The Role of Natural Capital and Aggregate Thermodynamic Metrics for Assessing the Life Cycle of Some Biomass and Fossil Fuels

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This paper advances the scope of life cycle analysis by considering resource qualities and integration of materials and energy to offer complementary insight to existing process LCA studies of biofuels. Resource qualities were partially accounted for by introducing ecological cumulative exergy analysis (ECEC). Integration of materials and energy of ecological goods and services was achieved via ECEC and industrial cumulative exergy consumption (ICEC) which facilitates comparison of disparate units (mass and energy) on a common thermodynamic unit. Four categories of metrics were developed from hybrid ecological life cycle assessment (Eco-LCA): (1) disaggregated metrics, (2) return on investment (ROI) metrics, (3) renewability metrics, and (4) efficiency metrics to elicit complementary insight. Results indicate that biofuels—corn ethanol and biodiesel—consume less non-renewable ICEC per km than gasoline and diesel, however, number of non-renewable resources consumed more by biofuels relative to petroleum-based fuels is higher. Exergetic efficiencies (km/ICEC) and returns on exergy investment (rEx) are lower for biofuels implying that biofuels consume more materials and fuels combined to produce 1 Joule of exergy output. Improving photosynthetic efficiency and minimization of soil erosion and water consumption may enhance exergetic efficiencies of biofuels. ICEC analysis shows that contribution of non-fuel materials is appreciable relative to fossil fuels and electricity for biofuels. Low yield ratios of biofuels indicate that more resources from the economy are needed to process freely available low quality sunlight into high quality bioenergy suggesting they may not be energetically competitive with gasoline/diesel. Unlike well-to-wheel exergetic efficiencies (km/ICEC), ecological efficiencies (km/ECEC) obtained by adjusting the quality aspect of exergy are higher for corn ethanol and biodiesel implying that they do not depend on as high quality resources as gasoline/diesel. Better ecological efficiencies but lower yield ratios, energy and exergy returns on investment present us with a unique trade-off as we move down the emergy hierarchy to tap in low quality sunlight for liquid fuel production.

1. Introduction

Life cycle assessment studies of transportation fuels have focused mainly on fuels from biomass, with primary emphasis on emissions and their impact, and consumption of nonrenewable resources (5-7, 10, 11). Sustainability of all activities relies primarily on ecosystem goods and services or natural capital, since this is the underlying foundation of all other goods and services via its supporting, provisioning, regulating and aesthetic services (ref mea). However, the role of natural capital is only considered partially and indirectly, at best, and most life cycle studies are unable to provide information about the role of natural capital or the vulnerability of the selected product to the depletion of specific ecological goods and services. Existing studies overwhelmingly focus on consumption of fossil fuels and emission of greenhouse gases (5-7, 10, 11), and pay scant attention to the consumption of other ecological resources such as soil, minerals, metallic and non-metallic ores, water, wood, sunlight, etc. A few biofuel studies do
account for some ecosystem goods such as land use, soil erosion, and water (refs) while ignoring other resources, which may also be important, and should be included for a more holistic view.

Furthermore, due to the highly multivariate nature of the results of life cycle studies, many methods have been devised for comparing and aggregating the results. Increasing dimensionality due to inclusion of natural capital makes such aggregation even more important. Such metrics are appealing for communicating the findings, particularly to non-experts, for convenient comparison between alternatives, and for decision making. Although most LCA methods focus mainly on quantifying the impact of emissions, methods for aggregating resource consumption are also needed for obtaining a holistic view of the life cycle. Thermodynamic concepts such as heating value of fuels and exergy have been suggested for developing such metrics and have been particularly popular for comparing various transportation fuels (1-5). The popularity of metrics such as energy return on investment, even among lay people (6), is testament to their broad appeal.

However, comparison and aggregation via conversion to a common unit, which itself may not be possible for some resources, does have several disadvantages. The reduction in dimensionality due to aggregation usually leads to loss of information about the variables being combined. An implicit assumption of aggregation that often receives little attention is that the resources being aggregated are substitutable. Thus, popular metrics such as energy return on investment and net energy add the energy content of crude oil, natural gas and coal, implying that a joule of natural gas energy may be substituted by a joule of coal energy. Depending on the materials and their application, such substitutability may not be possible since, for example, natural gas may be converted to electricity more efficiently than coal. Thus, for generating electricity, natural gas is a higher quality resource than coal. If the resources being aggregated include both renewable and nonrenewable resources, the disparity between their qualities can be even more significant – clearly a joule of sunlight or biomass energy is not able to do the same work as a joule of coal energy. The presence of such quality differences and ignoring them in energy analysis has led some researchers to even question the relevance and usefulness of such studies for decision making (6).

