ABSTRACT

Title of Document: INTEGRATED ENERGY, ENVIRONMENTAL AND FINANCIAL ANALYSIS OF BIOFUEL PRODUCTION FROM SWITCHGRASS, HYBRID POPLAR, SOYBEAN AND CASTORBEAN

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Biofuels are considered a substitute for petroleum-fuels, but to be viable they should not depend heavily upon non-renewable resources. The objective of this study was to estimate the ultimate amount of energy required to produce liquid-fuels from switchgrass, hybrid poplar, soybean, and castorbean. Emergy (with an “m”) accounting was used to integrate all environmental, fossil fuel, and human-service inputs used throughout the production chain from agricultural field to processing facility. Depending on feedstock type and conversion yields, environmental inputs were between 21-44%, fossil fuels were 18-73% and human-derived services were 2-61%. Gallons of transportation fuel produced per gallon of petroleum used ranged from 0.06 to 4.2 for ethanol and 2.6 to 4.4 for biodiesel. No biofuel was made with less than 75% non-renewable resources. Energy embodied in ‘hidden’ indirect paths ranged from 38-99%. The viability of replacing petroleum with cellulosic ethanol or biodiesel is highly questionable.

INTEGRATED ENERGY, ENVIRONMENTAL AND FINANCIAL ANALYSIS OF BIOFUEL PRODUCTION FROM SWITCHGRASS, HYBRID POPLAR, SOYBEAN AND CASTORBEAN

By

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Thanks to my grandmother for being a role model, for teaching me the value of education, for always believing in me and mostly for giving me her love. I know that wherever she is, she is proud of my new accomplishment. Thanks to my parents, relatives and friends for believing in me and always supporting my decisions. I dedicate my work to Marquitos and Andrew.

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Spanish:
Gracias le doy a mi abuela quien desde niña me enseñó a valorar la educación, quien siempre creyó en mí y sobre todo quien me dio su amor. Yo sé que donde quiera que ella se encuentre, estará muy orgullosa de mis logros. Gracias a mis padres, hermanos y a toda mi familia y amigos por su apoyo y por nunca cuestionar mis decisiones. Dedico en especial mi trabajo educativo a la próxima generación: a Marquitos, Andrew, Alexis, Cisco, Daisy, Gaby, Leo, Josué y todos los demás. Como una vez me dijo mi abuela: *la educación es la llave del éxito*, ahora yo les digo que recuerden esto y trabajen duro para salir adelante.

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Unit Conversion Table

Unit	Symbol	Relationship		
	AREA			
square meter	m^2			
hectare	ha	1 ha	=	10 000 m^2
square kilometer	km^2	1 km^2	=	100 ha
acres	acre	1 acre	=	0.405 ha
square feet	ft^2	1 ft^2	=	0.093 m^2
	DISTANCE			
millimeter	mm	10 mm	=	1 cm
centimeter	cm	100 cm	=	1 m
meter	m			
kilometer	km	1 km	=	1000 m
feet	ft	1 ft	=	0.3048m
miles	mi	1 mi	=	1.61 km
inches	in	1 in	=	2.54 cm
	ENERGY			
watt	W			
kilowatt	kW	1 kW	=	1000 W
joules	J	1 kg per m^2 per s^2		
kilowatt-hour	kWh	1 kWh	=	3,600,000 J
kilocalorie	Kcal	1 kcal	=	4184 J
British thermal units	Btu	1 Btu	=	1055 J
	MASS			
milligram	mg	1000 mg	=	1 g
gram	g			
kilogram	kg	1 kg	=	1000 g
metric ton	t	1 t	=	1000 kg
pound	lb	1 lb	=	454 g
short ton	T	1 T	=	0.9072 t
	VOLUME			
milliliter	mL	1000 mL	=	1 L
cubic centimeter	cm^3	1 cm^3	=	1 mL
liter	L	1000 L	=	1 m^3
gallon	gal	1 gal	=	3.785 L
US quart	qt	1 qt	=	1.101 L
Oil barrel		1 oil barrel	=	160 L

Table of Abbreviations

Abbreviation	**Meaning**
Institutions	
EIA	U.S. Energy Information Administration
IFIAS	International Federation of Institutes for Advanced Studies
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
USDA	United States Department of Agriculture
USDOC	United States Department of Commerce
USDOE	United States Department of Energy
USDOI	United States Department of Interior
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
General terms	
B10	A blended fuel compromised of 10 percent biodiesel and 90 percent petroleum diesel
B20	A blended fuel compromised of 20 percent biodiesel and 80 percent petroleum diesel
B100	Pure biodiesel
Biofuels	Fuels made from agricultural crops like corn or soybeans and waste products like used lumber and manure
BFDP	Biomass Feedstock Development Program
BRDI	Biomass Research and Development Initiative
dry wt.	Dry Weight
E85	A blended fuel compromised of 85 percent ethanol and 15 percent gasoline
EIR	Emergy Investment Ratio
ELR	Environmental Loading Ratio
EYR	Emergy Yield Ratio
fresh wt.	Fresh Weight
gal	Gallon
GGE	Gasoline Gallon Equivalent
MM	Million
O.M.	Organic Matter
sej	Solar Emergy Joules
yr	Year

Chapter 1: INTRODUCTION

Problem Statement

The recent interest in finding viable substitutes like ethanol or biodiesel for society's petroleum-based transportation fuels excites much of the public and many politicians because it is perceived as environmentally friendly, freeing of foreign fuels and economically helpful to rural, farm-based communities. However, the transformation of cellulosic sources such as switchgrass to ethanol requires the use of natural resources like land and water, fossil fuels and electricity, and human-derived services and materials.

In 2004, the primary energies driving the U.S. economy were coal, natural gas, petroleum, nuclear electricity from uranium and renewable energy primarily from hydropower and wood residues. According to the Energy Information Administration (EIA), petroleum, natural gas and coal represented 40%, 23%, and 23 %, respectively of the total U.S. primary energy consumption (EIA, 2004b). Of this mix, 90% of coal was used for electricity generation while most of the natural gas was consumed in heating and electricity production. On the other hand, about 67% of the petroleum was used in the transportation sector.

Estimates on future global oil demand are projected to increase from 12.7 billion liters per day (80 million barrels per day) to 18 billon liters per day (118 million barrels per day) (EIA, 2006a) by 2030. This projected increase in oil demand coupled with speculations on the decline of global oil reserves has generated anxiety throughout the international community (Lovins, 1996). The Unites Sates (U.S.) as the primary petroleum consumer in the world with has an estimated annual consumption of 1200 billion liters (7.5 billion barrels, 317 billion gallons,) of petroleum products (EIA, 2004b). Moreover, because the U.S. internal oil demand has long exceeded domestic supply capacity, more than half of the petroleum now use is imported from other countries. These imports typically originate from countries that are currently politically unstable or at conflict with the U.S. (EIA, 2004a). In 2004 national energy expenditures were equivalent to 7% of the U.S. Gross Domestic Product (GDP) with petroleum expenditures representing about 5% of the total energy expenditures (EIA, 2004a).

The results of current global energy production and consumption patterns together with the political unrest in oil exporting countries have heightened the U.S. vulnerability to future availability of oil supplies. A disruption to the oil supply chain will be most harmful to the transportation sector, where the annual demand accounts for more than half of the entire national petroleum consumption. For example, the annual consumption of gasoline is estimated at 404 billion liters (104 billion gallons) and diesel is estimated at 227 billion liters (60 billion gallons) (EIA, 2006d). Thus, a crucial element when addressing national energy security issues is the need for a reduction on the reliance of petroleum based-fuels in the transportation sector. As a result, current national energy policies are encouraging the diversification in the mix of liquid energy sources by promoting domestically produced biofuels like biomass-derived ethanol and biodiesel that can conceivably offset some of the demand for petroleum in the transportation sector.

Environmental concerns on air quality problems and increasing levels of carbon emissions associated with fossil-fuel use are also motives on the search for alternative energies in the transportation sector. In particular, alternative energy programs are considered an opportunity to develop less carbon intensive energy sources capable of contributing to reductions in carbon emissions. Biomass-based energy is being strategically promoted because of its ability to recycle carbon (Bagby, 1998). Thus, if produced sustainable, plants can remove carbon dioxide from the atmosphere during photosynthesis; store this carbon in plant structures and the carbon that is released back to the atmosphere when biomass is burned can then be recycled into the next generation of growing plants (Bagby, 1998; Cushman et al., 1995). Historically, use of fuels derived from biomass was an important source of energy; these fuels were typically produced from vegetable oils and animal fats and from wood (Hodgson, 1997). However, as fossil fuel production and dependence increased, reliance on liquid-biomass derived fuel (biofuels), decreased and their production nearly disappeared.

Although the growth of the role of agriculture as a source of energy feedstock has been primarily concentrated on ethanol, concerns on diverting agricultural production away from food crops like corn for ethanol, have turned attention to the utilization of dedicated energy crops like switchgrass and hybrid poplar to produce ethanol. As part of this effort, the US Department of Energy Biofuels Feedstock Development Program (BFDP) in cooperation with the Department of Agriculture has explored a wide variety of annual and perennial plant species -- 34 herbaceous species and 125 tree species -- as potential biomass crops (Tolbert and Schiller, 1996). In recent years, the focus of the BFDP research has been on exploring switchgrass (*Panicum virgatum)* and several fast-growing woody crops such as hybrid poplar (*Populus* spp.), as model species for testing crop production at larger scale (Mclaughlin et al, 1999). On the other hand, the Biomass Research and Development Initiative (BRDI) coordinated by the U.S. Department of Energy and Department of Agriculture, has focused on research and technology development in the processing of biomass feedstock to biofuels (USDOE, 2006b; ORNL, 2006g).

U.S. energy policies are also been implemented to stimulate the market growth for the production of biomass-derived fuels. For example, in 2005, the Energy Policy Act (EPACT) signed by President Bush, provided tax incentives to promote the manufacturing and use of biodiesel (USDOE, 2006c). More recently, in his January 2006 State of the Union, President George W. Bush set a national goal of replacing more than 75% of oil imports by 2025 (Bush, 2006). In order to achieve this goal, the President introduced the Advanced Energy Initiative. This initiative is directed to fund research including the advancement of technologies needed to improve ethanol production from lignocellulosic sources (Bush, 2006).

The transformation of cellulosic and oil-crop sources to biofuels requires the use of natural resources like land and water, fossil fuels and electricity, and financial inputs from human-derived services and materials. Therefore, an integrated analysis approach that can capture the environmental, energy and financial requirements that are critical to the biofuels process is needed. However, measuring units for environmental, energy and financial inputs include a range of units like monies joules, grams, ($) that represents a problem in integrating inputs. Emergy methodology provides a common framework that allows for the comparison across disparate units because it quantifies energy, financial services from human-derived and materials inputs into equivalents of one form of energy. Developing indicators to 1) measure the value of producing biofuels to replace petroleum fuels and 2) recognize the potential of biofuels as renewable sources of energy need to be developed. An integrated emergy analysis provides the framework to develop indicators essential to estimate the fraction of biofuel that is renewable, fraction that is derived from other liquid fossil fuels like petroleum, fraction derived from non-liquid fossil fuels i.e. natural gas, coal; and the fraction that enters the systems through indirect inputs. These indicators are necessary to provide a comprehensive analysis that can assess the viability of biofuels as an alternative source of energy and their potential role in supporting the economy.

