficient and sustainable way.

In conclusion, the Emergy evaluation can be seen as an additional tool (like other traditional analyses e.g. economic, technological) to assess the feasibility of a process. With such tools the policy makers can make their choice whether it is better to focus on efficiency and not so much on the environment or to privilege renewability, maybe loosing on the efficiency side.

Acknowledgments

Input values from Danish Meteorological Institute, from Ingeborg Callesen (Technical University of Denmark) and Preben Olsen (University of Aarhus) are acknowledged as well as discussions with Henrik Haugaard-Nielsen (Technical University of Denmark).

Appendix A.

Input and output calculations for the Emergy assessment in the LC (loamy conventional) scenario are described in Table A1.

Appendix B.

For the Emergy assessment, the inputs necessary to build and maintain the combined heat and power plant (CHP) are needed in order to have an estimation of the total Emergy flow for the entire bioethanol production process. However, to avoid the difficult data collection for these inputs for the reference plant (Asnæs CHP plant), we estimated i) which proportion of coal used in the CHP plant is substituted by lignin (Table B1) and ii) how much this fraction weight on the total Emergy flow per ha per year (Table B2). The calculations are explained in the following.

i) As the primary energy used up to produce 1 MJ electricity is equal to 2.71 MJ of coal, it is calculated that 3.54 million t of coal are used up every year by the Asnæs power plant. Making the ratio of the energy produced from the quantity of lignin produced per hectare per year (average amount, for the four scenarios is 1.25 t) to the energy produced from the total quantity of coal used, it results only in the 0.00004% of the power plant feedstock.

ii) Another calculation considers the total Emergy flow per year necessary to sustain the annual production of electricity from the Asnæs CHP using coal as primary energy input (5.70×10^{21} sej y^{-1}). The Emergy flow necessary to

Table A1 - Input and output calculations for the Emergy assessment in the LC (loamy conventional) scenario.

			References
Agricultural phase			
Cultivated area	1.00E+00	ha	
	1.00E+04	m^2	
Input			
Solar energy			[23]
Solar radiation	3.73E+09	$J\,m^{-2}\,y^{-1}$	
Energy = (area) × (isolation)	3.73E+13	$J\,ha^{-1}\,y^{-1}$	
Rain (evapotranspiration)			[24]
Rain evapotranspirated	4.20E-01	$m\,y^{-1}$	
Water density	1.00E+03	$kg\,m^{-2}$	
Quantity = (area) × (rain) × (water density)	4.20E+09	$g\,ha^{-1}\,y^{-1}$	
Wind			[23]
Density of air	1.30E+00	$kg\,m^3$	
Drag coefficient	1.00E-03		
Wind velocity	4.80E+00	$m\,sec^{-1}$	
Energy = (Energy on land) × (area) × (density) × (drag coeff.) × (wind speed)^3 × (time)	4,53E+10	$J\,ha^{-1}\,y^{-1}$	
Geothermal heat			[36]
Heat flow per area	2.21E+06	$J\,m^{-2}\,y^{-1}$	
Energy = (area) × (heat flow per area)	2.21E+10	$J\,ha^{-1}\,y^{-1}$	
Soil erosion			[37]
Erosion rate	4,55E+01	$g\,m^{-2}\,y^{-1}$	
% Organic in soil	5,00E−02		
Energy content/g organic	2.26E+04	$J\,g^{-1}$	
Net loss = (area) × (Erosion rate)	4.55E+05	$g\,y^{-1}$	
Energy of net loss = (net loss) × (% organic)	5.14E+08	$J\,ha^{-1}\,y^{-1}$	

Table A1 (continued).