The issue of energy quality and aggregation of different resources has received some attention (8) and various quantities such as exergy, emergy and monetary value of the resources being combined have been suggested for capturing differences in resource quality. However, there is no consensus on the most appropriate approach. Even studies that apply and compare multiple resource aggregation schemes to the same data are uncommon since most papers focus on mainly one scheme (3, 9, 10).

This work relies on detailed data about the life cycle of gasoline, corn ethanol, diesel and soybean biodiesel included in the supporting information and in (7). The original contributions of this work are at least two fold. It quantifies, for the first time, the role of a large number of ecosystem goods and services that are relevant for supporting the selected fuels. This is based on the recently developed approach for Ecologically-Based LCA (ref Yi’s paper) and a hybrid Eco-LCA model that combines data from process based studies with those based on aggregate economic sectors. This provides unique insight about the vulnerability of the selected fuels to specific ecosystem goods and services. Secondly, this work sheds new light on the pros and cons
of various thermodynamic aggregation methods, via their application to the selected fuels. Such studies are essential for understanding the features of various approaches and determining appropriate uses for each approach. A hierarchical approach is also suggested in this work for combining the benefits of the details in raw data and the holistic view from aggregation.

2. Methods

2.1. Ecologically-Based Life Cycle Assessment

The hybrid Eco-LCA model developed in this work combines detailed information about relevant industrial processes and their reliance on natural capital with a model of the 1997 U.S. economy and the role of natural capital in each sector. The economic model based Eco-LCA is similar to the thermodynamic input-output analysis approach of Ukidwe and Bakshi (18). The main equation used in this is given as follows (19):

\[ Y = MX^{-1}(I - A)^{-1} \]  

Here, \( Y \) is the life cycle resource consumption per dollar of final demand, \( M \) is the resource use or emission for corresponding economic sectors, \( \hat{X} \) is a diagonal matrix of the total economic throughput, \( I \) is an identity matrix, and \( A \) is the direct requirements matrix. If the final demand is known, the cumulative consumption or emission of resources may be obtained by multiplying it with \( Y \).

This approach is similar to that used in EIO-LCA, but with some significant differences in the resources considered and the aggregation methods used. Both methods rely on an economic input-output model. EIO-LCA is closely integrated with the U.S. EPA’s Toxics Release Inventory database and provides details about a large number of emissions. It also uses demand side information about fossil energy use in each sector to quantify the life cycle energy consumption. Eco-LCA, as used here, focuses mainly on resource consumption and also uses demand side information for fossil energy consumption. However, Eco-LCA also considers many more renewable and nonrenewable resources than EIO-LCA or any other LCA approach to capture the contribution from ecosystems. Furthermore, Eco-LCA can use various physical aggregation schemes based on mass, energy, industrial cumulative exergy consumption (ICEC) and ecological cumulative exergy consumption (ECEC) or emergy (20). The emissions considered here only include some of the major pollutants.

2.2 Resource Aggregation

All the common aggregation schemes including those considered in this work may be represented as,

\[ \bar{x} = \sum \lambda_i x_i \]  

Here, \( x_i \) represents the physical property of the \( i \)-th resource, usually fuel value, exergy or mass, \( \lambda_i \) is the quality correction factor for the corresponding resource and \( \bar{x} \) is the aggregate value for all resources. Equation (1) implies that \( \lambda_i x_i \) units of the \( i \)-th resource is substitutable for \( \lambda_{i+1} x_{i+1} \) units of the \((i+1)\)-th resource.
**Net Energy Analysis.** This approach only considers the fuel value of non-renewable resources, namely, coal, oil and natural gas, and the conventional approach of calculating aggregate metrics such as the energy return on investment and net energy ignores any differences in energy quality. The energy return on investment, $r_E$, is defined as the ratio of the heating value of the produced fuel to the total heating value of the resources used for converting the raw materials into the fuel. This ratio based on the Eco-LCA model is shown in Fig. 1, and is comparable to results from other studies.

Cleveland et al. have discussed various approaches for obtaining the quality correction weights, $\lambda_i$, and conclude that monetary value is most appropriate \(^8\). Their argument is that market values capture many quality aspects of resources such as their abundance, human preference, cleanliness and convenience of use. In this approach, the quality correction factor may be calculated as,

$$\lambda_i = \frac{p_i}{p_b} \quad (2)$$

where, $p_i$ is the price of the $i$-th resource and $p_b$ is the price of the fuel selected as the basis. Thus, $\lambda_i$ represents the equivalents of resource $i$ in terms of the base resource. A possible shortcoming of this approach is that since market values are dictated by subjective human factors, they may have temporal and spatial variations even though the qualities of the resources under consideration are the same. Also, for environmental analysis, market prices may be inadequate since they may not capture many externalities or may not even be available for many ecosystem goods and services including those quantified in \(^7\).