Biomass Feedstock

Switchgrass is a perennial warm-season grass native to the U.S. and a natural component of the tall-grass prairie ecosystems (Keyser, 1994). Nowadays, switchgrass is primarily grown as a protective cover against soil erosion in marginal lands not well suited for conventional row crops (Duffy & Nanhou, 2002). Since the 1970's energy crisis, the U.S. Department of Energy and Department of Agriculture have been investigating the potential use of switchgrass as an energy crop (ORNL, 2006a). This research has been primarily focused on the agricultural evaluation of switchgrass crops to investigate yields for different varieties, biotechnological approaches for seed improvement, and identifying improved switchgrass seeding and establishment practices (NETL, 2004).

Hybrid poplar (*Populus spp.*) is one of the sources of lignocellulose that is under consideration for the production of ethanol in the U.S. The genus *Populus* includes around 30 species able to grow across a wide climatic range from the subtropics in Florida to sub-alpine areas in Alaska (Purdue University, 2006). In North America, hybrid poplar species are among the fastest-growing trees (ORNL, 2005). Since the 1970's, the U.S. Department of Energy's Bioenergy Feedstock Development Program

(BFDP) has coordinated research efforts to improve hybrid poplar yields, increase pest and disease resistance and develop efficient plantation management systems. For example, when grown under short-rotation silviculture, hybrid poplars can produce between 8 and 22 dry metric tons (MT) of wood per hectare per year and achieve a height of 60 feet (20 m) in as little as six years (ORNL, 2005). As a result of this effort, commercial plantings have been established in the Pacific Northwest, the Midwest, the Lake States, and the Southeastern U.S. (ORNL, 2005). Moreover, laboratory and field test trials thus far have indicated that poplars have an approximate fuel content of 20.9 megajoules/kilogram (MJ/kg, Scurlock, 2005) that makes it an attractive energy alternative.

Currently, the University of Maryland Cooperative Extension, Washington Sanitary Suburban Commission (WASA) and ERCO, Inc (Brandywine, MD) are coordinating a reclamation project in Prince George's County, Maryland demonstrating how deep row application of biosolids can be used to establish nitrogen-demanding hybrid poplar trees in a six year rotation (Kays et al, 2000). The project was prepared in response to a need to utilize large volumes of biosolids from the Washington, D.C. area and reclaim gravel spoils (Kays et al., 1999). This production system has the potential to supply hybrid poplars that could be used for ethanol production or electricity generation while restoring environmentally spoiled areas.

The most important feedstock in the production of biodiesel in the U.S. is soybean (*Glycine maximus*). The oil content of the soybean varies on average from 18% to 25% (ASASEA, 2005) and has an energy content of 39.5 MJ/kg (USEPA, 2002a). The United States is currently the lead producer of soybean crop in the world, with an estimated annual production of 84 million metric tons (3.1 billion bushels) (USDA, 2006g). Although the oil yield of soybeans is considerably lower than other oil-crops like sunflower and canola, extensive crop production makes soybean a primary feedstock for production of biodiesel. At present, soybean oil dominates the US vegetable oil market, comprising over 75% of the total vegetable oil volume (8.1 billion kg per year; Pearl, 2002). Moreover, according to the Soybean Research Advisory Institute (1984), one-fourth of the world's supply of vegetable oil comes from soybean.

Castorbean (*Ricinus communis*) is another possible feedstock for the production of biodiesel. The use of castorbean to process biodiesel is currently being promoted in Brazil (Comar et al., 2004). In the 1980's castorbean was one of the species identified as a promising bioenergy crop by the US government (Brigham, 1993). The oil content of castorbean ranges from 24% to 50% (Dovebiotech, 2005). At the present time, there is no production of castorbean in the U.S. However, imports on castorbean, primarily for use in manufacturing processes, are estimated at around 45,000 metric tons per year (Bhardwaj et al., 1996).

The primary reason for not producing castorbean in the US is related to its toxicity. The bean contains ricin, a protein seven times more deadly than cobra venom (USDA, 2001). The seeds also contain allergens that can cause people who work with the ground meal to develop allergic reactions such as hives or asthma (Garcia-Gonzalez et al., 1999). In 2001, the USDA Agricultural Research Service reported that preliminary experiments on a genetically modified variety of castorbean showed promising results on eliminating toxic effects. The value of castorbean as a dedicated energy crop is that it avoids displacing soybean vegetable oil from edible production.

Industrial Conversion of Biomass to Liquid Fuels

The industrial conversions of biomass to ethanol or biodiesel are distinctly different systems. The conversion of biomass to ethanol involves the use of microorganisms to ferment sugar components embedded in biomass feedstock into ethanol. On the other hand, the production of biodiesel involves the extraction of oil from biomass through a series of mechanical processes and chemical reactions using alcohols like methanol to form biodiesel. A detailed summary of the two production processes follows.

Cellulose Conversion to Ethanol

The application of fermentation processes is an ancient tradition that is still in use today to preserve foods; to produce bread and cheese; and to convert sugar into ethanol in wine production (Nova, 2006; Battcock and Azam-Ali, 1998). The fermentation process uses microorganism like yeast to convert natural sugar contents from a variety of raw materials into ethanol (Mathewson, 1980). Based on their chemical composition, these raw materials are classified under three categories: sugars, starches, and lignocellulose materials, also referred as cellulosic materials (USDOE, 2006a). The most suitable feedstock for producing ethanol is from high sugar content crops like sugarcane, sugar beets, molasses, and fruits because their main component is glucose, a simple sugar that can be readily converted to ethanol (DiPardo, 2002). The conversion of starch-based crops like corn, grains, and potatoes is more complex than the fermentation of sugar-based crops because they contain carbohydrates (sugar chains) that must first be converted to simple sugars (glucose) and then fermented into ethanol. Likewise, lignoncellulose feedstock derived from agricultural forestry residues, industrial waste, trees, grasses and material in municipal solid waste also require the breakdown of sugar chains into simple sugars prior to fermentation (USDOE, 2006a). Lignocellulosic feedstock contains cellulose, hemicellulose, and lignin components that are more difficult to breakdown than starch (USDOE, 2006a). The hemicellulose and cellulose components are sugar-based chains that can be fermented into ethanol whereas lignin is a structural component to the plant that can not be fermented into alcohol (Van Zessen et al., 2003).

To date the core ethanol conversion technology from lignocellulose involves a pre-treatment step using thermochemical (acid and heat) techniques to break lignin. In this step, the high temperature splits the hemicellulose component into a mixture of simple sugars that includes a mix of mainly 5-carbon xylose and to lesser extent 6-carbon glucose. Once the lignin is broken, enzymes have access to the cellulose carbohydrate chains for digestion. The following step involves the addition of cellulase enzymes to breakdown cellulose chains into 6-carbon glucose sugars (Mosier et al., 2005). The 6-carbon glucose undergoes fermentation by using conventional yeast. On the other hand, xylose (5-carbon sugar) is not readily fermented by conventional yeast and its fermentation requires special microorganisms capable of fermenting 5-carbon sugars (McAloon et al., 2000; Sheehan et al., 2004). After fermentation, the ethanol is recovered via distillation (Mosier et al., 2005; Sheehan et al., 2004; Wight, 1998).

The two most common methods for producing ethanol from lignocellulose are dilute acid hydrolysis and concentrated acid hydrolysis using sulfuric acid (DiPardo, 2002). However, technical challenges have prevented the commercial application of these techniques to produce ethanol from lignocellulose (Judd, 2003). Recently, a series of pilot plants that employ dilute acid hydrolysis and concentrated acid hydrolysis have started operating in Canada, Sweden, Spain and Denmark (Iogen, 2006; European

Commission, 2006). One of the technical barriers associated with the production of cellulosic ethanol is the use of energy intensive processes to break down lignin. Among the alternatives that are currently being explored to address this technical challenge is the development of enzymes that can efficiently hydrolyze lignin and free the sugars (Stephanopoulos et al., 2006; USDOE, 2006a).

Oil Crop Conversion to Biodiesel

Biodiesel in the U.S. is primarily produced from soybean oil. However, other crops like sunflower, cottonseed and rapeseed (canola) are also potential feedstock (Peterson, 2006). Production of biodiesel derived from oil-crops dates back to the mid 1800's when biodiesel was produced as a by-product in the manufacture of soaps from vegetable oils (Yokayo Biofuels, 2006). The development of the diesel engine prompted a demand for biodiesel as a liquid-motor fuel. In the early 1900s, biodiesel was popular in the U.S., but over the years petroleum-based diesel eventually displaced biodiesel (Yokayo Biofuels, 2006). In recent years, biodiesel has once again reappeared as a liquid fuel alternative for diesel engines, this has resulted in an increased on biodiesel commercial production (Radich, 1994). Currently, it is available in pure form (100%) or in a blend of 20% (20% biodiesel, 80% diesel known as B20) (USDOE, 2001a). Soy-derived biodiesel (soy-diesel) is currently being used in bus fleets in Washington, California, South Dakota, Missouri, Colorado, New Jersey, Illinois, Kansas, and Ohio (National Biodiesel Board, 2006b). Bus fleets operate primarily with biodiesel blends ranging from 20% to 50%, while some waste-hauling trucks operate with pure biodiesel (100%) (USDOE, 2001b). The production of biodiesel requires two processes; a crushing process to extract the crude oil and an oil refining process. Each is presented in more detailed below.

Oil-Crushing

The oil can be extracted via mechanical processes by using a press machine or via a combination of mechanical and chemical methods using chemical solvents (Sheehan et al., 1998). In the United States most of the oil extraction is performed by using chemical solvents such as hexane to extract the oil (Erickson, 1995). In this process, the initial step is the preparation of the beans for oil extraction. This step involves mechanically breaking and opening the bean to remove about 20% of the oil content and produces a residual bean “cake” (Behnke, 2006). The residual “cake” is then exposed to hexane where about 75-80% of the remaining oil is extracted. Following solvent extraction, the oil rich solvent, called "miscella", is heated and distilled. At the end of the extraction process, two products are produced, “crude” or unrefined oil and protein meal (Ye, 2004). The meal is used primarily as a protein source in animal feeds for the production of poultry, beef, pork, milk, butter, and eggs (Shurtleff & Aoyagi, 2004). The “crude” vegetable oil is processed for edible consumption and non-edible uses like biodiesel (Shurtleff & Aoyagi, 2004).

Oil Refining

“Crude” or virgin vegetable oil and animal fats are technically converted to biodiesel through a transformation process called transesterification (Sheehan et al., 1998). Although there are other technologies available for producing biodiesel, transesterification is the primary process used in the U.S. (Ma & Hanna, 1999). Transesterification reactions are not unique to the production of biodiesel; they are also used in other relevant industrial processes to produce different types of compounds like polyethylene and terephthalate (Schuchardtet et al., 1998). In the process the catalyst, typically sodium hydroxide (caustic soda) or potassium hydroxide (potash), is dissolved in an alcohol (ethanol or methanol) using a standard mixer. The vegetable oil is added to the alcohol/catalyst mixture in a closed reaction vessel to prevent alcohol vaporization (National Biodiesel Board, 2002). This reaction produces biodiesel (fatty acid methyl ester) and glycerin as products (Sheehan et al., 1998). The biodiesel can be readily used in diesel-engines but is typically blended with petroleum diesel.