Fertilizers			[21]
Nitrogen (N)	1.66E+05	$g\,ha^{-1}\,y^{-1}$	
Phosphorus (P)	2.00E+04	$g\,ha^{-1}\,y^{-1}$	
Potassium (K)	7.00E+04	$g\,ha^{-1}\,y^{-1}$	
Pesticide	1.38E+03	$g\,ha^{-1}\,y^{-1}$	[21]
Seeds	1.70E+05	$g\,ha^{-1}\,y^{-1}$	[21]
Lime	5.00E+05	$g\,ha^{-1}\,y^{-1}$	[21]
Diesel			[21,22]
Quantity (78.42 $l\,ha^{-1}$)	6.67E+04	$g\,ha^{-1}\,y^{-1}$	
Energy content	4.34E+04	$J\,g^{-1}$	
Energy = (quantity) × (Energetic content)	2.89E+09	$J\,ha^{-1}\,y^{-1}$	
Lubricants			[21,22]
Quantity	6.67E+03	$g\,ha^{-1}\,y^{-1}$	
Energy content	4.02E+04	$J\,g^{-1}$	
Energy = (quantity) × (Energetic content)	2.68E+08	$J\,ha^{-1}\,y^{-1}$	
Human labour			[21]
Labour hours	5.50E+00	$h\,ha^{-1}\,y^{-1}$	
Metabolic man-daly energy	1.26E+07	$J\,d^{-1}$	
Metabolic energy man-hour	5.23E+05	$J\,h^{-1}$	
Total energy = (Energy of metabolism) × (Work hours)	2.88E+06	$J\,ha^{-1}\,y^{-1}$	
Steel machinery			Own calculations
Total Machinery	6.34E+06	g	
Life time	1.00E+01	years	
Quantity 1760 $h\,y^{-1}$	6.34E+05	$g\,y^{-1}$	
Quantity	1.98E+03	$g\,ha^{-1}\,y^{-1}$	
Electricity			[22]
Consumption(grain drying 3 points %)	1.20E+09	$J\,ha^{-1}\,y^{-1}$	
Straw transport to CHP			[17,27]
Quantity	2.04E+06	$g\,ha^{-1}\,y^{-1}$	
Diesel	770	$J\,km^{-1}\,kg^{-1}$	
Distance for transport	1.80E+02	km	
Quantity	2.83E+08	J per 180 km	
Output			
Wheat grain	8.00E+06	$g\,ha^{-1}\,y^{-1}$	[21]
Energy content	1.40E+04	$J\,g^{-1}$	
Energy content	1.12E+11	$J\,ha^{-1}$	
Wheat straw	4.40E+06	$g\,ha^{-1}\,y^{-1}$	[21]
Energy content	1.44E+04	$J\,g^{-1}$	
Energy content	6.34E+10	$J\,ha^{-1}$	
Industrial phase (G1 bioethanol production, no recycled input) Feedstock from 1 hectare in 1 year.			
Conversion plant			[16]
Steal	5.23E+04	$g\,ha^{-1}\,y^{-1}$	
Concrete	9.30E+04	$g\,ha^{-1}\,y^{-1}$	
Electricity			[17]
Consumption (1 tons of grain)	1.00E+02	kWh	
Consumption	8.00E+02	$kWh\,ha^{-1}$	
Total consumption (coal) (a)	7.84E+09	$J\,ha^{-1}$	
Steam			[17]
Consumption (1tons grain)	3.60E+09	J	
Consumption	7.5E+04	J	
Total consumption (coal) (b)	2.16E+10	$J\,ha^{-1}$	
Sum of a and b	2.94E+10	$J\,ha^{-1}$	

(continued on next page)

Table A1 (*continued*).