**Industrial Cumulative Exergy Consumption Analysis.** Exergy analysis has been used widely in engineering for evaluating systems and identifying opportunities for improvement \(^11\), \(^12\). This quantity is often proposed as a way of accounting for the quality of resources \(^13\)-\(^15\). This is because exergy only considers that part of a resource that can be converted to useful work. This makes it a better indicator of quality than energy, since it can account for differences such as those due to different temperatures of heat or different chemical potentials of materials. In terms of Equation (1), the quality indicator, $\lambda_i$ for exergy analysis may be written as,

$$\lambda_i = \frac{Ex_i}{x_i} \quad (3)$$

where $x_i$ may be the calorific value, enthalpy or mass, and $Ex_i$ is the exergy content of the $i$-th resource.

Since both fuels and non-fuel materials have exergy, this quantity can be used to compare and aggregate many different types of resources, a distinct advantage over energy analysis. The benefits of utilizing exergy in lifecycle assessment have been elegantly explained by Ayres et al. \(^12\). Several studies based on exergy analysis of the life cycle of transportation fuels have been published recently \(^3\)-\(^5\). These studies present aggregate metrics such as life cycle efficiency, renewability factor \(^3\) and exergetic breeding factor \(^4\). The aggregate quantity obtained by
using Equations (1) and (3) is usually called the Cumulative Exergy Consumption or demand (CEC) or the Industrial CEC (ICEC) to indicate the emphasis on industrial and economic activities (16). This refers to the total exergy consumed directly and indirectly in the industrial processes in a life cycle.

While aggregation based on exergy is appealing due to its ability to capture only useful energy and combine energy and material resources, the results can still be misleading since a joule of exergy of different resources is not necessarily substitutable. For example, a joule of exergy in the form of coal, natural gas, biomass and sunlight are not fully substitutable and further differences in quality of exergy should also be considered before calculating aggregate metrics. Thus, statements such as biofuels are less exergetically efficient than fossil fuels or any other information based on aggregate exergy metrics must be interpreted carefully since they may simply reflect the larger quantity of lower quality exergy needed for processes based on solar or biomass energy as compared to those based on fossil fuels.

Dewulf et al. (17) have recently proposed a variation that only considers the exergy that is actually used from nature in industrial processes. This approach calculates the Cumulative Exergy Extraction from the Natural Environment (CEENE) and ignores resources that do not directly enter the selected life cycle. For example, only 2% of the incident sunlight on land is included in CEENE since that is the fraction metabolized by plants. Similarly, overburden in mining is not included since it is not used by industry. However, the part that is not used still must be produced to get the fraction that enters the economy, that is, it is not possible to produce only 2% of the total sunlight and have all of it metabolized by plants. This situation is analogous to allocation in LCA. The correction factor used in this approach is a modification of Equation (3) with the numerator being the extracted or used exergy instead of the total exergy of the resource. Thus, the numerator may be written as $\gamma_iE_x$ where $\gamma_i$ is the fraction extracted. For solar exergy, $\gamma_i = 0.02$. This approach still does not account for quality differences between various sources and considers the metabolized solar exergy to be equivalent to oil exergy. While this is an improvement over approaches that consider all the sunlight to be substitutable for energy in other resources, additional energy besides the metabolized quantity is needed to convert biomass into the concentrated and higher quality of fossil fuels (18). This additional energy is ignored by CEENE along with differences in the quality of other resources.

**Ecological Cumulative Exergy Consumption or Emergy Analysis.** A theoretically appealing approach for addressing the issue of energy quality was developed by Odum (19) via emergy analysis. Emergy is equivalent to cumulative exergy consumption when ecosystems are also included in the calculation, and may be referred to as Ecological CEC (ECEC) (16). This approach aims to represent all resources in terms of a common numeraire, usually as solar equivalents. As a simple illustration, consider a hypothetical supply chain for a biofuel where 100 J of sunlight are needed to produce 10 J of biomass, which is used to produce 1 J of fuel. This implies that a joule of fuel is equivalent to 10 J of biomass, which is equivalent to 100 J sunlight. Thus, 1 J of the biofuel is equal to 100 solar equivalent joules (sej), and adding different resources in terms of their solar equivalents satisfies the assumption of substitutability. This approach retains information about resource quality and therefore diminishes the criticism about the loss of information due to aggregation (20).
The quality correction factor in emergy analysis is given as,