Energy Accounting for Biofuel Production

As the US attempts to identify alternatives to petroleum for supplying the nation's liquid fuel demand, the political and scientific debate has focused on the potential use of 'biofuels,' like conversion of cellulose to ethanol or soybean to biodiesel. The process for converting energy-crops to ethanol or biodiesel involves the use of fuels, like coal and natural gas, land and water to transform solar energy into liquid fuels via photosynthesis (Wang et al., 1999; Graboski, 2002). Since one of the motivations for the use of biofuels is in their potential to reduce petroleum use, the production of biofuel requires that the energy associated with the agricultural production and industrial processing operations be small compared with energy available from the biofuels. A surplus energy in biofuels can in turn be used to replace petroleum in the transportation sector.

In the case of ethanol production from lignocellulose feedstock, the processing technology is still under development. As a result, there are physical limits associated with the production of lignocellulose-ethanol that may ultimately affect the viability of crop-ethanol as a net energy source, one that is able to produce enough energy for its own transformation process while also contributing energy to society. Physical limitations related to enzyme yields and thermodynamic effects on the conversion of switchgrass to ethanol can lead to the use of energy intensive methods to overcome fundamental technical limitations (Patzek, 2005a). The extensive use of intensive energy approaches can in turn hamper the feasibility of lignocellulose ethanol as a net energy source.

An energy-based analysis of primary sources of fuel can examine their ultimate viability based on physical limitations (Costanza, 2004). This type of scientific-based study provides the framework for investigating the energetic aspects of an energy production system. Such analysis is grounded in thermodynamic principles that examine the physical activity of production systems (Wilting, 1996). It is a means to estimate the energy intensity of a production process and to quantify the total amount of energy required directly or indirectly to produce energy. This can then be used to estimate the net energy of a proposed source and indicate its potential to contribute to the larger economy (Odum, 1996; Pimentel, 2005).

Since an energy-based accounting system is founded on physical and energetic limits imposed by natural laws (Farber et al., 2002; Crane, 2003; Costanza, 2004), its perspective is counter to economics which takes human needs and wants as a starting point (Wilting, 1996; Cleveland, et al., 2000; Rotering, 2005). Neoclassical economic models address institutional rather than technical arrangements thus they assume a perfect substitutability and technological viability (Costanza et al., 1984; Daly, 1992; Daly 1996; Farber et al., 2002; Cleveland, 2003). On the other hand, an analysis based on thermodynamic principles identifies fundamental physical limitations to substitution and technology that can impair process viability (Ruth, 1993; Cleveland, 1999).

For over 100 years scientists have been looking at energy principles as an indicator to study the relationship between environmental systems and economic activity (Odum

1971b; Odum and Odum 1976). The oil crisis in the 1970's provided the momentum to directly question whether economic measures such as price or cost captured the relevant features of energy supply processes (Cleveland, 2006). Because the production-consumption cycle of neoclassical economics poorly represented the use of natural resources in production (Wackernagel & Rees, 1995), and since energy is always drawn from the environment (O'Conner, 1994), energy analysts proposed a theory of economic and social value based on energy as a tool to evaluate the viability of energy production systems (Odum, 1971a; Hannon, 1973; Costanza, 1980).

Emergy accounting was one of the energy-based approaches developed in the 1970’s. Emergy quantifies both the values of natural and economic resources on a common basis to derive the value of nature to the human economy (Odum, 1998). The energy analysis technique approved by the International Federation of Institutes for Advanced Studies (IFIAS), quantified all energy inputs that were used directly, but selectively included indirect sources. Since IFIAS energy analyses did not include “free” environmental energies, like freshwater or soil organic matter (Slesser, 1977), the IFIAS standard expressed embodied energy in terms of fossil fuel equivalents. Emergy accounting, on the other hand, recognized that solar energy, deep earth heat, and tidal energy were the three ultimate primary sources of energy for the Earth that were transformed in various living and non-living systems of the planet to form the basis for all other forms of energy (Hau and Bakshi, 2004), and appreciated the relevance of including energy embodied in financial inputs from human-derived services that were critical to energy production systems. In emergy accounting, freshwater has nearly 18,000 times as much embodied solar energy as the visible radiation used in photosynthesis because freshwater required the dissipation of solar energy over land and sea for its generation and delivery to an ecosystem. Once freshwater is used in plant transpiration, it is no longer available for downstream ecosystems, signifying that it was a form of solar emergy consumed to make crop biomass. Therefore, in emergy accounting solar energy is typically used as the 'base' of energy equivalency. The emergy unit is the solar embodied joule (sej) (Odum, 1996). Thus, emergy accounting principles, in addition to including all the inputs that would be required in an IFIAS-styled energy analysis, provides a way to capture the contribution of the environment and the economy (i.e. human services and monetary transactions) which widens the analytical boundary.

Another contentious argument concerning energy analysis of proposed fuel alternatives is how to account for the embodied energy of financial resources like human services and manufactured goods, if its include at all. Some analyses exclude these altogether (Farrell et al., 2006), while others may include a portion (Pimentel and Patzek 2005). IFIAS energy analyses did not include energy embodied in human services, however, emergy does account for energy in services. The philosophy in emergy accounting is to include every type of input that was required (i.e., essential for the process or system to work). That means that the energy embodied in purchased goods, services and capital equipment is accounted for in emergy accounting.

Converting crops to fuels requires a variety of direct inputs at the scale of production. However, from a larger-scale perspective the field-to-tank system ultimately requires that energies like coal and natural gas be dissipated somewhere in the economy to manufacture goods and support services, which implies that indirect inputs are important also. (Wang et al., 1999; Graboski, 2002). Energy enters the production system either directly as, for example, tractor diesel, or indirectly as energy embodied in goods and services that were generated in other sectors of the economy. For example, according to the International Fertilizer Association, about 97% of nitrogen fertilizers were synthetically produced from the Haber-Bosch process which synthesizes ammonia by fixing atmospheric nitrogen and hydrogen from natural gas in a high-pressure, intermediate-temperature process fueled by natural gas (IFA, 2006). In effect, nitrogen fertilizers are basically only a step away from being natural gas.

One conjecture put forth recently by Farrell et al. (2006) was that crop-ethanol systems, by relying more on native natural gas and coal resources than on increasingly foreign petroleum, will make the U.S. less dependent on other countries for energy, particularly petroleum for transportation fuels. This conjecture was addressed with emergy accounting by refining the accounting to keep track of each type of fossil fuel used both directly and indirectly. This refined emergy accounting lead to new emergy indicators focused on understanding how much petroleum was used to make ethanol or biodiesel.

Energy analysis of crop-fuels

Multiple input-output energy analyses on ethanol production from corn have been published showing positive 'net energy' returns as well as 'negative' energy profits (Pimentel, 1991; Shapouri et al., 1995; Graboski, 2002; Shapouri et al., 2002; Shapouri et al., 2004; Pimentel & Patzek, 2005). Pimentel's 1991 corn-ethanol input-output energy analysis contended that the production of biofuels consumed 29% more energy than it produced. On the other hand, a 2002 study by Shapouri et al. reported a 34% net gain in energy for corn-ethanol production. In 2004, Shoupuri et al. updated their previous analysis to include energy efficiencies observed in the corn-ethanol industry and reported a 67% positive net energy return. Likewise, Graboski (2002) published an energy input-output analysis on corn-based ethanol indicating that the industry exhibited a net energy value of 21%.

In 2005, Pimentel et al. published the results on an input-output energy analysis on ethanol production from switchgrass and wood biomass. This study showed that ethanol production from switchgrass and wood biomass required 50% and 57% more energy respectively than they produced (Pimentel and Patzek, 2005). In contrast, an analysis by Farrell et al. (2006) on cellulosic ethanol based on Wang and colleagues' (1999) lifecycle analysis on switchgrass, showed a net energy value four times greater than corn-based ethanol.

Ulgiati's 2001 comprehensive emergy analysis of ethanol production from corn in Italy, which specifically evaluated the feasibility of producing biofuel at a large-scale using solar energy as the primary energy source indicated that it was not a viable alternative for future energy because the net energy was low and the availability of physical resources such as land, water, fertilizers, and labor was highly limiting.

In 1998, Sheehan et al. performed a life cycle assessment on the production of biodiesel. This study quantified all the energy and environmental flows associated with soydiesel production in a "cradle to grave" framework. It accounted for raw materials extracted from the environment, energy resources consumed, air, water, and solid waste emissions generated. The study found that the energy in a gallon of biodiesel was 3.2 times greater than the fossil-based energy required to produce it. In 2005, Pimentel and Patzek published an energy balance for biodiesel production showing that biodiesel production actually required 27% more fossil energy than what is embodied in biodiesel. In addition, several life cycle studies of biodiesel production from rapeseed feedstock in various European countries have indicated a net positive energy balance (Levy, 1993; Gover, 1996; Scharmer and Gosse, 1996; Richards, 2000, Choudhury et al., 2002).

The divergence in values reported across the different energy analyses are the result of variation on local farming practices, systems boundaries and processing practices that determine the inputs included as well as data assumptions made across studies (Shapouri, 1995; Farrell et al., 2006). A recent article by Farrell et al. 2006 standardized six energy analyses on corn-based ethanol, including the ones mentioned above, applying the same assumptions about boundary conditions and credit accounting for co-products (Farrell et al., 2006) to show that there was a small ‘net’ energy return of between 10% and 20%. A study by Van Gerpen and Shrestha 2006 that reviewed biodiesel studies from Pimentel & Patzek (2005) and Sheehan et al. (1998) showed that the divergence in values was affected by different assumptions on crop yields and lime application rates, but that the primary difference was related to the accounting on the input energy allocated to the various output streams (oil and meal). The study concluded that in correcting lime input to reflect field practices (i.e use is limited and if used, it is not applied on an annual basis) the energy required to produce biodiesel was only 77% of the energy in the fuel. Furthermore, once the energy value for meal was computed based on weight, the energy content of the meal was larger than the sum of the energy inputs indicating that biodiesel produced more energy than it consumed. The authors concluded that this was possible because solar energy inputs were not accounted for in their calculation.

Objectives and Plan of Study

The objectives of this study were (1) to estimate the ultimate amount of energy required to produce ethanol from switchgrass (*Panicum virgatum* L.) and hybrid poplar (*Populus spp.*); and biodiesel from soybean (*Glycine max.*) and castorbean (*Ricinus communis*) by integrating all environmental, fossil fuel, and financial inputs human-from derived services used throughout the production chain from agricultural field to processing facility; (2) to determine whether there was more liquid fuel produced in the form of ethanol or biodiesel than was required from petroleum sources; 3) to determine how much non-renewable energy was required to make ethanol from biomass and biodiesel; (4) to quantify the amount of energy derived from ‘hidden’ indirect paths such as services and machinery; (5) to evaluate the sensitivity of the net energy analysis of switchgrass-ethanol production to changes in price of inputs and to assumptions about technical efficiencies in lignocellulose-to-ethanol conversion; and 6) to quantify net above-ground biomass production at a hybrid poplar forest plantation that received deep trenched biosolids and to develop allometric equations useful for this type of forest.

The present study applied the systems ecology-based environmental accounting methodology, emergy analysis, to evaluate the total resource requirements for producing ethanol from switchgrass and hybrid poplars based on a model production system and producing biodiesel from soybean and castorbean based on US biodiesel production practices. The emergy evaluations included inventorying all inputs from field to processing plant and converted them all to solar emergy joules. Conventional emergy indicators, such as the net emergy yield ratio and emergy investment ratio, were used to address some of the objectives, while a new set of emergy indicators were developed, based on a refinement to the emergy accounting method, to address others.