Human labour			[38]
Labour hours	9.03E-01	$h\,ha^{-1}\,y^{-1}$	
Metabolic man-daly energy	1.26E+07	$J\,day^{-1}$	
Metabolic energy man-hour	5.23E+05	$J\,h^{-1}$	
Total energy = (Energy of metabolism) × (Work hours)	4.72E+05	$J\,ha^{-1}$	
Water (95% recycling)			[17]
Quantity per t of grain	5.94E+05	$g\,t^{-1}$	
Quantity per t of grain real used	2.97E+04	$g\,t^{-1}$	
Quantity per ha	2.38E+05	$g\,ha^{-1}$	
Enzymes			
A-amylase			[17]
Quantity per t of grain	3.56E+02	$g\,t^{-1}$	
Quantity per ha	2.85E+03	$g\,ha^{-1}$	
Energy per kg of enzymes (Joule of oil)	6.32E+06	$J\,kg^{-1}$	
Energy per enzymes per ha (Joule of oil)	1.80E+07	$J\,ha^{-1}$	
AMG(amyloglucosidase)			[17]
Quantity per t of grain	7.12E+02	$g\,t^{-1}$	
Quantity per ha	5.70E+03	$g\,ha^{-1}$	
Energy per kg of enzymes (Joule of oil)	6.32E+06	$J\,kg^{-1}$	
Energy per enzymes per ha (Joule of oil)	3.60E+07	$J\,ha^{-1}$	
Protease			[17]
Quantity per t of grain	3.26E+02	$g\,t^{-1}$	
Quantity per ha	2.61E+03	$g\,ha^{-1}$	
Energy per kg of enzymes (Joule of oil)	6.32E+06	$J\,kg^{-1}$	
Energy per enzymes per ha (Joule of oil)	1.65E+07	$J\,ha^{-1}$	
Additives			
Sulphuric acid			[17]
Quantity per t of grain	7.43E+03	$g\,t^{-1}$	
Quantity per ha	5.94E+04	$g\,ha^{-1}$	
Energy per kg of add. (Joule of oil)	3.00E+06	$J\,kg^{-1}$	
Energy per add. per ha (Joule of oil)	1.78E+08	$J\,ha^{-1}$	
Phosphorous acid			[17]
Quantity per t of grain	1.72E+03	$g\,t^{-1}$	
Quantity per ha	1.38E+04	$g\,ha^{-1}$	
Energy per kg of add. (Joule of oil)	2.00E+07	$J\,kg^{-1}$	
Energy per add. per ha (Joule of oil)	2.76E+08	$J\,ha^{-1}$	
Sodium hydroxide			[17]
Quantity per t of grain	1.07E+03	$g\,t^{-1}$	
Quantity per ha	8.55E+03	$g\,ha^{-1}$	
Energy per kg of add. (Joule of oil)	1.04E+07	$J\,kg^{-1}$	
Energy per add. per ha (Joule of oil)	8.89E+07	$J\,ha^{-1}$	
Ammonia water			[17]
Quantity per t of grain	3.56E+03	$g\,t^{-1}$	
Quantity per ha	2.85E+04	$g\,ha^{-1}$	
Energy per kg of add. (Joule of oil)	5.20E+06	$J\,kg^{-1}$	
Energy per add. per ha (Joule of oil)	1.48E+08	$J\,ha^{-1}$	
Urea			[17]
Quantity per t of grain	1.72E+03	$g\,t^{-1}$	
Quantity per ha	1.38E+04	$g\,ha^{-1}$	
Energy per kg of add. (Joule of oil)	6.20E+06	$J\,kg^{-1}$	
Energy per add. per ha (Joule of oil)	8.54E+07	$J\,ha^{-1}$	
Calcium chloride			[17]
Quantity per t of grain	3.56E+02	$g\,t^{-1}$	
Quantity per ha	2.85E+03	$g\,ha^{-1}$	
Energy per kg of add. (Joule of oil)	1.55E+06	$J\,kg^{-1}$	
Energy per add. per ha (Joule of oil)	4.41E+06	$J\,ha^{-1}$	

Table A1 (continued).

Yeast			[16]
Quantity per t of grain	5.49E+03	$g\,t^{-1}$	
Quantity per ha	4.39E+04	$g\,ha^{-1}$	
Energy per kg of yeast (Joule of oil)	6.32E+06	$J\,kg^{-1}$	
Energy per yeast per ha (Joule of oil)	2.78E+08	$J\,ha^{-1}$	
DDGS transport to pig farm			[17,27]
Quantity	2.85E+06	$g\,ha^{-1}\,y^{-1}$	
Diesel	770	$J\,kg^{-1}\,km^{-1}$	
Transport distance	1.80E+02	km	
Quantity	3.95E+08	J per 180 km	
Grain transport to bioethanol facility			[17,27]
Quantity	8.00E+06	$g\,ha^{-1}\,y^{-1}$	
Diesel	770	$J\,kg^{-1}\,km^{-1}$	
Transport distance	1.80E+02	km	
Quantity	1.11E+09	J per 180 km	
Output			
Bioethanol			[17]
Product quantity	2.38E+06	$g\,ha^{-1}\,y^{-1}$	
Energy content	2.67E+04	$J\,g^{-1}$	
Product quantity = (Quantity) × (Energetic content)	6.34E+10	$J\,ha^{-1}\,y^{-1}$	
DDGS			[17]
Product quantity	2.85E+06	$g\,ha^{-1}\,y^{-1}$	
Energy content	1.87E+07	$J\,SFU^{-1}$	
Energy content	3.08E+03	$SFU\ DDGS\ ha^{-1}$	
Total energy content = (Quantity) × (Energetic content)	5.76E+10	$J\,ha^{-1}$	
Output of slurry tons per input of DDGS			[26]
Slurry	6.72E+06	$g\,ha^{-1}$	
Nitrogen in slurry	4.82E+04	g N	
Phosphorus in slurry	7.89E+03	g P	
Potassiun in slurry	1.91E+04	g K	
Energy intake of 1 pig (74 kg meat) per year	210.9	SFU	
Slurry output per intake energy per year	4.6E+05	g	
Energy from DDGS output	3.08E+03	$SFU\ DDGS\ ha^{-1}$	
g of nutrients from 4.6E+05 g of pig slurry	3.3E+03	N	
	0.54E+03	P	
	1.31E+03	K	
Industrial phase (G2 bioethanol production, no recycled input) Feedstock from 1 hectare in 1 year			
Conversion plant			[16]
Steal	5.23E+04	$g\,ha^{-1}\,y^{-1}$	
Concrete	9.30E+04	$g\,ha^{-1}\,y^{-1}$	
Electricity			[17]
Consumption (1 tons of straw)	2.20E+02	kWh	
Consumption	9.68E+02	$kWh\,ha^{-1}$	
Total consumption (coal) (a)	9.49E+09	$J\,ha^{-1}$	
Steam			[17]
Consumption (1tons of straw)	3.8E+09	J	
Consumption	7.5E+04	J	
Total consumption (coal) (b)	1.25E+10	$J\,ha^{-1}$	
Sum of a and b	2.20E+10	$J\,ha^{-1}$	
Human labour			[38]
Labour hours	3.55E-01	$h\,ha^{-1}\,y^{-1}$	
Metabolic man-daly energy	1.26E+07	$J\,day^{-1}$	
Metabolic energy man-hour	5.23E+05	$J\,h^{-1}$	
Total energy = (Energy of metabolism) × (Work hours)	1.86E+05	$J\,ha^{-1}$	