$$\lambda_i = \frac{E_{mi}}{x_i}$$

where, $x_i$ is usually the exergy or mass of the $i$-th resource, and $E_{mi}$ is the ECEC or emergy of the same resource. The quality indicator, $\lambda_i$ is referred to as the transformity and converts all resources into solar equivalent joules. It has been proposed that resources with higher transformities are of higher quality and may be scarcer (19). Unlike all the approaches discussed in this section, ECEC or emergy is able to quantify the contribution of a variety of ecosystem goods and services, which may make it more appropriate for evaluation of environmental aspects. Although Odum and others have put significant effort into calculating the solar equivalents of a variety of resources, this approach relies on knowledge about complex ecosystems which is likely to be inaccurate and incomplete. Thus, although this approach is conceptually appealing, it has been controversial, and there is little empirical evidence yet about the validity of its claims including about being an appropriate aggregation method for environmental accounting. Other pros and cons of ECEC and emergy are discussed by Hau and Bakshi (21).

3. Results

3.1 Data Sources

Input data used for constructing hybrid models were taken from the process level information of crop farming, biofuel production, transportation and use. Emissions data for the production and use phases were calculated based on emissions factors corresponding to the equipment and vehicle where the fuels under consideration were used. Emissions factors for the production phase were collected from GREET (21). Emissions for the use phase of corn ethanol and gasoline were based on EPA annual certification results for a Chevrolet Impala 2006 (22) whereas use phase emissions for diesel and biodiesel were modeled after a light duty truck (21). Detailed discussions on data requirements and sources are provided in the supporting information.

Relevant exergy and transformity numbers were obtained from the literature (13, 19, 22, 23) for inputs from ecosystems to processes in the life cycle and to economic sectors. Such information has been used to calculate ratios of physical to monetary flow for each economic sector (24), which were used in this work for calculating the cumulative energy, ICEC and ECEC values for resources entering the life cycle of each fuel from economic sectors. The data in (24) was enhanced by including additional mineral resources and energy consumption data. The ECEC values of resources were combined to avoid double counting by considering allocation rules applied to emergy/ECEC analysis (16, 19). In general, the ECEC of most coproduced resources may not be added, while that of resources produced over different time frames or obtained by splitting a resource may be added. Examples of coproduced resources include sunlight, biomass, wind, and rain, and hydropotential since they are driven by solar input and produced concurrently. ECEC of soil was added to that of sunlight since soil may be considered to be the product of energy available in the past. Also, the ECEC of various non-renewable resources may be added since their transformities are calculated by allocating the inputs in proportion to the
quantity of each resource. Additional details are available in (16, 19). A similar approach has also been used for calculating CEENE (17).

The rest of this section presents disaggregated data and aggregate data in terms of the methods discussed in Section 2. ICEC was allocated among co-products in proportion to their mass, exergy, and market value to evaluate the effect of the allocation method. The results of ICEC analysis presented in this section mainly refer to mass-based allocation. Results for market-value based allocation are available in the supporting material. The latter approach assigns more weights to fuels than their corresponding co-products, causing the ICEC metrics to be larger than those for mass-based allocation. However, the overall trend between different fuels remains unchanged. No allocation was done for ECEC since emergy analysis forbids allocation among co-products. Sensitivity towards ICEC and ECEC was analyzed by varying crop yields per hectare.

3.2 Disaggregated Normalized Data
For comparing data about multiple resources it is useful to normalize it to make it dimensionless. Fig. 4 shows the results for corn ethanol and gasoline after normalization with the national consumption or flow of each resource. This graph is for the scenario in which all of the corn produced in the U.S. is devoted to ethanol production. This would substitute 12% percent of motor gasoline use (17 billion gallons) in 2006 (10), and would require 24.4 billion gallons of corn ethanol to displace that amount of gasoline based on the capacity of the fuel to drive a vehicle. The normalized values can indicate the limiting factors and vulnerabilities of the selected fuel.

As shown, soil erosion, cropland use, and nitrogen and phosphorus from mineralization would account for 4%, 8%, and 4%, of the national consumption, respectively. These numbers are for mass-based allocation. Without allocation, these numbers will double. Such appreciable soil erosion can offset carbon gains obtained through sequestration in soil or plants. It has been reported that 0.8-1.2 Gt of carbon is released into the atmosphere worldwide through soil erosion (27). Soil management practices like no-till farming are important to biofuel production because they not only improve soil fertility by retaining carbon in soils but also minimize carbon releases into the atmosphere by minimizing soil erosion. In this paper, it was assumed that 23% of cropland is associated with no-till farming (28). Trends for market-based allocations are similar and are provided in the supporting material (Tables S34, S36). A market-based allocation assigns larger weights to corn ethanol, biodiesel, gasoline, and diesel; as a result, consumption and emissions would be larger than for mass-based allocation. However, the trends between corn ethanol and gasoline, and biodiesel and diesel remain similar. Among the resources considered, consumption of nitrogen and phosphorus from mineralization, soil erosion, and cropland use can vary appreciably depending on corn and soybean yields as shown by the sensitivity bars in Fig.4.
Fig. 4. Consumption relative to current national resource consumption in the US when all the corn is used to make ethanol fuel. Then, ethanol substitutes 17 billion gallons of gasoline (mass-based allocation).
3.3 Disaggregated Thermodynamic Data