A field study was conducted on a local hybrid poplar plantation to estimate biomass production rates, which was then incorporated into the emergy analysis on hybrid poplar-to-ethanol. This field study provided data needed to develop allometric models for estimating standing biomass.

Chapter 2: MATERIALS AND METHODS

Emergy Analysis

Traditional emergy analysis consists of two steps: (1) accounting for systems inputs and transforming them to solar emergy and (2) determination of indices that can estimate system properties like net yield, environmental contribution and sustainability (Odum 1996). In addition to completing these traditional steps, this study developed a refinement to the second step (i.e., indicator development) that partitioned resource inputs according to their ultimate source, which were from renewable environmental (R), non-renewable environmental (N_o), non-renewable minerals (N_m), non-petroleum fuels (N_f), and petroleum (N_p). This refinement, as explained below, was essential to estimate the fraction of biofuel that was renewable, the fraction that was derived from other liquid fuels (i.e., petroleum), the fraction derived from non-liquid fossil fuels and the fraction that came indirectly through the economy embodied in goods and services.

Emergy Accounting

The emergy accounting started by drawing an energy systems diagram using the energy systems language developed by H.T. Odum (Odum and Odum 2000) to identify the main components in each of the biofuel production system. The diagram was a window into the system of interest that provided a holistic view of the sources, flows, interactions, storages and products. The diagram defined (1) the boundary of the system, (2) timeframe of interest, and (3) the input resources, interactions, and outputs. Once the systems diagram was defined, the inputs and outputs became line items in the emergy accounting table, which inventoried the inputs and contained the calculations for transforming the raw units into solar emergy. Data on inputs, outputs and solar transformities were obtained from published literature. Typically the values of inputs were expressed as energy (joules), mass (grams) or money ($) and were converted to solar emergy by multiplying by the respective Transformation Ratio as given in Equations 2.1, 2.2 and 2.3, respectively.

$$Energy\ Transformation\ Ratio\ (ETR) = \frac{SolarEmergy\ (sej)}{energy\ (J)} \tag{2.1}$$

$$Mass\ Transformation\ Ratio\ (MTR) = \frac{SolarEmergy\ (sej)}{gram\ (g)} \tag{2.2}$$

$$Dollar\ Transformation\ Ratio\ (DTR) = \frac{SolarEmergy\ (sej)}{money\ (\$)} \tag{2.3}$$

A table like Table 1 was used to organize information and perform calculations. Table 1 demonstrates how energy, mass, and money flows were converted into solar emjoules by multiplying by the Transformation Ratio (transformity).

Table 1: Template for identifying and quantifying resource inputs and outputs in an emergy analysis

Note	*Item*	*Data*	*Units*	*Transformity (sej/unit)*	*Solar Emergy (sej/yr)*
1	Energy	e_i	joules	ETR_i	ETR x e_i
2	Mass	m_j	grams	MTR_j	MTR x m_j
3	Human Service	d_k	$	DTR_k	DTR x d_k
Total Emergy					TE

The solar emergy of all items were then summed to find the total solar emergy used by the system. Total Emergy of a system (TE) can be mathematically represented as

$$TE = \sum_{i=1}^{n} ETR \cdot e_i + \sum_{j=1}^{p} MTR \cdot m_j + \sum_{k=1}^{q} DTR \cdot d_k \tag{2.4}$$

e_i – energy of input *i*
m_j – mass of input *j*
d_k – dollars of input *k*

Traditional Emergy Indices

The second step in traditional emergy analyses classified flows that crossed the system into two main categories: nature's contribution (I) and input resources purchased from the economy (F) (Fig. 1). Nature's contributions were local environmental inputs that were classified either as renewable (R) or non-renewable (N) sources (slowly renewable due to higher use than accumulation rate). The purchased feedbacks (F) consisted of financial resources in paid human services (S) and material items (M) such as fertilizers, pesticides, and fuel. The specific items included in each of these categories are given in detail for each emergy table.

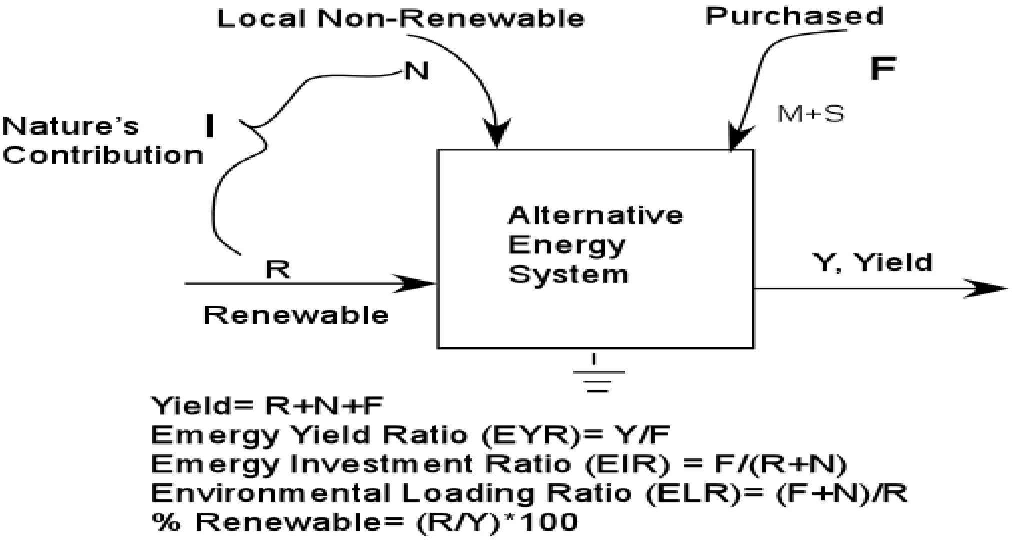

Figure 1. Aggregated emergy diagram with definitions of traditional emergy indices.

The summary of the network flows in Figure 1 was used to derive the traditional emergy indices. In addition to including an estimate of net yield (i.e., Emergy Yield Ratio, EYR), the set of traditional emergy indicators also included a measure of how much economic resources were purchased and invested in the emergy system relative to how much nature contributed, which is called the Emergy Investment Ratio (EIR). A low EIR (i.e., less than one) indicates that the economic investment is low and that nature is contributing the majority of the emergy. As agricultural systems and industrial processes become more energy intense, the EIR increases indicating that nature is contributing proportionately less to the process. A presumption in emergy accounting is that systems that use more “free-renewable” emergy and less “purchased” emergy relative to the intensity of the surrounding economy will be more competitive. The metric called Environmental Loading Ratio (ELR) quantifies the relative load that imported and non-renewable emergy use place on the environment. A more intense load will give a higher ELR indicating a high potential for environmental impact on the surrounding ecosystem. Finally, maybe the most basic of indicators is the percent renewable metric, which simply quantifies the percentage of the total emergy used that was contributed by renewable resources.

Emergy Indices for Biosolid Recycling in Hybrid Poplar Farm

The emergy flows in Figure 2 were used to derive emergy indicators for recycling of biosolids in hybrid poplar tree farm (Buranakarn, 1998). These recycling indices analyzed the effectiveness of recycling biosolid at the hybrid poplar tree farm as an alternative to disposing of the biosolids at the landfill. The objectives of these indicators were to 1) assess the benefits of recycling of biosolids at the farm relative to disposing of biosolids at the landfill and 2) measure the net benefit that society receives from recycling the biosolids. The landfill recycle ratio (LRR) measured the emergy required to landfill the biosolids relative to the emergy used to recycle biosolids at the farm. A relatively high LRR indicates that society spends more emergy landfilling biosolids than recycling, thus investing in recycling is beneficial. The recycle yield ratio (RYR) evaluated the net benefit that society receives for recycling biosolids. High RYR will result from a small investment of emergy in recycling biosolids relative to emergy embodied in biosolids.

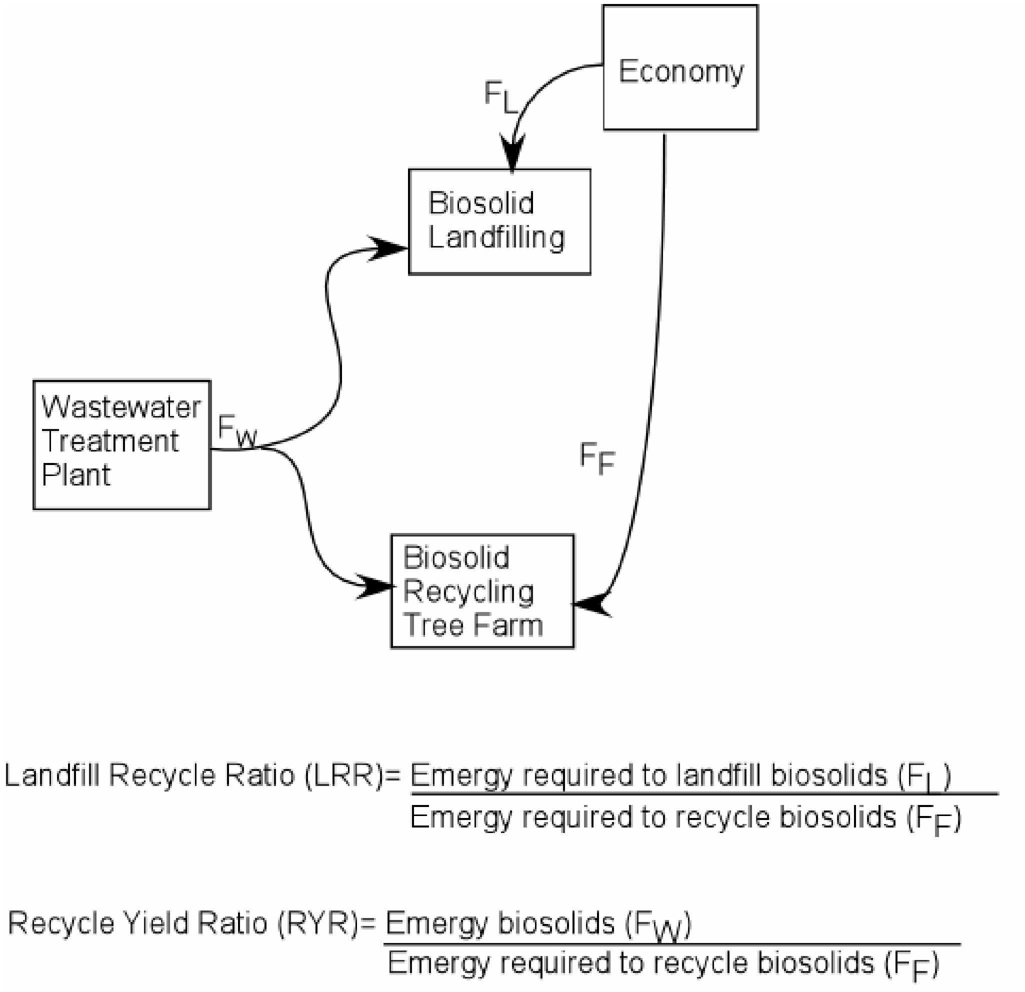

Figure 2. Aggregated emergy diagram with definitions of emergy indices for biosolid recycling.

