Comparative study of biofuels vs petroleum fuels using input-output hybrid life-cycle assessment

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1. Introduction

With growing interest in alternative fuels owing to rising fossil fuel prices and global climate change concerns, biofuels have drawn a considerable interest from a life-cycle assessment (LCA) perspective (1-6). Although the majority of studies suggest the net environmental benefits for biofuels in comparison to petroleum fuels, the results have not been immune to criticisms (7-8). A part of the problem lies in the methodological/practical limitations of process-based LCAs which fail to present comprehensive accounting of energy and materials consumption from economy and ecosystems. The reported conflicting net energy and hence environmental impacts of corn ethanol relate with differences in system boundary selection, assumption, and inputs. Since there has been no agreed upon method for system boundary selection for process LCA, the conflicting results about biofuels such as corn ethanol and biodiesel are not surprising. When an artificial boundary for analysis is drawn for process-based LCA, it always leads to truncation errors. The subjectivity of system boundary selection renders life-cycle assessment susceptible to manipulation and creates a lack of confidence in comparative studies (9).

In a process-based LCA, the number of processes associated with a product and the order of upstream processes are limited making the system incomplete. Normally third and higher tier inputs are ignored. Almost all studies on corn ethanol are process-based life cycle analysis, therefore, the choice of inputs have influenced the outcome of the results. The problem of system boundary selection can be mitigated by using economic input-output life-cycle assessment (EIOLCA). Since economic sector-wide data are utilized, dilemma regarding inputs selection encountered in process LCA is inherently eliminated. The economic input-output life cycle assessment utilizes sectoral monetary transaction within a national economy and takes into account capital goods and overheads. A hybrid life cycle assessment integrates economy-wide data with process level data making the upstream input requirements complete (9). EIOLCA does not cover the use phase of a product and has to be modeled separately by process-based LCA. Combining economic input-output inventories with process-based inventories results in a hybrid model. In this paper, we analyze and compare ethanol and biodiesel based transportation fuels with gasoline and diesel by utilizing input-output hybrid life-cycle assessment (IOHLCA). Although the hybrid LCA technique in its various renditions has been applied for other products (10-12), *its application for the comparative study of biofuels and petroleum fuels does not exist*. This paper provides salient features of input-output hybrid life cycle assessment and summarizes the results obtained from its application for bio-based and petroleum fuels.

At present we are also working on *a novel life-cycle assessment model called thermodynamic hybrid life-cycle assessment (THLCA)* by utilizing the thermodynamic input-output table developed by Nandan and Bakshi (13). The results will be presented later. The thermodynamic input-output table takes into consideration ecological cumulative exergy consumption (ECEC). ECEC analysis extends industrial cumulative exergy consumption (ICEC) by incorporating the quality aspects of contributions from ecosystems and impact of emissions. By convention ICEC analysis does not differentiate 1 joule of natural gas and 1 joule of solar energy. ECEC, on other hand, captures quality differences between natural gas and solar energy by taking into account transformities. By incorporating contributions of ecological goods (e.g., ores, soil, pasture) and services (carbon sequestration, photosynthesis, pollution mitigation), not accounted in process-based LCA, THLCA can provide a comprehensive and holistic assessment that offers unique insight to the problem. Ignoring the importance of ecological goods and services in life-cycle assessment may lead to *wrong decision-making and selection of the sub-optimal alternative* that does more harm than good to the long-term sustainability of the earth. Moreover, by expressing all the data in one unifying thermodynamic unit, i.e. solar equivalent joule (seJ), THLCA can facilitate a comparison of disparate data (for example, ecotoxicity with global warming potentials). This provides a definite advantage over process-based and input-output hybrid LCAs which are beset by the subjectivity involved in weighing various impacts when making comparisons among various products. Such a problem arises when one product has a lower global warming potential and higher ecotoxicity while the other has a higher global warming potential and lower ecotoxicity.