Fig. 1 depicts the relative contributions of each resource in terms of ICEC, ICEC with metabolized sunlight, and ECEC of various fuels. As can be seen from Fig. 1a, sunlight emerges as the predominant contributor to ICEC, even for gasoline and diesel. Although sunlight is not directly involved in the production of petroleum-based fuels, it is consumed indirectly via economic activities that support the production of these fuels. In this approach, sunlight exergy is based on the amount irradiated to the land per year which is very large. Therefore, even a small fraction of sunlight transferred to other economic sectors from the forest and agriculture sectors translates into very high exergy consumption in comparison to the exergy consumed via other resources. Sunlight is a very dilute and low quality source of energy as compared to crude oil and other resources, but this difference is ignored in this approach. This dominance of sunlight in fuels that are generally accepted to be nonrenewable indicates the problem with comparing resources without considering their quality.

The result of an approach analogous to CEENE (17) based on our data is shown in Fig. 1b. Here, only 2% of the sunlight is included. Now, the exergy of nonrenewables, primarily crude oil dominates for gasoline and diesel, as is generally expected. However, solar exergy still contributes 5%, which seems to be too high. For ethanol and biodiesel, solar exergy dominates, while other resources such as soil, minerals and fossil fuels seem to play a relatively minor role. As discussed in Section 2, this approach still does not account for substitutability and quality differences between resources.

A similar plot based on representing the resources in terms of emergy or ECEC is shown in Fig. 1c. In general, nonrenewable resources contribute more to total ECEC since they require more ecosystem work causing their transformities to be relatively large as compared to most renewables. Unlike Figs. 1a and 1b, sunlight is nearly invisible, while fossil fuels and other nonrenewables such as minerals and ores are relatively large contributors, particularly to ethanol and biodiesel. Other resources such as soil, detrital matter and nutrients from mineralization are much more prominent for biofuels than fossil fuels. Biofuels are also seen to capture CO₂ via photosynthesis for the national analysis boundary and static snapshot provided in this work.

By comparing Fig. 1b and 1c, it can be seen that contribution of detrital matter in terms of ICEC is 2.2 times larger than that of soil for corn ethanol but its contribution in terms of ECEC is 1.7 times lower than that of soil. The difference reflects the fact that detrital matter requires less ecosystem work than soil which may indicate soil’s relative scarcity and importance, which is recognized via ECEC analysis (19). If soil is eroded at a rate faster than its rate of replenishment, productivity of biofuels declines and more resources need to be devoted to attain the same yields. As seen from Fig. 1c, correcting qualities of resources through use of transformities in ECEC analysis does seem to be beneficial, but as mentioned in Section 2, the uncertainties in the underlying ecological processes and associated transformities need to be better understood (8).
Fig. 1. Relative contribution of various resources in terms of different thermodynamic units. (a) ICEC including all the sunlight. (b) ICEC with metabolized (2%) sunlight. This approach is analogous to CEENE (17). (c) ECEC for various fuels. Only major resources are shown here. Electricity not including coal means electricity produced from hydropower, wind, and geothermal.
3.4 Aggregated Thermodynamic Metrics

3.4.1 Return on Investment (ROI)

Five different types of return on investment (ROI) metrics are plotted in Fig. 2 based on conventional energy ($r_E$), monetarily weighted energy ($r_{E\$}$), ICEC ($r_{Ex}$), ICEC with metabolized sunlight ($r_{Ex(2\%)}$) and ECEC ($r_{Em}$). The conventional energy ROI is discussed in (7). In general, except for the monetarily weighted ROI, biofuels have a lower $r_E$ than fossil fuels. The monetarily weighted EROI ($r_{E\$}$) for biofuels calculated using weighting factors based on the relative prices of fuels per joule with respect to crude oil (8) are significantly larger than the traditional energy returns on investment ($r_E$). The relative differences are larger for biofuels, particularly for biodiesel, than for gasoline and diesel due to higher 1997 prices of biofuels as compared to gasoline and diesel. The higher prices of biofuels ($0.50$/liter for biodiesel vs $0.15$/liter for diesel in 1997 price) may reflect people’s willingness to pay for the perceived benefits of biofuels such as renewability, reductions in greenhouse gas emissions and greater energy independence even though there is not much difference in quality of the fuels in terms of doing work. If current escalating crude oil price is any indication, the trends would be reversed when prices of gasoline and diesel exceed those of biofuels.

