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Designing Sustainable Supply Chains

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The Office of Research and Development within the U.S. Environmental Protection Agency (EPA) has recently put forth a new vision for environmental protection that states that sustainability is our "True North". In support of this new vision, an effort to design supply chains to be as sustainable as possible has been undertaken. This effort has two focus areas: consumer products and the transportation sector (biofuels). Starting with more than one hundred environmental metrics (e.g., energy, economic, and process) and sustainability metrics (e.g., ecological footprint, emergy, and exergy), a subset of the most relevant metrics have been identified and is currently being employed to evaluate the sustainability of the supply chains of multiple facilities of similar consumer products. From this evaluation, a set of rules or guidelines will be established that can be used to design a new supply chain or suggest improvements to current supply chains. Concurrently, an effort focusing on evaluating supply chains in the transportation sector is also contributing to the development of these design rules and guidelines. An approach for evaluating the sustainability of a supply chain and for designing them to be as sustainable as possible has been described. The premilinary results highlight the tradeoffs that will need to be considered when comparing alternatives especially for the biofuels; they also highlight the need for care in selecting and interpreting the metrics.

1. Introduction

In 2010, the Assistant Administrator for the United States Environmental Protection Agency's (U.S. EPA) Office of Research and Development put forth a new vision to address the complex environmental problems of the 21st century (U.S. EPA, 2010). This vision, entitled the Path Forward, highlights the fact that sustainability is the Agency's "true north" indicating that solutions to these complex environmental problems will only be developed by examining the entire systems in which the problems exist. To support this vision, the EPA initiated a research effort into designing supply chains to be as sustainable as possible. This is a two-pronged effort with focus areas in biofuels (transportation sector) and consumer products. The biofuels portion was in response to the Energy Security and Independence Act of 2007 (EISA), which set minimum levels for total renewable fuel production as well as production of advanced biofuel, cellulosic biofuel, and biomass-based diesel. The EISA also required that new renewable fuels production achieve at least a 20% reduction in life cycle greenhouse gas (GHG) emissions when compared with a baseline 2005 gasoline. These changes led to a revised version of the Renewable Fuel Standard (RFS2). In order to determine the impacts associated with RFS2, the EPA Office of Transportation and Air established a reference point from which GHG reductions should be measured and to determine reference GHG levels for biofuels production. The biofuels component of ORD's sustainable supply chain design effort focuses on

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developing data, models, and tools which can be applied to the assessment of bio-based and conventional transportation fuels required to achieve the goals of the EISA/RFS2. EPA must meet the dual demands of expanding production of renewable fuels while ensuring that GHG emissions are reduced, costs are kept under control, and that significant new environmental impacts are not generated as a result of changes to the U.S. energy system.

In the case of sustainable supply chain design of consumer products, the motivation is different than for transportation systems. Whereas regulation is the primary driver for changes in the transportation sector, sustainability within consumer product supply chains is largely driven by corporate responsibility (UN Global Compact and BSR, 2010) and marketing considerations. Many industries already have supply chain management systems in place to ensure well-scheduled delivery of process inputs, organized distribution products to a widely-dispersed marketplace, and to minimize cost (Hugos, 2011). The consumer products industry was critical in the early history of life cycle assessment (LCA) – one of the primary tools for evaluating the environmental performance of the supply chain – commissioning the development of product impact assessment tools (Heijungs and Guinée, 2012). In a recent survey of North American manufacturers, 70% responded that either their company or their clients request information on some aspect of environmental performance (IFS 2010). Many firms have set quantitative environmental targets for supply chain improvement (Schnoor, 2010). Despite the progress, large opportunities still exist.

The goal of sustainable supply chain management is to meet current consumer demand of goods and services in a way that allows future consumer demands to be met. This has traditionally been done by considering economic, environmental, and social aspects of sustainability. Assessing the sustainability of the supply chains of biofuels and consumer products requires a systems-level understanding of the relevant stocks and flows in the supply chain. It also requires understanding of opportunities within supply chains to make improvements. Supply chain aspects have a significant impact on economic costs and environmental impacts (Sims et al., 2010). Harvesting, treating, transporting, storing, and delivering large volumes of feedstocks and raw materials are all parts of the supply chains (both for biofuels and consumer products) that can contribute positively or negatively to the economic and environmental bottom line. Determining how those impacts interact with each other and affect the overall system requires an affective systems-level approach.