2. Methodology

2.1 Input-output hybrid model: Input-output hybrid (IOH) model is an extension of the economic input-output analysis. In input-output lifecycle assessment (EIOLCA), the whole economy is taken as a boundary of analysis thereby removing the problem of subjective boundary definition (14). EIOLCA utilizes an economy-wide input-output table developed on the pioneering work of W. Leontief. In the USA, Bureau of Economic Analysis associated with the US Department of Commerce develops economic input-output table, the latest being 1997 input-output table. In EIOLCA, a commodity sector direct requirements matrix is augmented with sector–level environmental impact vectors including energy consumption. Data on emissions and energy consumption come from variety sources such as US Department of Commerce, toxics release inventory (TRI) database of the US Environmental Protection Agency (US EPA), US Census of Manufactures, etc. Economic input-output life cycle inventories (EIOLCI) created in this way are almost complete in terms of upstream system boundary. However, EIOLCI do not cover the use and disposal phase of a product. To include the use and disposal phase in LCA, a process-based LCI has to be created separately and combined with the input-output LCI. The LCA developed in this fashion is often called hybrid LCA. Several variations of hybrid LCA such as tiered hybrid, integrated hybrid, and input-output hybrid have been reported (15), although distinction among them is not straightforward. The model employed here is similar to the Model II described by Joshi (10) to compare a plastic fuel tank with a steel fuel tank. Such a model is used, particularly, for a product which is either new or not-well represented by commodity sectors due to high levels of aggregation. Following this approach, a new hypothetical product sector, e.g., corn ethanol, can be created by combining emissions and energy consumption associated with inputs required to produce a product. This model is not free from the limitation of the process-based LCA vis-à-vis a dilemma involved in inputs selection. Since it is difficult and, often not economically feasible, to include all the inputs, particularly capital equipment for which data are difficult to obtain, some minor inputs are inevitably ignored. Despite such a limitation, such an approach makes upstream system boundary complete for the input chosen, a distinct advantage over process-based LCA.

2.2 *Model descriptions for Input-Output Hybrid LCA*: A new hypothetical corn ethanol was created by combining all the sectors represented by inputs used in ethanol production (corn farming, transportation, ethanol production and distribution). The underlying theoretical basis of this approach is amply described by Joshi (10) and hence is not described here. It suffices to mention that corn ethanol sector was built by combining the economic value of each input represented by the corresponding economic sector by using a custom feature of the EIOLCA calculator developed by the Green Design Initiative (16). For this production costs of inputs were determined, and converted to 1997 dollars if costs were reported in other years. The EIOLCA calculator utilizes a 491×491 commodity sector direct requirements matrix (1997 augmented with environmental vectors (emissions and energy consumption). Data on energy consumed and emissions obtained by combining inputs from EIOLCA calculator represent upstream energy consumption and emissions and are referred to here as economic input-output inventory (EIOLCI). Since the energy consumption and emissions in the ethanol production, and emissions in use phase were modeled separately using process-based life-cycle inventories (LCI), and combined with EIOLCI externally, this creates an input-output hybrid (IOH) model. Fig.1 depicts the framework for IOH model and can be represented mathematically as:

$$IOHLCA_{ethanol} = EIOLCI + \text{Process } LCI_{production} + \text{Process } LCI_{use} \quad (1)$$

A similar approach was adopted for gasoline to facilitate comparison on a same methodological basis, even though life cycle data can be obtained directly petroleum refineries sector using an EIOLCA calculator. Fuels used and corresponding emissions in production of gasoline are modeled separately based on process level inventory. Likewise emissions in the use phase were modeled using process level data. Energy and emissions data for transportation of gasoline from refineries to distribution centers involved in transportation were added externally from the pipeline transport sector (NAICS code: 486000). The resulting model can be represented by the same equation as corn ethanol.

$$IOHLCA_{gasoline} = EIOLCI + \text{Process } LCI_{production} + \text{Process } LCI_{use} \quad (2)$$

Biodiesel and diesel LCAs were conducted using the above methodology.