The exergy return on investment ($r_{Ex}$) calculated by including all resources needed for transforming the feedstock into fuel is shown as the fourth bar in Fig. 2, using mass-based allocation. This variable is defined as the ratio of output exergy to ICEC needed for processing the raw materials into products. Processing ICEC includes non-fuel materials and fuels including indirect sunlight used in the process. It does not include ICEC of feedstock exergy and direct sunlight. Due to the dominance of indirect sunlight, ($r_{Ex}$) is very small, almost invisible in Fig. 2, and less than one for all fuels. This would imply that all fuels are exergetically infeasible since they require more exergy for processing the feedstock into fuel than the exergy content of the fuel itself. Clearly, such a result is misleading and is due to ignoring the quality of various resources and the dominance of solar exergy in this approach.

Considering only the metabolized fraction of sunlight results in $r_{Ex(2\%)}$ which is shown as the third bar for each fuel in Fig. 2. This ratio is still lower than 1 for biofuels due to large sunlight consumption implying that biofuels are not feasible according this approach. However, fossil fuels look good with $r_{Ex(2\%)}$ for gasoline and diesel being about 6. Even when sunlight is excluded completely, biofuels still turn out to have lower $r_{Ex}$ due to significant consumption of materials such as soil and detrital matter.

The ROI based on ECEC ($r_{Em}$) is analogous to the emergy yield ratio (19) and was obtained by dividing ECEC of the output by ECEC from the economy, which includes materials and fuels needed for processing the feedstock, but not the feedstock. As shown in Fig. 2, the yield ratios of biodiesel and corn ethanol are smaller than those of gasoline and diesel. This trend suggests that fossil fuels require less effort from economic activities for converting them into transportation fuels. Another interpretation is that the fossil feedstock is of higher quality and easier to process than biomass feedstock since in case of the latter resource, human activity is needed to do the type of work that nature has already done for producing fossil fuels.
Except for the monetarily weighted ROI, all other ROI metrics indicate that corn ethanol and biodiesel consume more resources for processing the feedstock into fuel as compared to gasoline and diesel, implying that the latter fuels are thermodynamically superior to the former. It also implies that since the processing energy and exergy reflect inputs from the economy, minimizing these inputs would increase the ROI of biofuel production. All metrics except \( r_{ES} \) indicate higher ROI for fossil fuels. ROI metrics for biodiesel are favorable than that for ethanol which are partly due to lower fossil fuel consumption. \( r_{Ex} \) does not provide meaningful results for biofuels since all ROIs are less than 1 which result from the dominance of sunlight and, therefore, indicates the need for adjusting the quality of sunlight.

### 3.4.2 Renewability Indicator

Since all fuels rely on a combination of renewable and nonrenewable materials, a renewability indicator may be used to determine the relative contribution of renewable resources to total resource consumption. Thus, the percent renewability, \( R \), may be defined as follows,

\[
R = \frac{\bar{x}_{\text{ren}}}{\bar{x}} \times 100
\]  

(5)

where, \( \bar{x}_{\text{ren}} \) is the aggregate quantity of renewable resource, and \( \bar{x} \) is the total resource. In general, resources considered to be nonrenewable include goods and services from the lithosphere such as metallic ores, non-metallic minerals, fossil fuels, etc. whereas renewable resources include contributions from the atmosphere, hydrosphere, hydropower, geothermal, wind power, sunlight, and soil erosion, etc. In this study, resources have been classified as renewable and non-renewable depending on how fast a given resource is produced. If resources can be regenerated within the time frame of 50 years, they have been classified as renewable. Odum (19) defines a resource as renewable or non-renewable depending on whether its
production rate exceeds its consumption rate. In this paper, soil was treated as a renewable source. Classifying soil as non-renewable does change the renewability indicator but biofuels still turn out to be much more renewable than petroleum-based fuels. Other approaches based on considering stocks and rate of use of resources could also be used for quantifying the renewability of a product.

The renewability index is shown in Fig. 3 based on the aggregation schemes of this article. Energy analysis cannot provide such a metric due to its emphasis only on nonrenewable fuels. In terms of ICEC and ECEC, both biodiesel and corn ethanol are indicated to be more renewable than gasoline and diesel. In case of ICEC, however, the degree of renewability is exaggerated for all fuels due to the high contribution of solar exergy that overwhelms even fossil fuel consumption for gasoline and diesel. ICEC with metabolized sunlight indicates less renewability, but still considers gasoline and diesel to be about 5% renewable, which seems to be too high (Fig. 3). This approach indicates more than 90% renewability of ethanol and biodiesel. In contrast, ECEC indicates renewability of corn ethanol and biodiesel to be 26% and 48%, respectively, while gasoline and diesel have a renewability index of nearly zero. Other thermodynamic metrics related to renewability include the breeding factor (4) and emergy loading ratio (19).