New Emergy Indices under Refined Accounting

The refined emergy indicators included partitioning inputs according to a combination of their ultimate energy source type (R, N_o, N_m, N_f, or N_p) and their ‘route’ through the ecological-economic system (i.e., direct or indirect) to the production system which is described schematically in Figure 3. The refinement of emergy indicators required the partition of the emergy of each input into R, N_m, N_f, and N_p. This was accomplished by partitioning each original transformity into R, N_m, N_f, and N_p fractions, which were obtained by reviewing the detailed calculation provided for each original transformity. Fractions for the emergy-to-dollar ratio (sej/$) were calculated based on the fraction that R, N_m, N_f, and N_p contributed to the total U.S. national emergy budget for the year 2000 (Tilley 2006). A Detailed description of the partitioning is given in Appendix A.

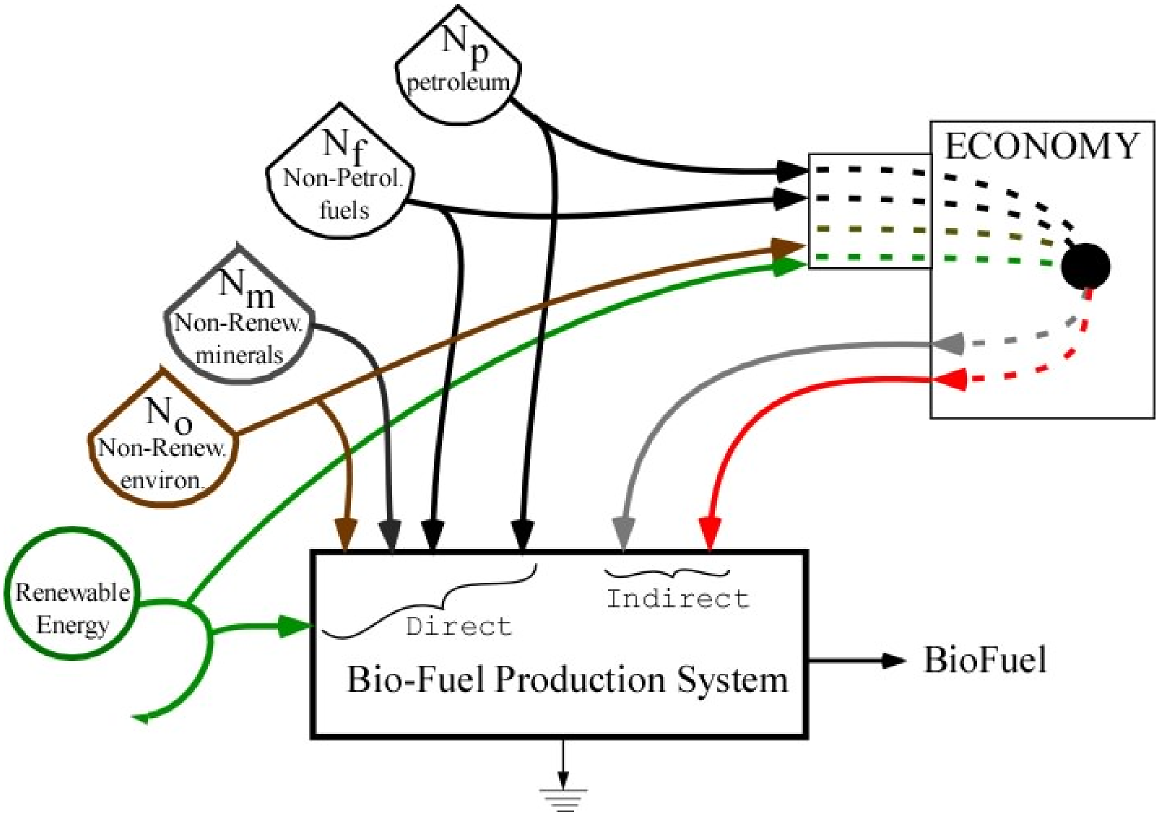

Figure 3. Emergy diagram of refined partitioning of inputs according to ultimate sources and whether they were direct or indirect.

The partitioned emergy sources were then aggregated into direct or indirect. Direct energy inputs derived from renewable and non-renewable sources were aggregated as D_I and direct inputs of fuel were lumped as D_f. Indirect energy associated with goods was aggregated as I_g, while energy embodied in financial services was combined as I_s. Renewable environmental inputs were solar energy, wind, and water from rain; non-renewable environmental flows (N_o) were loss of topsoil; non-renewable flows from minerals (N_m) included phosphate, limestone, and potash; non-petroleum fuels (N_f) included coal, electricity and natural gas; and petroleum (N_p) included gasoline, diesel and pesticides. These new categories were then aggregated as either direct or indirect flows as shown in Figure 3.

Description of Biomass to Ethanol Production System

In order to facilitate the analysis, the production of switchgrass-to- ethanol and hybrid poplar-to-ethanol was divided into three stages: agricultural production, crop transportation, and feedstock conversion to ethanol (Fig. 4). Each of these stages was recognized as a sub-system that was linked in a production chain. Thus, each of the production subsystems was evaluated separately with field production contributing biomass to the downstream processes. A detailed description of each sub-system follows.

Figure 4. Crop-Ethanol processing steps.

Switchgrass Agricultural Production

The system boundary consisted of the agricultural activities related to the production of switchgrass (Fig. 5). These activities determined the required inputs that were derived either from the environment or the economy; and quantified the emergy value of the end-product, which in this case was harvested switchgrass biomass. In this particular case a subsystem was designed to capture the agricultural activities performed during establishment and reseeding years. Input estimates were primarily based Duffy and Nanhou (2002).

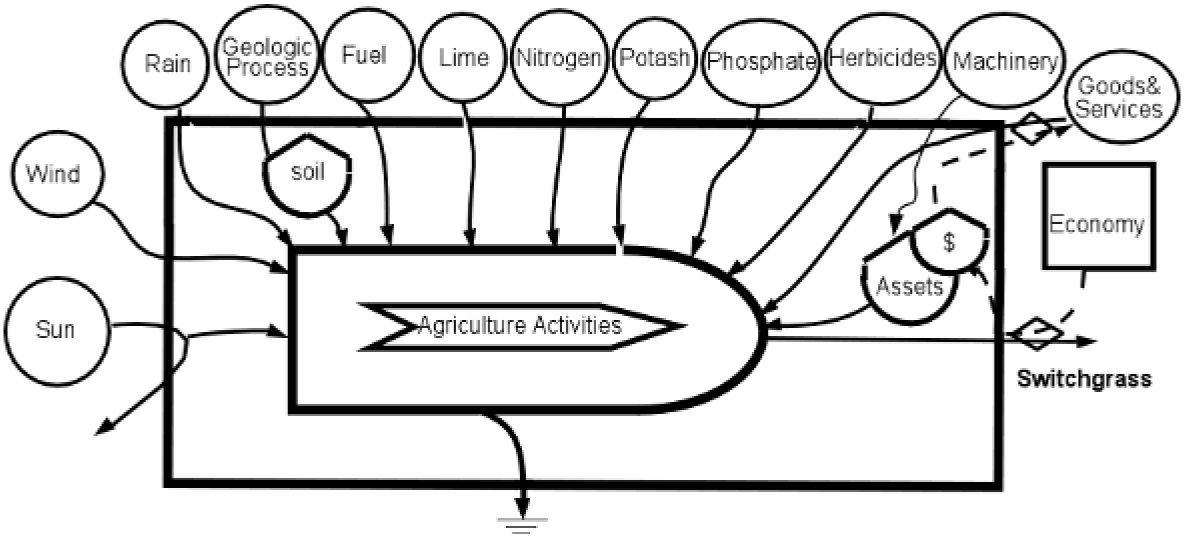

Figure 5. Energy systems diagram of agricultural production of switchgrass.

The general assumptions included in this analysis were as follows: (1) production yield was 9.9 metric tons fresh weight (fresh wt.) per hectare with moisture content of 13.5%; (2) planting was not harvested in the seeding and reseeding year; (3) cost for machinery operations was from Lazarus 2001; (4) fuel requirement for machinery were estimated at 35.1 liter per ha during establishment and reseeding and 28 liter per ha during production. These values were taken from Hanna and Ayres 2001, which varied by as much as 30%; (5) fertilizer application during establishment and reseeding years were 33.6 kg of P_2O_5 and 44.8 kg K_2O per ha. Fertilizer application during each production year was 112 kg of nitrogen, 8.7 kg of P_20_5; and 85 kg K_2O per ha. In addition, during the 11 year cycle there was a one time application of lime estimated at around 4.48 metric ton per ha (Qin et al., 2005); (6) herbicides were used in establishment and reseeding as well as during production years at a rate of 3.5 liters of 2-

Chloro-4-ethylamino-6-isopropylamino-1,3,5-triazine (commercial name: Atrazine) and 1.77 liters (0.47 gallon) of [2,4-dichlorophenoxy]acetic acid or 2,4-D (commercial names: Aqua-Kleen, Barrage, Lawn-Keep, Malerbane, Planotox, Plantgard, Savage, Salvo, Weedone, and Weedtrine-II) per ha; (7) no irrigation was necessary; (8) the ethanol yield was estimated to be 273 liters (72 gallon) per metric ton of switchgrass (USDA, 2006c); (9) airflow seeding was used.

Hybrid Poplar Agricultural Production

In this study, hybrid poplars were planted using municipal biosolids produced from the local wastewater treatment facility. Currently, the University of Maryland Cooperative Extension, Washington Sanitary Suburban Commission and ERCO, Inc are coordinating a reclamation project in Prince George's County, Maryland demonstrating how deep row application of biosolids can be used to establish N-demanding hybrid poplar trees in a six year rotation (Kays et al., 2000). The project was prepared in response to a need to utilize large volumes of biosolids from the Washington, D.C. area and reclaim gravel mining spoils (Kays et al., 1999). Although the primary objectives of the hybrid poplar plantation are the recycling of municipal biosolids and the environmental restoration of the gravel mine, this type of production system has the potential to supply hybrid poplars biomass feedstock that could be used for ethanol production.

In terms of emergy accounting this type of production system presented a unique situation due to the recycling of a waste product. Applying biosolids to farmland captures a productive potential of a by-product that historically has been sent to the municipal landfill. By farming hybrid poplar trees on trenched biosolids the nitrogen and phosphorus fertilization is accomplished. One challenge posed by the environmental accounting of biosolids was to estimate how much embodied energy of the biosolids was ‘required’ to produce the tree biomass and therefore how much emergy should be included in the accounting. This study analyzed three cases to consider the spectrum of assumptions about how much emergy to include in the environmental accounting of biosolids. Under Scenario 1, it was assumed that the biosolids were not required, which meant that their emergy was not included, but rather considered a “free” resource. Under Scenario 2, all of the emergy of the municipal biosolids was included in the accounting and added to the total emergy. In Scenario 3, the emergy accounting was performed assuming that the biosolids contributed the emergy of its macro-nutrients and moisture. The emergy of the nitrogen, phosphorous, lime and moisture of the biosolids was estimated based on their measured content and equivalent solar transformity of chemical fertilizers, lime and irrigated water. Since these three scenarios represented either ‘none’, ‘all’ or ‘some’ of the emergy of the biosolids, they cover the spectrum of possibilities for including them in the accounting.

The system boundary for the hybrid poplar plantation consisted of the agricultural activities related to the production of hybrid poplar using deep-row biosolid application (Fig. 6). These activities dictated the required inputs derived from the environment, fuels and the economy and determined the emergy value of the end-product, which was harvested hybrid poplar biomass. The analysis presented in this study was for a 6-year production cycle. Therefore, the inputs were estimated based on a 6-year rotation, except for those inputs that were a one-time requirement that were amortized over the 6-year rotation i.e. burying of municipal biosolids, labor for planting or harvesting of biomass, operating cost, utilities. The emergy evaluation was primarily based on information provided in Felton et al. (2006).