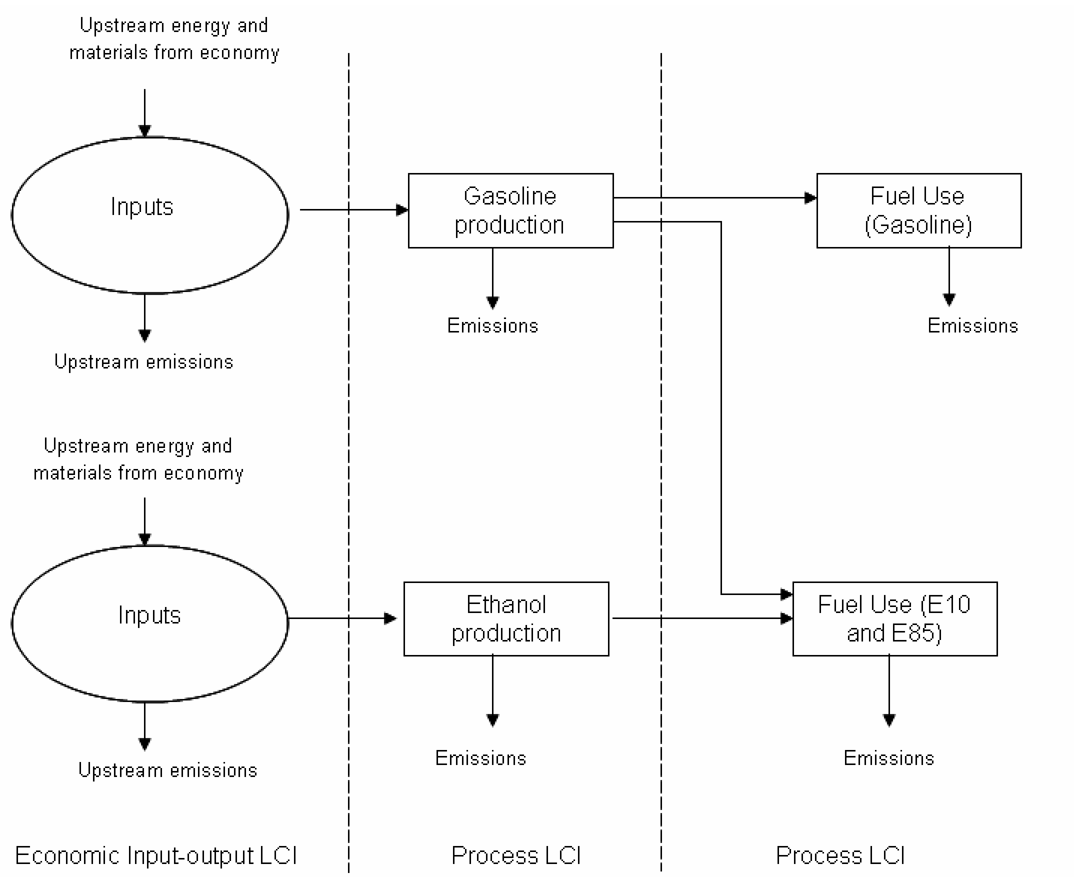

Fig. 1 Framework for input-output hybrid model for corn ethanol and gasoline

2.3 Data requirements and sources: The input data for ethanol were based on production of 1 million gallons of ethanol. The input data for corn ethanol and gasoline were obtained mainly from the National Renewable Energy Laboratory database (NREL) (17). Corn transportation and ethanol distribution data were used from GREET (18). Data for steel and PVC were taken from Graboski (4). Emissions from fuel use in corn farming, ethanol production, and distribution were calculated using emission factors reported in GREET model. Phosphorus and nitrogen releases into water and N_2O emissions into the atmosphere from corn farming were derived from NREL database. Emissions data for the use phase of E10, E85, and gasoline were based on emission test results for Chevrolet Impala 2006 (19). The fuel economy of Chevrolet Impala 2006 for gasoline, E10, and E85 is 13.2 km/liter, 12.8 km/liter, and 9.8 km/liter, respectively. Emissions of CO_2 and SOx were determined from the carbon and sulfur contents in fuels. N_2O emissions are based on the GREET data. Emissions of CO_2 from ethanol in E10 and E85 were ignored since it is eventually sequestered by corn in the next farming cycle. Carbon sequestration by soil was taken into account and was assumed to be 567 CO_2 metric tons/year (6), although the question of whether agriculture soil is a net carbon sinks is highly debatable. For example, it is estimated that the US farming loses about 4 gigatons (Gt) of carbon from soils annually due to erosion which is eventually released back into the atmosphere as CO_2 (20). Energy consumed and emissions associated with human labor and wastewater treatment were ignored.

The input data for biodiesel were calculated based on production of 1 million gallons of biodiesel. Input data for soybean production were obtained from NREL data, Hill et al. (21), and Sheehan et al. (22). Data on capital equipment/machinery for soybean and biodiesel production were taken from Hill et al. (21). Emissions from the use of biodiesel and diesel were modeled based on GREET data for a light duty truck (LDT1) and a 2002 EPA study (23).

2.4 Allocation

Energy consumption and emissions were allocated on mass and market value basis for all studied fuels. On market value basis, ethanol was allocated 81% share which was based on annual average wholesale price of ethanol and distillers dried grain with solubles (DDGS) from 1997-2005. On the mass basis, allocation for ethanol was set at 49%. For gasoline mass-based and market value allocations were 42% and 57.6%, respectively. The former was determined from the relative mass % of gasoline among co-products (17) and later was taken from the refinery level market value-based allocation reported by Wang et al. (24). Similarly, mass-based and market-value based allocations were applied for diesel and biodiesel.

3. Summary of preliminary results

3.1 Net energy: Net energy of biofuels has been a source of almost endless debate spanning over more than two decades. It is interesting to note that net energy of ethanol has received more attention than that of gasoline it intends to substitute. The IOH model allows us to calculate the net energy of transportation fuels. EIOLCA provides upstream energy consumed in producing inputs utilized in corn farming and ethanol production (fuels and chemicals, materials). If we combine this energy with energy consumed in the use of fuels in ethanol production (gasoline, electricity, natural gas, etc), we obtain the total energy consumed to produce a given amount of ethanol. Unlike process-based LCA, upstream energy consumption is complete in IOHLCA.