![Fig. 3. Renewability index of fuels based on ICEC, metabolized ICEC and ECEC analysis.](image)

### 3.4.3 Efficiency Measures

Efficiency metrics provide a picture of the overall resource consumption and can be useful for identifying opportunities for improvements. Unlike the ROI metric in Section 3.3.1, efficiency includes the feedstock in the denominator. Since the fuels under study are specifically used for transportation, it is relevant to measure efficiency in terms of kilometers traveled per unit of resource consumed. To determine the well-to-wheel efficiency, distance traveled per unit of
ICEC and ECEC for a Chevrolet Impala 2006, a large size car and a light duty truck (LDT2) was calculated (Fig. 4). The larger the value, the higher is the well-to-wheel efficiency. A km/ICEC ratio provides exergetic efficiency without adjusting for qualities of resources consumed whereas a km/ECEC ratio provides quality adjusted exergetic efficiency, also known as ecological efficiency.

As shown in Fig. 4, km/ICEC decreases from gasoline to E85 and from diesel to BD100. A lower km/ICEC ratio for biofuels suggests a potential of improving efficiency by lowering material and fuel consumption. Since sunlight accounts for 99% of ICEC, it indicates that utilization of plants with better photosynthetic efficiency or higher biofuel yield such as algae (25) may improve exergetic efficiency. Superficially, it may appear that sunlight is plentiful and there may be no incentive to conserve it. However, economic gains can be realized if photosynthetic efficiency is improved since it entails reductions of land area use, chemical, materials, and labor inputs by producing more output per unit area.

Efficiency information obtained from traditional energy analysis is incomplete as it is handicapped by its focus on fuel content. For example, fuels consumed in producing fertilizers are accounted for, fertilizer consumption is not. This can make a difference for products that utilize appreciable amounts of non-fuel materials in comparison to fossil fuels and electricity. For diesel and gasoline contribution of non-fuel materials (renewable plus nonrenewable) to ICEC is minuscule in comparison to contribution of fossil fuels and electricity. However, ICEC of non-fuel materials is about 64% and 41% of total ICEC (not including sunlight) in biodiesel and corn ethanol production, respectively for mass-based allocation. It shows that ignoring contribution of non-fuel materials may prevent us from realizing potential efficiency improvements. For example, the largest contribution to non-fuel material ICEC comes from detrital matter, water and soil for biofuels. Minimizing soil, water and detrital matter consumption would, therefore, increase the overall system efficiency. Detrital matter is also important for maintaining soil fertility and reducing soil erosion, minimizing detrital matter would be detrimental.

Another metric of interest is kilometer traveled per unit of non-renewable ICEC. Due to lower non-renewable ICEC consumption by biofuels, this ratio decreases in going from biomass to fossil fuels. E85 reduces non-renewable ICEC over gasoline by a factor of 2 and BD100 reduces non-renewable ICEC by a factor of 5 per kilometer traveled. For biofuels, there is a direct relationship between \( r_E \) and a km/non-renewable ICEC ratio because process energy and non-renewable ICEC mainly refer to fossil fuels. Except for crude oil, almost all other kinds of non-renewable resources considered in this study are consumed in larger quantities by biofuels in comparison to petroleum-based fuels. However, km/non-renewable ICEC is larger for biofuels than gasoline/diesel. It suggests that cumulative exergy consumption of crude oil by fossil fuels outweighs the cumulative exergy consumption of all other non-renewables by biofuels.

The km/ECEC metrics decreases from E85 to gasoline and from BD100 to diesel. These are in the opposite direction of the km/ICEC trends. This seems to imply that corn ethanol and biodiesel are ecologically more efficient than gasoline and diesel. The smaller cradle-to-wheel ecological efficiencies of gasoline and diesel are attributed to their reliance on non-renewable crude oil as feedstock which requires more ecosystem work. Since ECEC analysis assigns
significantly less weight to freely available resources such as sunlight, even the contribution of an exceptionally large quantity of sunlight in crop farming, a major source of inefficiency in ICEC analysis, turns out to be insignificant towards total ECEC. Conversely, non-renewable resources contribute significantly to total ECEC. As a result, there are two ways ecological efficiency can be improved: (1) utilizing more renewable resources into a production system and minimizing the use of non-renewable resources. The higher ecological efficiencies of biofuels stand in contrast to their lower yield ratios, energy and exergy returns on investment indicating a trade-off. Since land, which is an important and limiting resource is not considered, its inclusion in ECEC may affect the overall results and needs to be investigated further in the future.

