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

Wenjie Liao*, Reinout Heijungs, Gjalt Huppes

Institute of Environmental Sciences (CML), Faculty of Science, Leiden University, P.O. Box 9518, 2300 RA Leiden, The Netherlands

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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 GHG 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.

1. Introduction

Our concerns about greenhouse gas (GHG) emissions, energy security and rural development are motivating the development of biofuel technology [1–3]. The use of biofuel, e.g., bioethanol, for transportation is already being promoted as a national policy, for instance in the United States [4] and in Europe [5]. The global biofuel production totalled 78 billion liters in 2008 [6] and provided 1.8% of total transport fuels in 2007 [7]. There is, however, ongoing debate on the extent to which biofuel could be regarded as a "sustainable energy source" [8–10] and what biofuel technology would be preferable [11,12]. 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 behavior

* Corresponding author. Tel.: +31 71 5271478; fax: +31 71 5277434.
E-mail address: liao@cml.leidenuniv.nl (W. Liao).

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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

of techno-systems like that for biofuel [13–16]. 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 analysed 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.

2. Materials and methods

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 Fig. 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 Fig. 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 resource (RRs) and primary non-renewable resource (NRRs). Scale C principally includes the biospheric processes that provide the primary resources, and the related socio-economic processes that provide the societal resources, viz. labor and services (LS), for all the industrial processes occurring at scale B.

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). 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 [17], Luo et al. (2009) [18], and a report by NERL [19]. However, due to lack of

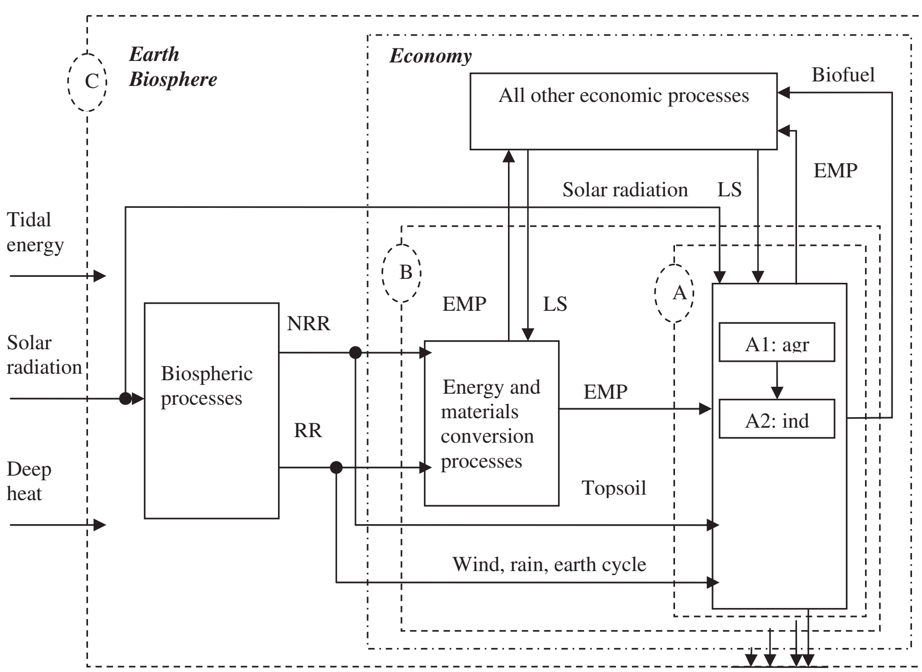

Fig. 1. The diagram of biofuel techno-system showing various scales for thermodynamic system analysis. Level A: the foreground production; Level B: the background industrial network; Level C: the supporting Earth biosphere. RR: renewable resources; NRR: non-renewable resources; EMP: energy and material products; and LS: labor and service.