Most studies show net energy of ethanol to be positive or energy return on investment more than 1 (1-6). Energy return on investment (rE) is defined as:

$$rE = \frac{E_{out}}{P_E} \qquad (3)$$

Where, E_{out} is energy in output and P_E is process energy.

Process energy is the energy that does not end up as a part of energy embodied in the output. In the case of ethanol, for example, diesel, natural gas, electricity, energy used in the production of chemicals, etc. are considered as process energy. Energy embodied in the feedstock, i.e., corn, is omitted. rE greater than 1 suggests the net energy is positive.

rE less than 1 suggests that the net energy is negative. rE differs from energy efficiency. Energy efficiency is given as:

$$\text{Energy efficiency} = \frac{E_{out}}{\Pr_E} \qquad (4)$$

$$\Pr_E = F_E + P_E \qquad (5)$$

Where, $\Pr_E$ and F_E are the primary energy and feedstock energy, respectively.

The energy benefit offered by ethanol is less than that of gasoline (Fig. 2, Table 1). The IOHLCA resulted in rE value of 0.94 and 1.42 based on mass and market value-based allocation, respectively. It suggests that net energy of ethanol is highly sensitive to allocation method. The mass-based allocation method which returns a favorable figure of rE= 1.42 disproportionally distributes energy between ethanol and DDGS since ethanol production, particularly, distillation step, is a highly energy intensive. Even after allocation, rE for ethanol is lower than rE for gasoline with or without allocation. Upstream energy consumption accounts for 33% while ethanol production (from corn production to ethanol distribution) accounts for 67% of the total energy consumed on the mass allocation basis. For gasoline, upstream energy consumption is lower (22%) on the mass allocation basis. Reported rE for gasoline lies in the range of 4-4.5 whereas it varies from 0.78-2.28 for ethanol (Table 1). One exception is rE of 0.76 for gasoline reported by Hammershlag (25).

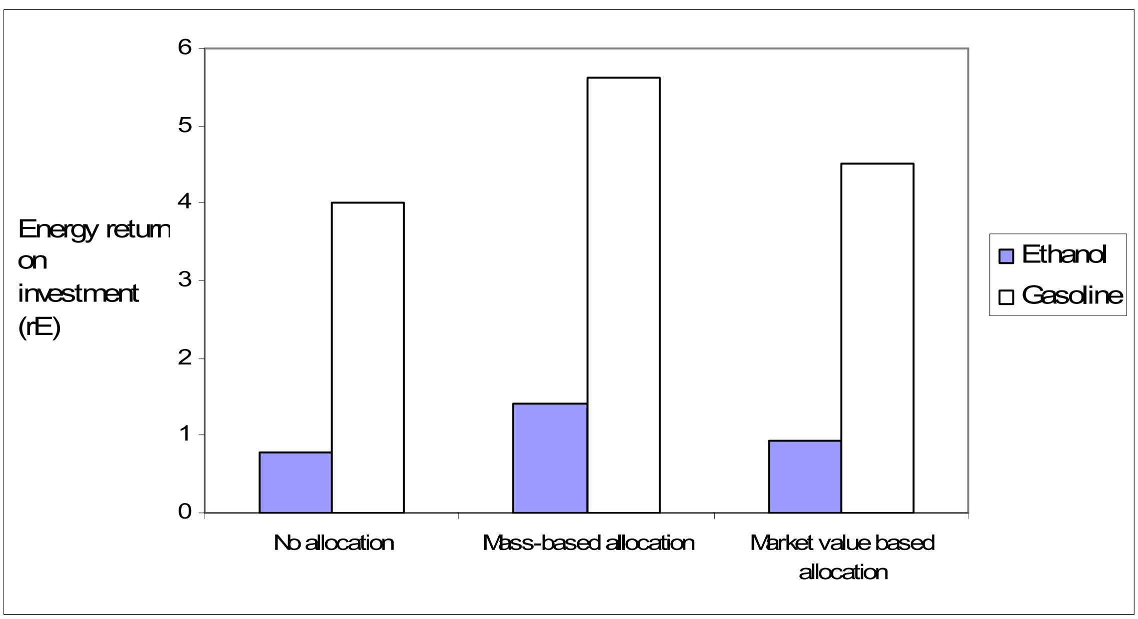

Fig. 2 Energy return on investment for gasoline, E10, and E85.

Return on energy investment is better for biodiesel than corn ethanol. It is 0.92 without allocation (Fig. 3). Mass-based allocation yielded rE of 3.55 whereas market-based allocation resulted in rE of 2.88. However, rE of biodiesel is lower than that of petroleum diesel. Mass-based and market value-based allocations for diesel yielded almost similar rEs of 8.10 and 8.32, respectively. Reported rEs based on process LCA are 4.78 (18) and 5.0 (22) which were lower than rE obtained by IOHLCA.