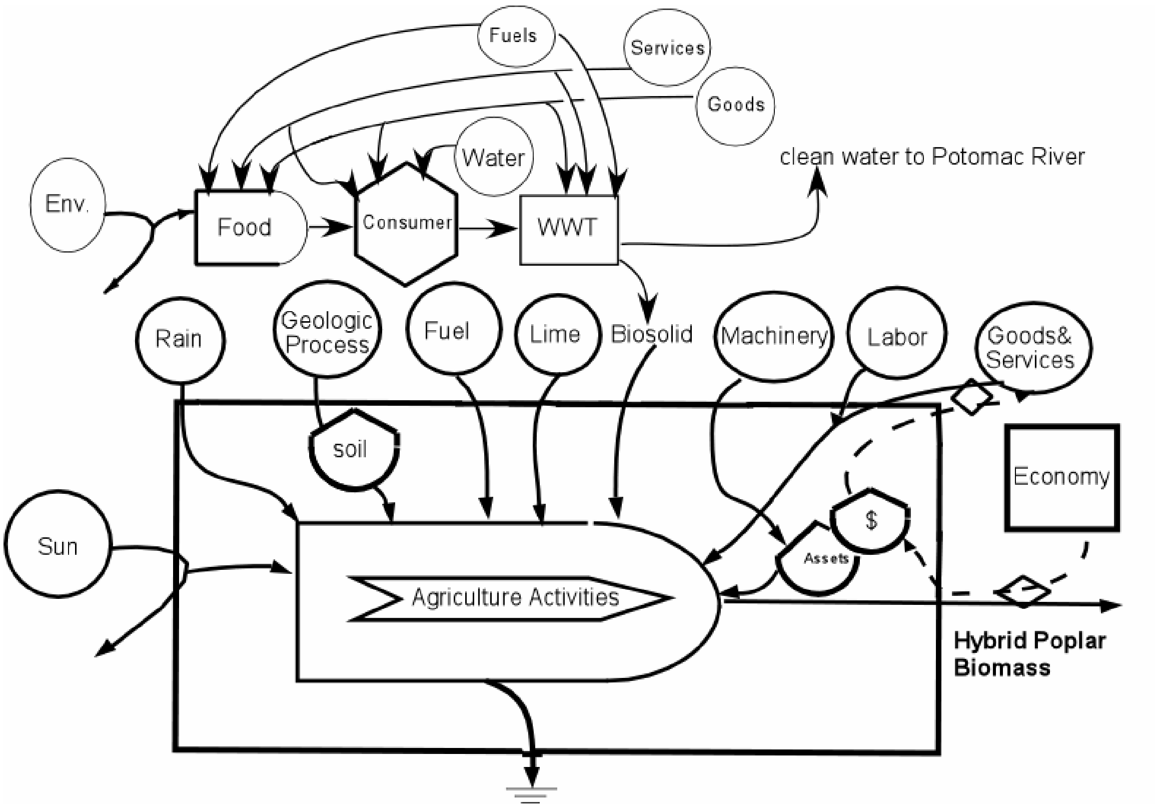

Figure 6. Energy systems diagram of agricultural production of hybrid poplar grown on biosolids.

The general assumptions for hybrid poplar farming using biosolids were as follows: (1) standing wood biomass after six years was 22 metric tons dry wt. per hectare (this study); (2) complete harvest was after the sixth year of production; (3) operational costs for machinery, labor, and other inputs, as well as fuel use was from Felton et al.(2006); (4) under Scenario 1 and Scenario 2, it was assumed that the tree plantation management was ‘low-intensity’ (i.e., there was no irrigation, supplemental fertilization, or pesticide or herbicide applications, instead nutrients came from a one-time application of municipal biosolids at a rate of 383,000 kg per ha, Felton et al., 2006); (5) Under scenario

3, municipal biosolids input was replaced with 13,322 grams of nitrogen (1.15% nitrogen weight (wt.) content of biosolids), 9,731 grams of phosphorous (0.84% phosphorus w.t. content of biosolids), irrigated water (76% w.t. content of biosolids); and 15,500 kg of lime used to stabilize biosolids; (6) Transportation for delivery biosolids to the farm was accounted for based on a 80 kilometer (50 mile) trip from gate at wastewater treatment plant to plantation; (7) Ethanol yield was estimated to be 402 liters (106 gallon) per metric ton of hybrid poplar biomass (USDOE, 2006b).

Transportation System of Switchgrass and Hybrid Poplar

The transportation sub-system boundary was from the field to the ethanol processing plant (Fig. 7). The evaluation included energy embodied in machinery (trucks), driver services and energy required in transportation fuels. The emergy contributed from trucking was estimated based on the use of an 8-ton truck made of 4540 kg of steel with a lifetime of 7 years based on 113,226 km (64,000 miles) driven annually to transport feedstock to a model ethanol plant (Lovins et al. 2004). For labor cost, it was assumed that a truck driver was paid $0.266 ($0.43 per mile) (Heartland Express, 2006). Fuel for transportation was estimated based on truck load capacity of 8 tons per trip. For switchgrass, it was estimated that 1.23 trips would be required to transport the 9.9 wet tons of biomass that were produced in one ha. For hybrid poplar biomass, it was estimated that 6.22 trips per ha were needed to transport the wet biomass produced in one ha. The average fuel consumption was based on 4.26 km per liter (10 miles per gallon) truck fuel efficiency (Urbanchuk and Kapell, 2002). Transportation distance was assumed to be 80 kilometers (50 miles) taken from Shapouri et al. (1995). The fuel price was estimated to be $0.425 per liter ($1.62 per gallon) (EIA, 2006c).

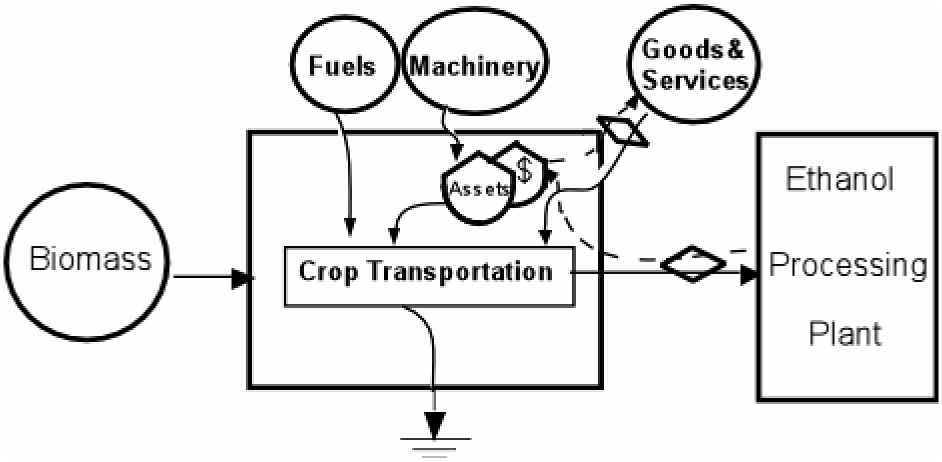

Figure 7. Energy systems diagram transporting crop from field to processing plant.

Ethanol Production

The ethanol production system consisted of the industrial processing of the biomass to ethanol (Fig. 8). The emergy evaluation of the biomass ethanol plant was based on studies investigating the production of ethanol from lignocellulosic biomass utilizing dilute acid pre-hydrolysis and enzymatic hydrolysis of corn stover (Aden et al., 2002).

The study provided a detailed summary of the ethanol production from biomass sources that included a step-by-step conversion process, heat and material balances, chemical analysis, as well as economic analyses. As a result, the report included a detailed plan for an ethanol production facility that included all equipment specifications, material inputs, in-house wastewater treatment requirements and on-site electricity production. However, this study differed from Aden et al. (2002) in that it assumed on-site production of enzymes necessary for the conversion of ethanol rather than purchasing enzymes (Wooley et al., 1999).

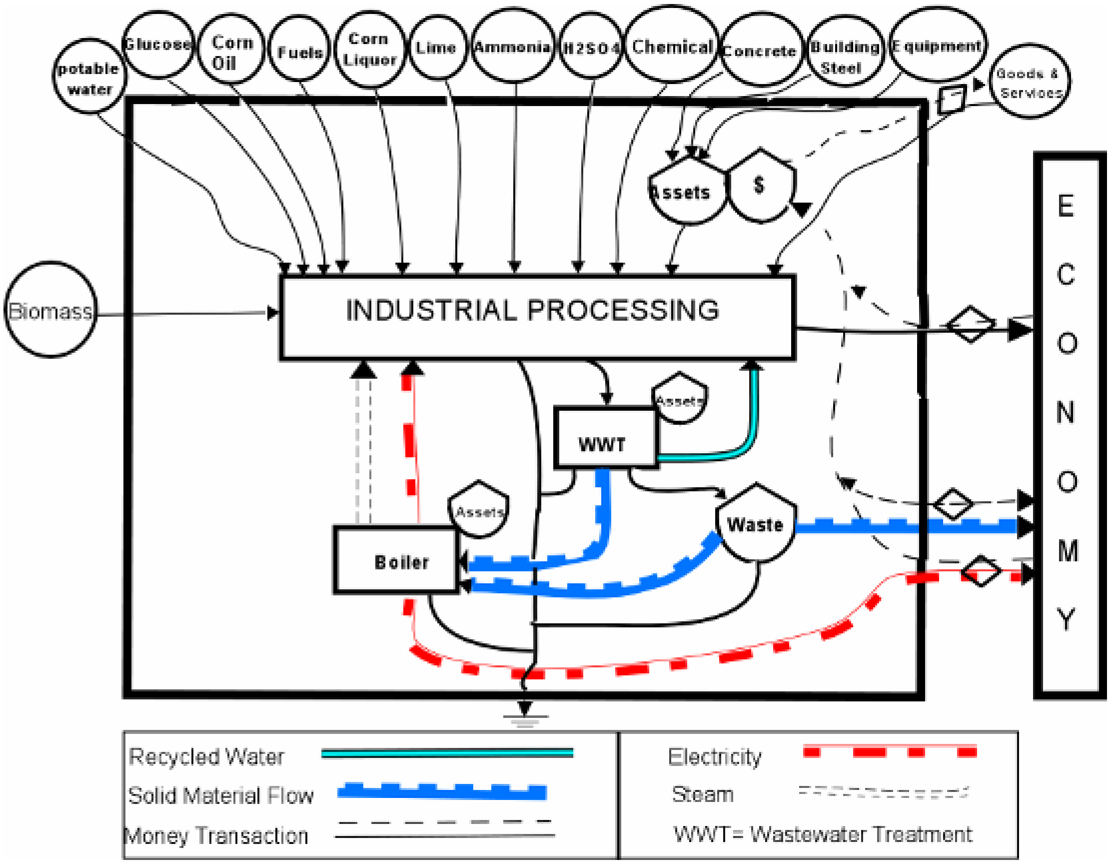

Figure 8. Energy system diagram of industrial process for converting biomass to ethanol.

The biomass-to-ethanol conversion analysis was based on the major steps described by Aden et al. (2002) for enzymatic conversion (Figure 9). The series of steps were:

1. *Pretreatment with Dilute Sulfuric Acid* was an important step of the biomass to ethanol process. This step “opened up” the biomass to make the cellulose portion of the feedstock more readily available to enzymatic hydrolysis. In terms of chemical outcome, the hemicellulose portion of the feedstock was hydrolyzed to soluble sugars and a small amount of cellulose to glucose.