(continued on next page)

Table A1 (*continued*).

Water (95% recycling)			[17]
Quantity per t of grain	5.94E+05	$g\,t^{-1}$	
Quantity per t of grain real used	2.97E+04	$g\,t^{-1}$	
Quantity per ha	1.31E+05	$g\,ha^{-1}$	
Enzymes			
Cellulase			[17,19]
Quantity per t of straw	1.10E+03	$g\,t^{-1}$	
Quantity per ha	4.84E+03	$g\,ha^{-1}$	
Energy per kg of enzymes (Joule of oil)	6.32E+06	$J\,kg^{-1}$	
Energy per enzymes per ha (Joule of oil)	3.06E+07	$J\,ha^{-1}$	
Additives			
Sulphuric acid			[17,19]
Quantity per t of straw	7.30E+03	$g\,t^{-1}$	
Quantity per ha	3.21E+04	$g\,ha^{-1}$	
Energy per kg of add. (Joule of oil)	3.00E+06	$J\,kg^{-1}$	
Energy per add. per ha (Joule of oil)	9.64E+07	$J\,ha^{-1}$	
Phosphorous acid			[17,19]
Quantity per t of straw	1.70E+03	$g\,t^{-1}$	
Quantity per ha	7.48E+03	$g\,ha^{-1}$	
Energy per kg of add. (Joule of oil)	2.00E+07	$J\,kg^{-1}$	
Energy per add. per ha (Joule of oil)	1.50E+08	$J\,ha^{-1}$	
Sodium hydroxide			[17,19]
Quantity per t of straw	1.10E+03	$g\,t^{-1}$	
Quantity per ha	4.84E+03	$g\,ha^{-1}$	
Energy per kg of add. (Joule of oil)	1.04E+07	$J\,kg^{-1}$	
Energy per add. per ha (Joule of oil)	5.03E+07	$J\,ha^{-1}$	
Ammonia water			[17,19]
Quantity per t of straw	3.50E+03	$g\,t^{-1}$	
Quantity per ha	1.54E+04	$g\,ha^{-1}$	
Energy per kg of add. (Joule of oil)	5.20E+06	$J\,kg^{-1}$	
Energy per add. per ha (Joule of oil)	8.01E+07	$J\,ha^{-1}$	
Urea			[17,19]
Quantity per t of straw	1.70E+03	$g\,t^{-1}$	
Quantity per ha	7.48E+03	$g\,ha^{-1}$	
Energy per kg of add. (Joule of oil)	6.20E+06	$J\,kg^{-1}$	
Energy per add. per ha (Joule of oil)	4.64E+07	$J\,ha^{-1}$	
Calcium chloride			[17,19]
Quantity per t of straw	3.50E+02	$g\,t^{-1}$	
Quantity per ha	1.54E+03	$g\,ha^{-1}$	
Energy per kg of add. (Joule of oil)	1.55E+06	$J\,kg^{-1}$	
Energy per add. per ha (Joule of oil)	2.39E+06	$J\,ha^{-1}$	
Yeast			[39]
Quantity per t of straw	2.00E+04	$g\,t^{-1}$	
Quantity per ha	8.80E+04	$g\,ha^{-1}$	
Energy per kg of yeast (Joule of oil)	6.32E+06	$J\,kg^{-1}$	
Energy per yeast per ha (Joule of oil)	5.56E+08	$J\,ha^{-1}$	
Straw molasses transport to the pig farm			[17,27]
Quantity	5.90E+05	$g\,ha^{-1}\,y^{-1}$	
Diesel	770	$J\,kg^{-1}\,km^{-1}$	
Transport distance	1.80E+02	km	
Quantity	8.17E+07	J per km180	
Straw transport to the bioethanol facility			[17,27]
Quantity	4.40E+06	$g\,ha^{-1}\,y^{-1}$	
Diesel	770	$J\,kg^{-1}\,km^{-1}$	
Transport distance	1.80E+02	km	
Quantity	6.10E+08	J per km 180	