The goal of this work is to develop a methodology that can be used to evaluate the sustainability of the supply chain of a product (biofuel or consumer product) and to design the supply chain to be as sustainable as possible. It is follow-up work from Smith (2010). The work presented here will focus on the evaluation of the corn-to-ethanol and soy-to-biodiesel biofuel supply chains, but aspects of other related supply chains will be included. A schematic of a biofuels supply chain is shown in Figure 1.

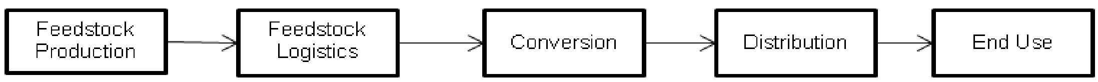

Figure1: A Schematic of a supply chain for biofuels

2. Sustainable Supply Chain Evaluation

The first step in the evaluation of the sustainability of the supply chain is to identify the appropriate metrics. Metrics have been developed to describe the performance of systems in many ways. In this sense systems can represent an entire supply chain or any subset of the supply chain. Companies usually develop metrics that focus primarily on the manufacturing process; for biofuels this would be the conversion of biobased feedstocks into biofuels, such as ethanol or biodiesel. Some companies, such as Walmart (Walmart, 2012) and Procter & Gamble (Procter & Gamble, 2012), have developed metrics to evaluate their suppliers. This evaluation will develop and use metrics to evaluate each of the stages of the supply chain separately and to evaluate the supply chain as a single system. The approach that is used in this research is to evaluate each of the steps of the supply chain individually and then to evaluate the life cycle of the supply chain as a system. This approach allows for a thorough analysis of the relationships of the different metrics at different levels (process and system). Examples of metrics that will be used in this study are presented in Table 1 and are separated by their appropriate level.

Table 1: Examples of metrics to evaluate supply chain sustainability

Process	Economic (Process)	Life Cycle/ Environmental	System Sustainability
Process emergy	Net Present Value	Resource use	System emergy
Atom economy	Cost of Manufacturing	GHG	Ecological footprint
Mass efficiency	Capital cost	Human health	Green Net Regional Product
⋮	Payback period	Eutrophication	⋮
	:	:	

There is a number of software tools that have been developed that can be used to calculate the metrics that will be used in this research. TRACI is a Life Cycle Assessment (LCA) tool that is used to track environmental metrics of an entire system (Bare et al., 2012). Tools, such as GREENSCOPE (Ruiz-Mercado et al., 2012a and 2012b) and WAR (Young and Cabezas, 1999), are designed to determine environmental, economic, and efficiency metrics of processes.

2.1 Process (conversion) descriptions

Corn-to-ethanol: The dry grind corn ethanol process model developed by the USDA (USDA 2011) is used to analyze the production of ethanol for a 40 million gallon per year plant. In this process, 367,000 MT/yr of corn is used to produce 40 million gallons of bioethanol. The process design contains all the essential aspects of ethanol production by fermentation process, including liquefaction of corn, saccharification, and fermentation. The process also contains separation and purification of ethanol using distillation and the use of molecular sieves to separate the ethanol from water. The wet solids are processed to recover corn oil and then dried to obtain marketable dried distillers grains with solubles (DDGS).

Soy-to-biodiesel: The biodiesel process was designed for the production of 9500 MT of biodiesel per year by alkali catalyzed transesterification process. The process design contains the transesterification reaction section, the purification of fatty acid methyl esters, and the recovery of glycerol as a by-product stream.

2.2 Evaluations

The processes described above were thoroughly evaluated at the conversion (process) level. The evaluation of the complete supply chain is in progress. However, there are some aspects of the supply chain evaluations that have been completed.