2. *Neutralization & Wash* with lime was performed to neutralize the acidic slurry. A wash was performed to remove compounds liberated during pre-treatment that are toxic to microorganisms used in the steps that follow.

3. *Cellulose Production* involved the production of cellulase enzymes from cellulose feedstock using *Trichoderma reesei*. Cellulase enzymes were then used to saccharify cellulose to glucose which can then be fermented to ethanol.

4. *Simultaneous Saccharification and Fermentation* (SSF) combined cellulose enzymatic hydrolysis by cellulase enzymes with ethanol fermentation by genetically-modified, ethanol-producing microorganisms, *Zymonas mobilis*, in the same reactor. The quick conversion of glucose to ethanol kept glucose levels low preventing inhibition of cellulase enzymes. In this way, SSF was a good strategy for increasing the overall conversion rate of cellulose to ethanol. In SSF the ethanol production rate was controlled by the cellulase hydrolysis rate and not by the glucose fermentation into ethanol.

5. *Ethanol Purification* was performed to distill ethanol; steps included passing the condense ethanol through a rectification column to remove water and by condensing the dilute beer through a series of heat exchangers and reflux columns.

6. *Denaturing of Ethanol* was performed by blending 95 parts of ethanol to 5 parts of gasoline.

7. *Waste treatment.* Waste was first centrifuged to suspend lignin. The lignin was sent to the boiler for burning. Some of the wastewater was recycled and delivered to pretreatment and cellulase production, while the remaining wastewater was sent for treatment.

8. *Wastewater Treatment* was processed through anaerobic and aerobic digestion and a low pressure vent system. The system captured methane from anaerobic digestion for use as fuel in the boiler.

9. *Electricity Production* was integrated into the production model by generating it from a high-pressure steam turbogenerator. The steam that fed the turbogenerator was produced from a boiler fired with lignin.

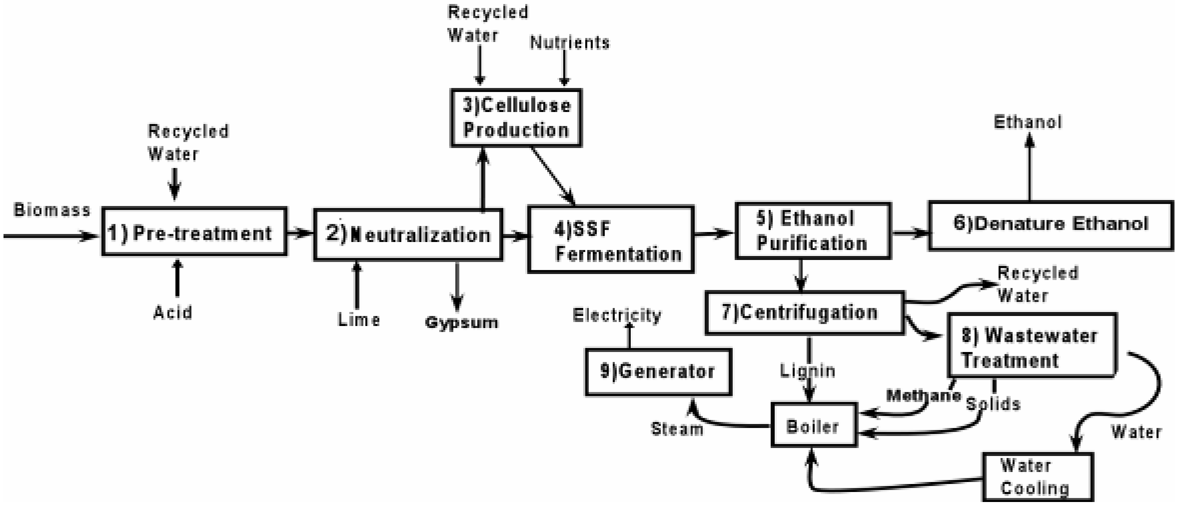

Figure 9. Flow diagram of enzymatic biomass-to-ethanol process. (Adapted from Aden et al., 2002 and Wooley et al., 1999)

Technical Assumptions

The conceptual design developed by Aden et al. (2002) included a set of underlying assumptions that were subsequently assimilated into the emergy evaluation:

1. The enzymatic biomass to ethanol process was based on a continuous Simultaneous Saccharification and Fermentation (SSF) conversion process as described in the Aden et al. (2002).

2. The plant was operated 8406 hours per year with a nominal capacity to process 772,000 dry metric tons of corn stover per year. The ethanol annual production was estimated to be 262 liters million (MM) of denatured ethanol (69.27 MM gallons).

3. The base feedstock in Aden et al. 2002 was corn stover. The carbohydrate composition of corn stover and switchgrass were different. Corn stover contained about 60% carbohydrate whereas switchgrass contained about 53% carbohydrate and wood carbohydrate content was around 70-80% (Alden et al., 2002; Ragauskas et al., 2006). As a result, the ethanol yield of switchgrass was lower than corn stover where the ethanol output for hybrid poplar was higher than corn stover. Switchgrass yielded about 273 liters (72 gallons) of ethanol per ton, hybrid poplar ethanol yielded are estimated at 401 liters (106 gallons) of ethanol per ton compared to corn stover 316 liters (83 gallons) on average. To keep the ethanol output constant, the amount of input feedstock was adjusted to be representative of the carbohydrate composition of switchgrass and hybrid poplar.

4. The design of the proposed plant was modeled on operating conditions experienced in the corn-to-ethanol industry.

5. Pretreatment used sulfuric acid.

6. All yield data for xylose fermentation, SSF and cellulase production were taken from bench scale experiments.

7. Neutralization was accomplished with lime, which produced gypsum as a byproduct.

8. Enzymes used in the process were produced from *Trichoderma reesei* for cellulase production and from *Zymonas mobilis* for co-fermentation of cellulose and hemicelluloses into ethanol.

9. Cellulase *Trichoderma reesei* enzymes were produced in-house by using xylose and cellulose as the substrates; these nutrients were supplied in recycled water and from purchased glucose; corn oil was also added to prevent foaming of the mixture.

10. Lignin dewatered from centrifuge and other solid wastes (sludge) were used to fuel the boiler.

11. Soluble organic wastes were processed via anaerobic and aerobic treatment to produce methane that was captured and used to fuel the boiler

12. Electricity was generated on-site using the excess steam and a turbogenerator with an efficiency of 78.5%. Excess electricity was sold to the electric power grid.

13. Water was recycled throughout the process.

14. Gypsum byproduct and ash were sent to landfill.

15. Pure ethanol was denatured with gasoline at a rate of 95 parts ethanol per 5 parts gasoline.

16. Final composition of the denatured fuel was estimated on a per weight basis as 90.3 % ethanol, 4.7 % water and 5.0% gasoline.

17. Capital investment for the base case scenario was estimated to be $211 million ($US 1999).

18. Annual budget for operating the plant was estimated to be $76 million.

Description of Biomass to Biodiesel Production System

In order to facilitate the biodiesel analysis, the production of biodiesel was divided into five stages: agricultural production, crop transport, oil crushing, oil transport, and biodiesel refining (Fig. 10). Each stage was recognized as an independent sub-system that was linked into a production chain. Each production stage was evaluated separately with upstream processes contributing feedstock to downstream processes. A detailed description of each sub-system follows:

Figure 10. Biodiesel processing steps.

Agricultural System Soybean and Castorbean

The system boundary consisted of the agricultural activities related to the production of soybean and castorbean (Fig. 11). These activities determined the required inputs from the environment and economy and quantified the emergy value of the end-product, which was the harvested soybean or castorbean.

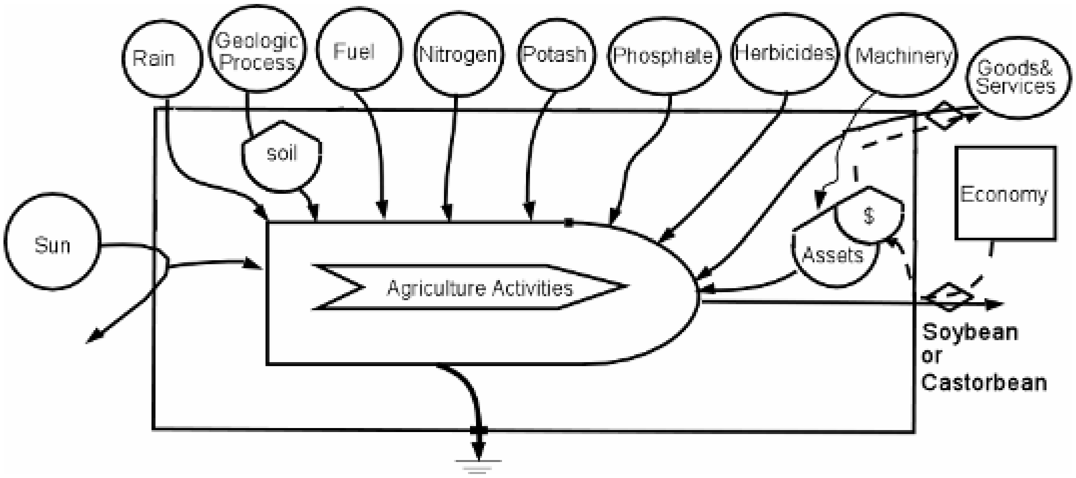

Figure 11. Energy systems diagram of agricultural production of soybean and castorbean.

Soybean Production

The general assumptions in the production of soybean included in this analysis were as follows: (1) average soybean production yield in Virginia was estimated at 2.6 tons wet w.t. per hectare (Holshouser, 2001); (2) biodiesel yield from soybean was estimated at 161 liters per ton (43 gallons), assuming an averages 18.5% oil content (Minnesota Farm Guide, 2006); (3) 2004 cost for soybean production in Virginia was estimated at \$649/ha (\$263/acre) (USDA, 2004a); (4) fertilizer application in Virginia per hectare was estimated at 8.41 kg of nitrogen, 8.38 kg of P_20_5; and 42.54 kg K_2O (USDA, 2004b); (5) combined use of herbicides and pesticide was estimated at 1.44 kg per hectare (USDA, 2004b); (6) it was assumed that no irrigation was necessary (USDOC, 1994); averaged diesel fuel consumption in VA soybean production was estimated at 17.6 liters per ha and gasoline was estimated at 11.2 liters per ha (USDA, 2006h); (7) electricity was 1.7 kWh per ha (USDA, 2006h).

Castorbean Production

Castorbean agricultural practices were based on Texas production in the 1960's. The general assumptions in the production of castorbean included in this analysis were as follows: (1) average castorbean production yield in Texas in 1960's was estimated at 2.3 tons wet w.t. per ha (Brigham and Spears, 1961); (2) biodiesel produced was estimated at 552 liters per ton of castorbean (147 gallons) assuming a 50% oil content (Dovebiotech, 2006); (3) 1961 cost for castorbean production in Texas for land preparation, planting, irrigation, fertilizer, cultivation, insect control, mechanical harvesting and hauling was estimated at $130/ha ($52.5 per acre) in 1961 chain-dollars (Brigham and Minton, 1969); (4) fertilizer application per ha was 90 kg of nitrogen, 46.5 kg of P_20_5 (Duke, 1983) and 17 kg K_2O (Brigham, 1993); (5) seeding was 14.6 kg per ha; (6) irrigation was estimated at 1750 cubic meters per ha (Duke, 1983).