The opposing trends for km/ICEC and km/ECEC are attributable to ICEC failing to capture the quality of resources consumed by gasoline and diesel by large margins. These are reflected by larger ECEC/ICEC ratios for gasoline and diesel which are 2 orders of magnitude larger than for corn ethanol and biodiesel. Non-renewable resources require more work and support from ecosystems and hence their ECEC tends to be relatively higher than ICEC in comparison to renewable resources. It follows that an industry sector or product such as gasoline that depends more on non-renewable resources will have a higher ECEC/ICEC ratio. As seen from Figs. 1a and 1b, fossil fuels constitute a significant part of ICEC consumption for gasoline and diesel but a small portion of ICEC for biofuels leading to large differences in ECEC/ICEC ratios.

4. Discussion
This study presents a hierarchy of metrics based on quantifying the consumption of a large variety of ecosystem goods and services to selected biomass and fossil fuels. The disaggregated normalized metrics help in identifying goods and services to which the selected product is likely to be most vulnerable. The high dimensionality of this metric makes it difficult to choose between alternatives. For this, various thermodynamic aggregation methods are considered. Aggregation and comparison of resources implies substitutability between them and to date most efforts including net energy and exergy analysis do not consider the validity of this assumption. Methods such as emergy analysis that do consider resource quality are conceptually appealing but have been controversial due to difficulty in getting all the relevant information. The comparison in this work provides new insight into the validity of the methods for quantifying resource consumption.

Net energy analysis only provides return on investment metrics and cannot quantify other aspects such as the renewability of fuels. Monetary weighting causes a relatively large increase in the energy ROI of biofuels and even increasing this metric for biodiesel to be more than that for fossil fuels. This may indicate the human preference for this fuel. Disaggregated ICEC values show that solar energy has a significantly larger contribution than all other resources. This provides misleading results since it implies high renewability even of fossil fuels. The approach of only including extracted resources (17) provides more meaningful results than those based on ICEC, but due to the contribution of sunlight, fossil fuels still have about 5% renewability and the return on investment for biofuels is less than one implying that both biofuels considered in this study are infeasible. Furthermore, this approach does not account for the substitutability between resources. Disaggregated ECEC values indicate the high nonrenewability of fossil fuels, limited renewability of biofuels, and account for the contribution of ecosystem services and substitutability between resources.
Fig. 4. ICEC- and ECEC-based efficiency metrics for various fuels.

The information in this work may be useful for targeting resources for possible efficiency improvements. For example, disaggregate ICEC and ECEC data show that, in addition to fuels, consumption of resources like soil in the form of soil erosion needs to be minimized for efficiency improvements. Disaggregated data provide indication of diversity and magnitude of resources consumed, the information which is lost in aggregated metrics.

Efficiency metrics show the poor well-to-wheel of fuels have very poor well-to-wheel exergetic efficiencies (km/ICEC) but consume less non-renewable ICEC per km traveled. Improving photosynthetic efficiency, and minimizing soil erosion and water consumption would enhance the overall exergetic efficiency. When quality corrected, well-to-wheel ecological efficiencies (km/ECEC) are higher for biofuels (i.e., requires less overall work in sej). By quickly processing low quality sunlight, albeit inefficiently, into high quality energy, biofuels offer an advantage over petroleum-based fuels in terms of less ecosystem work required and abundance. But the industrial pathways for biofuel processing (from crop farming to fuel production) exert more environmental impacts as evident from Part I (7).

The study shows an inherent trade-off encountered in pursuit of biofuels. They rely more on lower quality energy source (sunlight) and other renewable sources, and have better ecological efficiency, which is a good attribute. On the flip side, the present technology exerts more environmental impacts and requires a lot more effort from the economy (economic efficiency) to process it into a useable biofuel, probably making them less competitive energetically, to petroleum-based fuels which are derived from high quality but non-renewable crude oil. Any technology that efficiently translates sunlight into a biofuel with little economic inputs will
provide it a competitive edge. Alternatively, as the cost of extracting and transporting the crude oil becomes large later on that the yield ratios of gasoline and diesel may become lower than that of biofuels. Minimization of economic inputs and environmental impacts holds a key to the success of biofuels as the society moves away from fossil fuels and down the emergy hierarchy to extract low quality resources. Overall, the issues of resource qualities should be analyzed in tandem with energy and exergy analysis, and environmental impacts when comparing biofuels to make an informed decision. Moreover, usefulness of aggregated metrics can be amplified when used in conjunction with disaggregated metrics. Therefore, it is relevant to utilize both disaggregated and aggregated metrics in life cycle analysis.

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Supporting information available
Background data and calculations. These materials are available free of charge via the Internet at http://pubs.acs.org.

References