Although ethanol has a lower energy return on investment, focus on net energy alone does not reveal the entire picture. Should the net energy of corn ethanol dictate the policy decision? The answer is both yes or no. If a primary objective for ethanol production is to produce liquid fuel as a substitute for gasoline, it may not be a factor (26). Since natural gas and electricity combined constitutes the major energy input for corn ethanol, more liquid fuel (ethanol) is produced from less liquid fuel (diesel and gasoline combined). However, we will be importing more natural gas to produce a scarce liquid fuel (26) that negates the advantage offered by ethanol in reducing foreign dependency. If the main driver in pushing for corn ethanol is to generate renewable energy from biomass, net energy becomes a critical issue. Since energy embodied in the output ethanol is renewable energy, corn ethanol may become renewable when rE>1 and non-renewable rE<1.

Table 1. Energy return on investment for ethanol and gasoline.

References	***Present Study***	Marland &Turhollow 1991	Lorenz and Morris 1995	Graboski, 2002 (4)	Shapouri et al. 2002 (5)	Pimentel and Patzek 2005 (6)	Kim and Dale 2005 (7)
Methodology	*IOHLCA*	Process LCA (1)	Process LCA (2)	Process LCA	Process LCA	Process LCA	Process LCA
Ethanol (rE)	***0.74[a] (0.94[b], 1.42[c])***	1.28	1.59	1.21-1.40	1.30-2.25	0.78	1.23-2.28
References	***Present study***	GREET 1.7 (21)	GMC, ANL, BP, EM, and Shell 2001 (27)	LEL, ST &CI, and JE&A 2000 (28)	Hammer-schlag, 2006 (25)		
Gasoline(rE)	***4[a] (4.5[b], 5.6[c])***	4.5	4.5	4.25	0.76		

[a] Without allocation
[b] Market value-based allocation
[c] Mass-based allocation

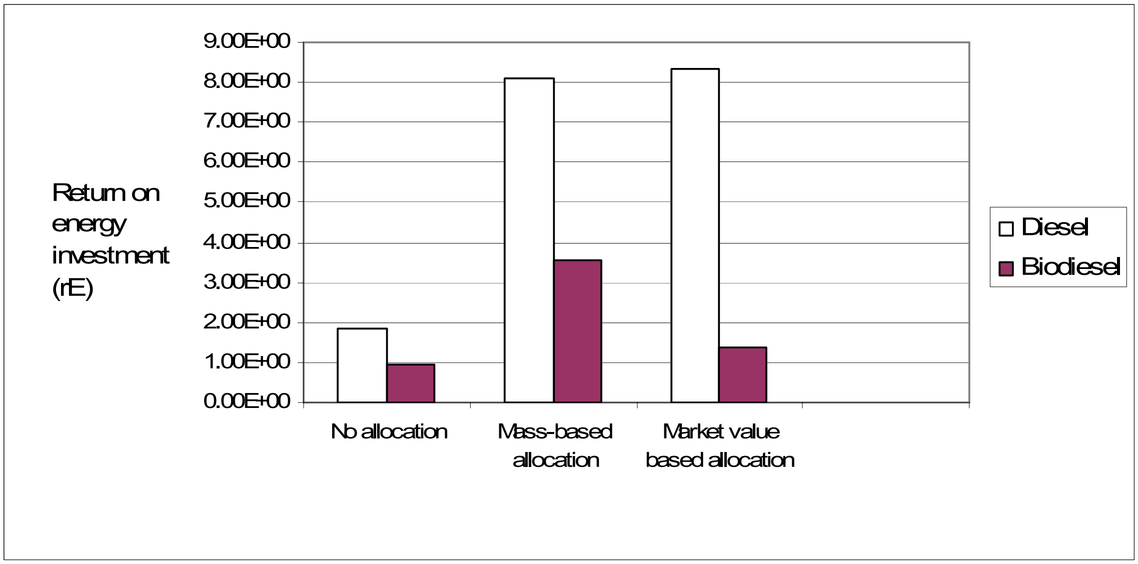

Fig. 3. Energy return on investment for biodiesel.