Table 2 describes the economic and emergy performance results of the two analyzed processes. The current prices of corn ethanol and biodiesel are used for the calculation of the Net present value (NPV), Capital cost (C_{TM}), and Manufacturing cost (COM). A plant life of ten years and a discount rate of ten percent were assumed in both economic process analyses. The NPV of both processes are negative, but the biodiesel process shows a better result. An opposite cost scenario is described by comparison of the two COMs, where the production of biodiesel is more expensive than the production of ethanol per unit of deliverable fuel energy. Another metric that can be used to evaluate the sustainability of a process is emergy. "Emergy is defined as the sum of all inputs of energy directly or indirectly required by a process to provide a given product when the inputs are expressed in the same form (or type) of energy, usually solar energy" (Brown and Ulgiati, 1997). Emergy can be used in process evaluations through comparisons of the emergy benefit of a product per unit of deliverable fuel energy. This metric correlates with process efficiency, especially with respect to using the emergy embodied in the purchased inputs. A high score of product emergy-energy ratio indicates an efficient use of emergy, while a low score indicates an inefficient process. Based on these conceptual design results, the biodiesel process describes a more efficient system for transforming purchased inputs. Note that this analysis differs from the more commonly used return on energy invested calculations.

Table 2: Economic and emergy metrics for the conversions of corn to ethanol and soybean to biodiesel.

Process	Current product price, \$/kg	NPV/fuel heat content, \$/MJ	C_{TM}/ fuel heat content, \$/MJ	COM/fuel heat content, \$/MJ	Product emergy/fuel heat content MseJ/MJ
Corn-to-ethanol	0.61	-0.0180	0.00597	0.0300	230000
Soy-to-biodiesel	1.275	-0.0274	0.00463	0.0371	1400000

Life cycle assessment (LCA) is one systems-level approach that has been used to quantify the environmental impact of consumer products and biofuels. It can capture the flows and impacts from the acquisition of raw materials through materials processing, manufacturing/construction, use/maintenance/upgrade, and retirement. However, LCA is not without its challenges. Taking biofuels as an example, McKone et al. (2011) noted seven challenges in applying LCA to biofuels, a few of which discussed the better understanding of emissions characterization, land use, and spatial heterogeneity. These are especially important as we strive to better understand the impacts of air, water, and land releases caused by consumer products and biofuels.

As part of this project, an LCA study has been completed for the production of biofuels solely focusing on the emission of Greenhouse Gases (GHG). The results of this LCA study are shown Figure 2. For comparison, the results for conventional gasoline and conventional diesel have been included. This analysis considers all of the steps of the supply chains, but only considers GHG emissions. These results are based on calculations performed using the GREET model, [v1_2011] without the inclusion of land use change (LUC) emissions (Wang, 2001). The lower GHG emissions for the biofuels support the required 20 % reduction in GHG emissions as compared to conventional fuels. Soy-to-diesel substantially surpasses the 20 % reduction (greater than 75%). From Figure 2, it is apparent that soy-to-biodiesel has lower GHG emissions as compared to corn-to-ethanol, which makes it preferable from this aspect.

An ecological footprint has also been conducted for the entire life cycle of those fuels. Ecological footprint is a metric that measures actual human consumption of biological resources and generation of wastes in terms of appropriated ecosystem area, which can be compared relative to the biosphere's productive capacity. It is measured in global hectares and groups land usage into seven categories – crop land, grazing land, forest, fishing grounds, carbon (uptake) land, nuclear energy land, and built-up land. In developing a systems-level approach to designing sustainable supply chains, the aim of the current work is to create a method for characterizing land use and greenhouse gas emissions in LCA by utilizing the Ecological Footprint approach, either as a complementary or impact assessment tool. This will help in improving the understanding of land use and ecological services within the context of supply chains and industrial systems.