Output

Table A1 (*continued*).

Bioethanol			[17]
Product quantity	9.37E+05	$g\,ha^{-1}\,y^{-1}$	
Energy content	2.67E+04	$J\,g^{-1}$	
Product quantity = (Quantity) × (Energetic content)	2.50E+10	$J\,ha^{-1}\,y^{-1}$	
Straw molasses			[17]
Product quantity	5.90E+05	$g\,ha^{-1}\,y^{-1}$	
Energy content	1.87E+07	$J\,SFU^{-1}$	
Energy content	5.78E+02	SFU DDGS ha^{-1}	
Tot energy content = (Quantity) × (Energetic content)	1.08E+10	$J\,ha^{-1}$	
Solid biofuel (lignin)			[17]
Product quantity	1.76E+06	$g\,ha^{-1}\,y^{-1}$	
Energy content	1.75E+04	$J\,g^{-1}$	
Product quantity = (Quantity) × (Energetic content)	3.08E+10	$J\,ha^{-1}\,y^{-1}$	
Output of slurry tons per input of straw molasses			[26]
Slurry	1.29E+06	$g\,ha^{-1}$	
Nitrogen in slurry	9.23E+03	g N	
Phosphorus in slurry	1.51E+03	g yP	
Potassiun in slurry	3.66E+03	g K	
Energy intake of 1 pig (74 kg meat) per year	210.9	SFU	
Slurry output per intake energy per year	4.6E+05	g	
Energy from Straw molasses output	5.78E+02	SFU straw mol ha^{-1}	
g of nutrients from 4.6 E + 05 g of pig slurry	3.3E+03	N	
	0.54E+03	P	
	1.31E+03	K	

Table B1 – Values used to estimate the fraction of CHP feedstock input on energy base.

Input	Value
Net power installed	1.057 MW
Energy produced	3.33E+10 MJ y^{-1}
MJ coal/MJ electricity[a]	2.71
Coal	9.03E+10 MJ y^{-1}
Lignin (average of four scenarios)	2.19E+04 MJ $ha^{-1}\,y^{-1}$

a Bentsen et al. [17].

Table B2 – Values used to estimate the fraction of CHP electricity used in Emergy terms.

Input	Value
Electricity to process grain & straw loamy conventional case	6.36E+09 J ha^{-1}
Emergy flow electricity to the industrial process	1.09E+15 sej y^{-1}
Electricity produced in the CHP plant	3.33E+16 J y^{-1}
Transformity of electricity from coal[a]	1.71E+05 sej J^{-1}
Emergy flow electricity produced at Asnæs CHP plant	5.70E+21 sej y^{-1}

a from Brown MT and Ulgiati S [40].

sustain the production of bioethanol from both grain and straw (considering the worst case LC scenario with the highest yield and electricity consumption) is equal to 1.09×10^{15} sej y^{-1} and per hectare. The ratio of these two Emergy flows, expressed in percentage, is equal to 0.00002%; this means that the electricity used in the bioethanol process accounts only for a very little percentage of the total electricity produced yearly by the Asnæs CHP plant. Further, the amount of external inputs needed to process the coal in a power plant, is about 18% of the total Emergy flow of the plant. Using these estimates, we obtain a contribution to the Emergy flow in the LC scenario of 1.96×10^{14} sej y^{-1} ha^{-1} that is practically negligible compared to the total Emergy flow (8.28×10^{15} sej y^{-1} ha^{-1}). Therefore, the CHP plant can be considered as a black box in all the scenarios.

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