3.2 Emissions: To facilitate comparison among E10, E85, and gasoline, well-to-wheel emissions were calculated based on metric ton per kilometer (km) basis. After adjusting for carbon sequestration, use of E10 and E85 reduced CO_2 emissions by 5% and 51%, respectively over gasoline when mass-based allocation was considered (Fig. 4). On the surface this appears contradictory as ethanol has a lower rE than gasoline and hence should have higher CO_2 emission. Return on energy investment depends on energy consumed upstream and in production phase. Since upstream CO_2 emission and production CO_2 emission are higher for ethanol than gasoline (Fig.4), it is natural that ethanol has a lower rE. Emissions of total greenhouse gases (GHG) which include CO_2, CH_4, N_2O and CFCs decrease in the order gasoline>E10>E85 (Fig. 4). Use of E85 results in 39% reduction in GHG emissions over gasoline. A similar trend was obtained for market-based allocation but reduction in GHG emissions was lower. Among greenhouse gases N_2O and CFCs emissions are higher for E10 and E85 but they are offset by decrease in emissions of CH_4 and CO_2. Results of this study concur with the net GHG benefits of ethanol-based fuels reported in the majority of studies (22, 29). For example, Kim and Dale (6) reported net GHG reductions of 41-61% for E85 in comparison to gasoline which takes into account allocation between ethanol and DDGS. However, one unknown factor that could significantly change the GHG audit is the recent revelation by Keppler et al. (30) that terrestrial plants can release methane. If proven conclusively, well-to-wheel GHG emissions from bio-based fuels may become higher.

Biodiesel also reduces greenhouse gas emissions in comparison to diesel. Both mass-based and market-value based allocation yielded net reductions in GHG emissions for BD20 and BD100 (neat biodiesel) with respect to diesel (Fig.5). The reductions of GHG emissions for BD10 and B100 are 6% and 59% respectively in case of mass-based allocation.

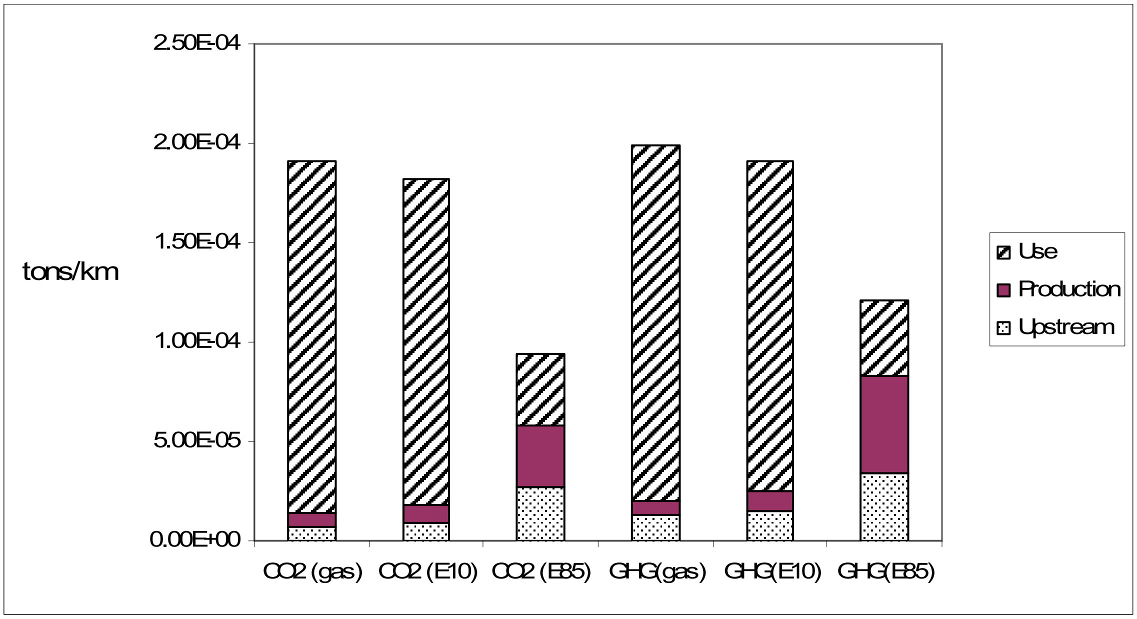

Fig. 4 Well-to-wheel emissions of CO_2 and GHG for gasoline, E10 and E85 (mass-based allocation)