The results of the ecological footprint evaluations are shown in Figure 3. Again, the ecological footprints for the conventional fuels have been included. The smaller ecological footprints for the conventional fuels are to be expected since they derive from mined raw materials, which are not captured well in ecological footprint calculations; on the other hand, bio based feedstocks require substantial land for growing the respective crops, which is captured by the ecological footprint calculation. The inclusion of metrics for conventional fuels is instructive on a couple of points. First, they provide a baseline measure of where alternative fuel technologies can compare themselves. Second, they highlight the fact that the usage of metrics to evaluate processes needs to be done carefully because metrics only capture a specific aspect of a system. Everybody knows fossil based fuels are a finite resource and thus, inherently unsustainable, which is not readily apparent from Figure 3. The effects on human health and the ecosystem have not been captured yet in this study. Obviously, the inclusion of these factors into a sustainability analysis will help in understanding some effects of fossil fuel usage.

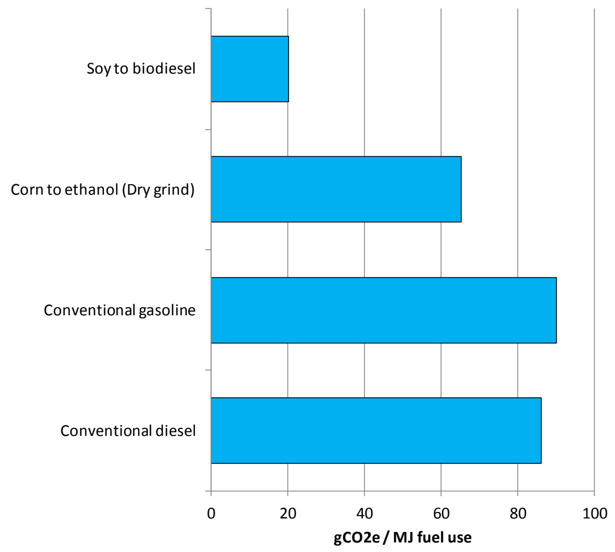

Figure 2: The greenhouse gas emissions for biobased and conventional fuels. The greenhouse gas emissions have been converted to g of CO_2 equivalents/MJ of fuel used.

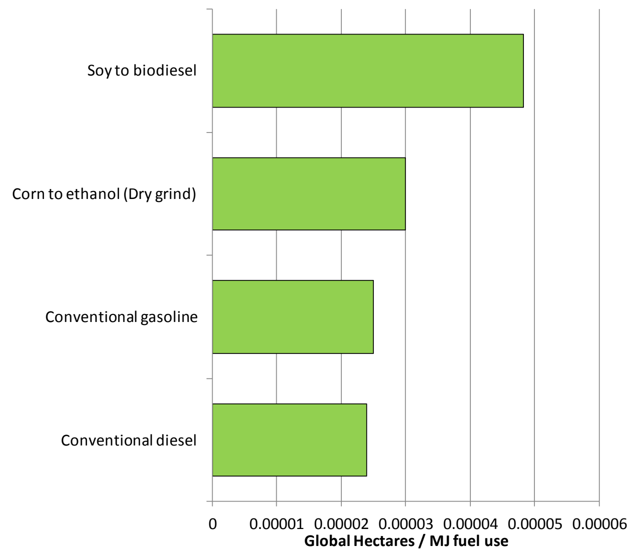

Figure 3: Ecological footprint results for biobased and conventional fuels.

3. Conclusion and next step

A methodology for evaluating the sustainability of product supply chains has been described. The first step in this methodology is selecting the appropriate metrics. Two examples have been described: the production of ethanol from corn and the production of biodiesel from soy. Sustainability metrics, such as GHG emission and ecological footprint, indicate that corn-to-ethanol is more sustainable than soy-to-biodiesel; however, the sustainability metric emergy indicates the opposite for the conversion process. Thus, while process metrics are important, this example shows that one needs to consider the whole supply chain or product network when designing for sustainability. The next step in this effort is to extend the analysis of emergy and other metrics to the entire supply chains. This analysis will set the baseline for the two most prominent biobased fuels. Then, other biobased feedstocks can be considered and evaluated against these baselines to determine relatively how sustainable they are. As mentioned in the Introduction there is a parallel study where industrial supply chains are being evaluated for sustainability. The goal in these parallel efforts is to establish which metrics are appropriate when evaluating the sustainability of supply chains and what are the relationships between the metrics. The ultimate goal is then to capture this information into a set of guidelines that can be used to design or re-design supply chains to be as sustainable as possible.

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