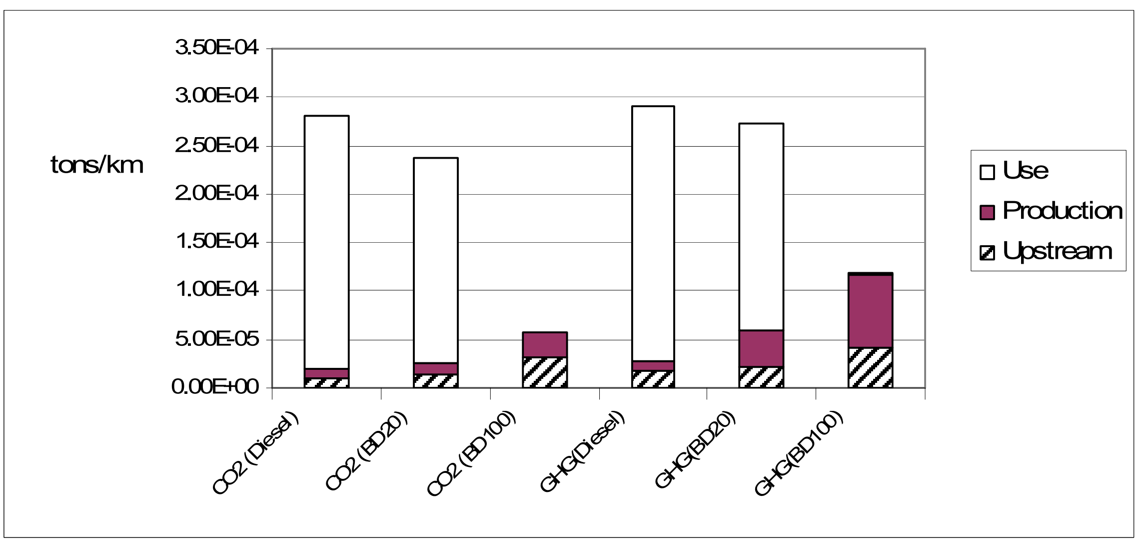

Fig. 5 Well-to-wheel emissions of CO_2 and GHG for Diesel, BD20 and BD100 (mass-based allocation)

With the exception of methane and carbon monoxide, IOHLCA revealed that gasoline has lower emissions for other pollutants including SOx, NOx, VOC, PM10, N_2O, total phosphorous (water), and total nitrogen (water) as compared to E10 and E85 (Fig.6). The use of E85 increases VOC, NOx, SOx, PM10, and N_2O emissions by 26%, 74%, 41%, 91%, and 75% with respect to gasoline. A similar trend was obtained in case of market value-based allocation with differences in emissions between gasoline and E85 become even larger. The use phase has the largest shares of emissions of CO, CO_2, and GHG for all three fuels. Since nitrogen, phosphorous, N_2O and NOx are released mainly from corn farming, ethanol production phase has the largest shares of these pollutants for E10 and E85. Runoffs from corn field contain nitrogen, phosphorous, herbicides, and insecticides which produce adverse effects on aquatic communities in the receiving waters. The most evident problem is the presence of anoxic zone in the Gulf of Mexico due to eutrophication. In case of VOC, SOx, and CH_4, upstream processes (EIOLCI) are responsible for the significant fractions of these emissions.

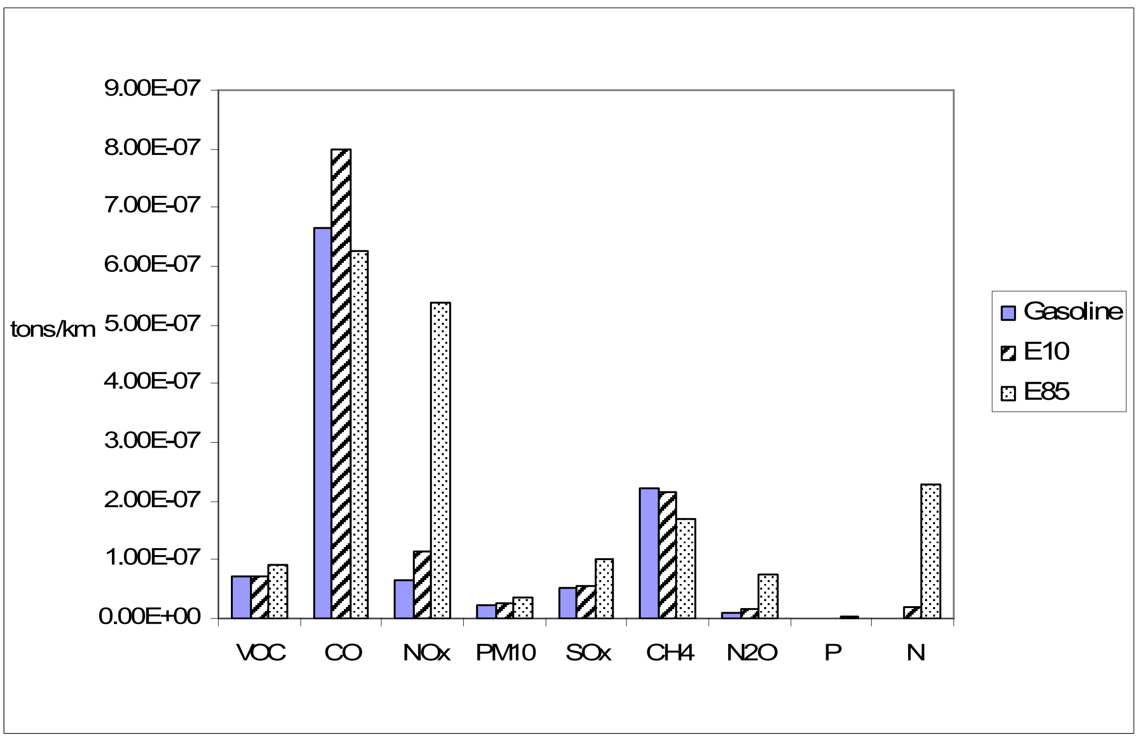

Fig. 6 Comparison of well-to-wheel emissions of gasoline, E10, and E85 (mass-based allocation method).

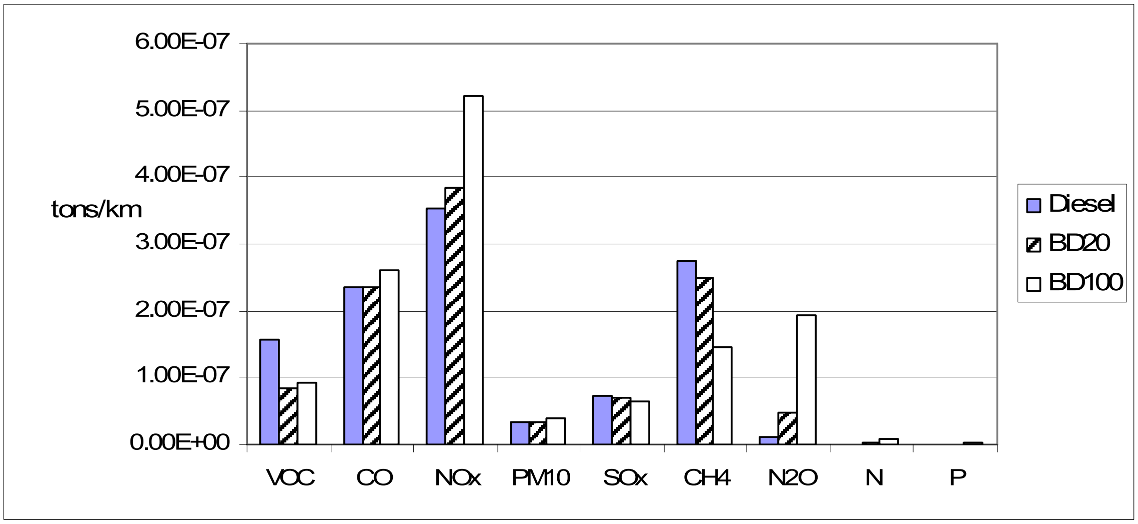

Fig. 7. Comparison of well-to-wheel emissions of diesel, BD20, and BD100 (mass-based allocation method).

Substituting biodiesel for diesel increases emissions of carbon monoxide, PM10, N_2O, CFCs, and nutrients such as N and P (Fig. 7). However, production of biodiesel releases less N and P than the production of corn ethanol. This is because the use of nitrogen and phosphorus fertilizers in soybean production is significantly less. The other pollutants that are produced in fewer quantities per km traveled in comparison to petroleum diesel are VOC, SOx, and CH_4.

4. Conclusions

Some of the uncertainties surrounding the biofuel discourse are partly a result of methodological constraints of process-based life-cycle analysis, particularly a problem associated system boundary selection. By using input-output hybrid model, this study eliminates the truncation errors. In addition to net energy and GHG emissions, this study provides comparison of well-to-wheel emissions of other pollutants for transportation fuels. However, by expanding the scope of analysis in input-output hybrid LCA, the level of precision is lost due to the use of highly coarse and aggregated data in input-output table that involved significant amounts of uncertainties and assumptions. Results obtained in this study are similar to those obtained from previous process LCA studies. The main conclusions that can be derived from this study are:

- Ethanol and biodiesel have lower returns on energy investment (rE) in comparison to gasoline and diesel, respectively. Biodiesel has better net energy than ethanol. Net energy of biofuels is highly sensitive to allocation procedure. This indicates the need for improving efficiencies of agricultural production and industrial processing of biofuels.
- Use of corn ethanol and biodiesel reduces well-to wheel greenhouse gas emissions.
- Use of corn ethanol and biodiesel results in increase in emissions of other air pollutants such as PM10, NOx, and N_2O. Releases of significant amounts of

nitrogen and phosphorous into water from corn and soybean production increase eutrophication potential of biofuels considerably.

Since biodiesel yield (58.2 gallons/acre) is substantially lower than corn ethanol yield (355-382 gallons/acre), approximately 4 times more land needs to be devoted to soybean production than for corn production to drive a vehicle by the same distance. Therefore, land requirements become a more limiting factor for biodiesel than ethanol. Corn ethanol and biodiesel can only meet a small portion of the burgeoning demand for transportation fuels as exemplified by the fact that even utilizing all of the soybean and corn produced in the U.S. for corn ethanol and biodiesel production meets 12% and 6% of gasoline and diesel demand (22).

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