Transportation System in Biodiesel Production

The system boundaries for transportation were 1) the crop from the field to the crushing facility, and 2) the "crude" vegetable oil from crushing facility to the refining plant (Fig. 12). These evaluations included energy embodied in machinery (trucks), driver services and fuels. The assumptions to estimate the emergy contributed from trucking, labor cost, price of fuel and distance traveled were the same as those used to estimate ethanol transportation. Based on these assumptions and crop yields, the fuel required for transportation from crop-to-crushing facility was estimated assuming 0.375

trip per ha for soybean crop and 0.312 trips per ha for castorbean. The fuel required for oil crushing-to-refinery was estimated at 0.0004 trips per gallon of “crude” vegetable oil transported.

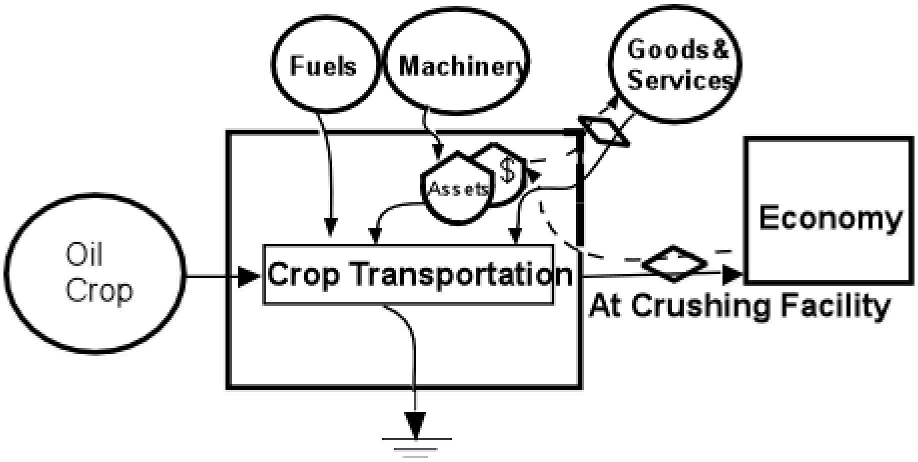

Figure 12: Energy systems diagram of transportation for biodiesel production.

Biodiesel Production

The production of biodiesel required two processes: a crushing process to extract the crude oil and an oil refining process. The extraction of the oil from the seed was performed at a crushing facility. The inputs to the crushing facility are schematically shown in Fig. 13. The assumption in the crushing facility was that oil was extracted using hexane and this was recovered and reused throughout the process (Behnke, 2006; Sheehan et al., 1998). The “crude” vegetable oil was then shipped to a refining facility. The extracted solid components were processed into animal feed meal and delivered to local animal feeding facilities. The total emergy required to generate the oil and meal was assigned equally to the two products. Crude vegetable oil refining to biodiesel (Fig. 14) was modeled based on local production in rural areas such as the biodiesel refinery located outside Richmond, Virginia, which began operation in 2004 (National Biodiesel Board, 2006a).

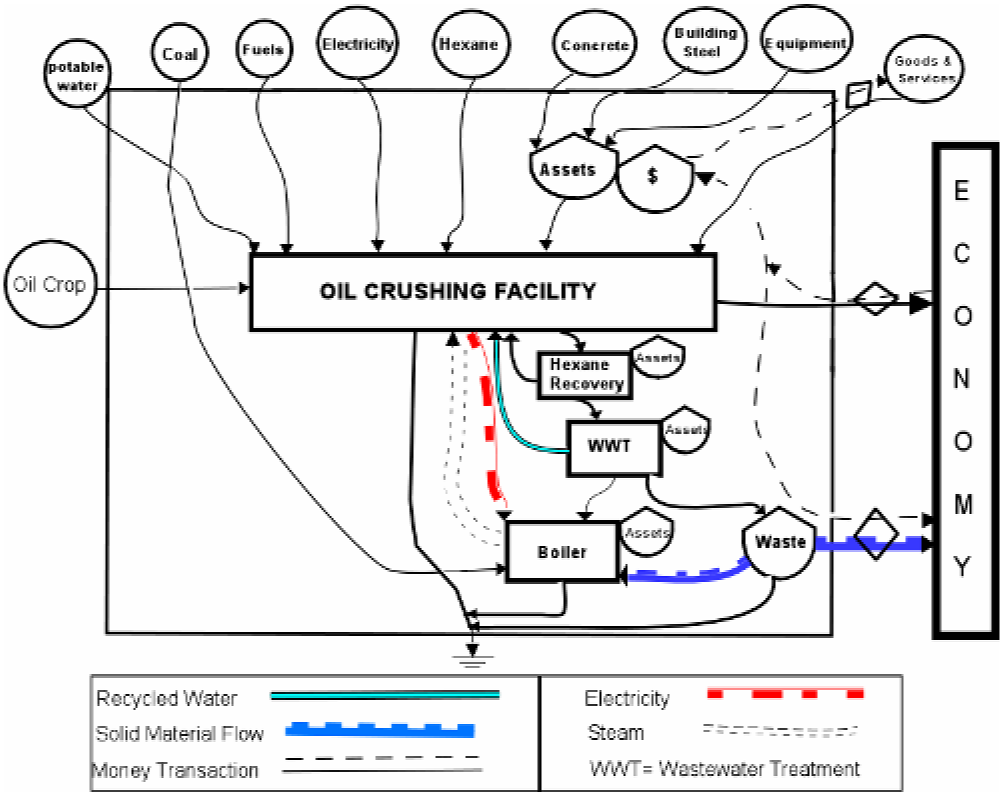

Figure 13. Energy system diagram of oil crushing for removing vegetable oil from oil- crops.

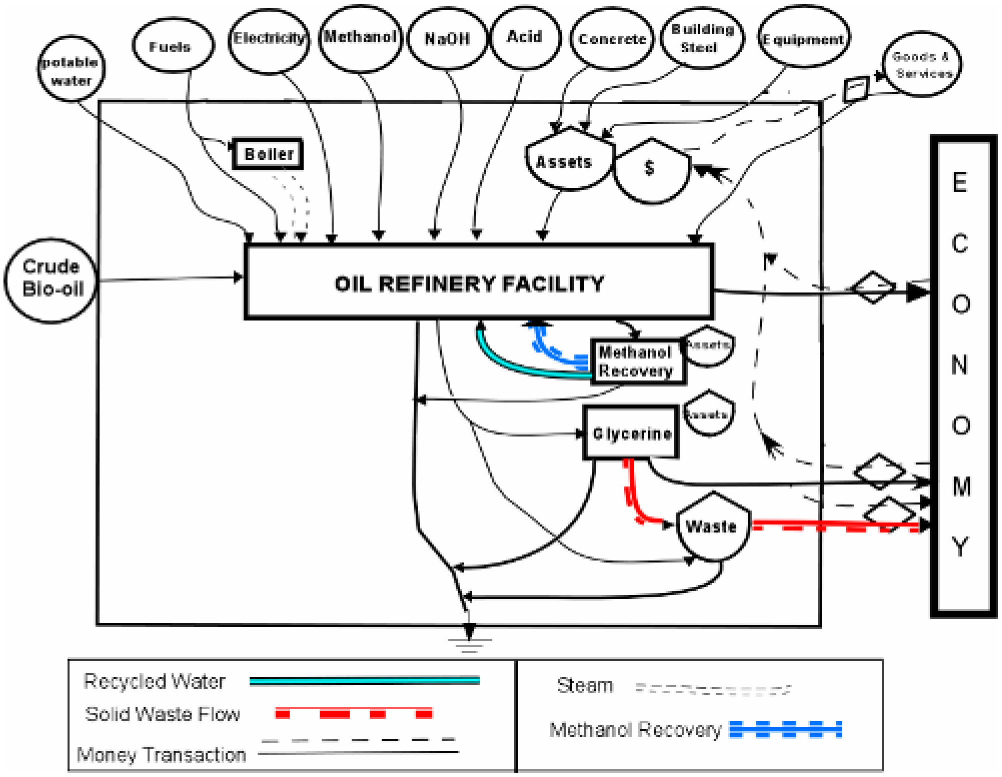

Figure 14. Energy systems diagram of vegetable oil refining.

Two key factors that facilitated the establishment of this refining facility were 1) local availability of soybean and 2) close location to an oil-crushing facility in Chesapeake, Virginia. This arrangement benefited the farmers by ensuring the sale of their crop to the Purdue Oil Crushing facility, provided animal feed to the local poultry industry and the unrefined oil was then refined locally into biodiesel. As a result, the model in this study incorporated some of the operating aspects of the Purdue Oil Crushing facility and the Virginia Biodiesel Refinery as well as basic engineering principles on energy and mass balance from Sheehan et al. (1998).

Oil Crushing

The crushing process used in the Purdue Oil Crushing Facility was based on the solvent oil extraction method. The process utilized hexane as the extracting solvent to recover the crude oil and processed meal. The processing required eight steps (Figure 15): receiving and storage, bean preparation, oil extraction, meal processing, oil recovery, solvent recovery, waste treatment and oil degumming.

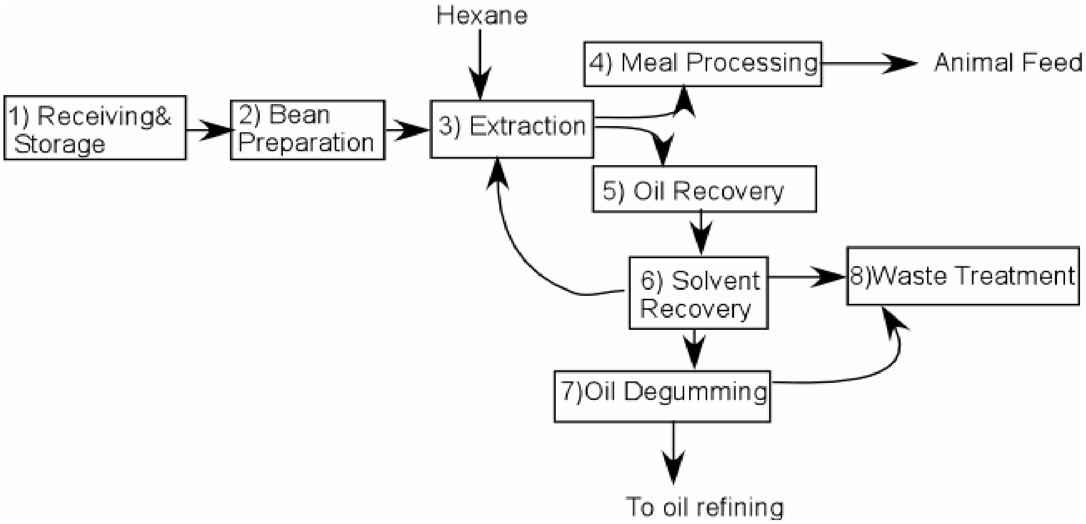

Figure 15. Flow diagram of oil crushing.
(Adapted from Sheehan et al., 1998)

Description of Soybean Crushing:

1. *Receiving and Storage* included receiving of bean by truck, drying to moisture content of 10.5%, screening, and storage of beans.
2. *Bean Preparation* involved cracking of the beans into six to eight pieces; dehulling to separate beans hulls from the meats; conditioning to adjust their temperature and moisture to make them more plastic and pliable; flaking to reduce size to 0.3 and 0.4 mm thick.
3. *Extraction* used hexane to produce a miscella (hexane oil mixture) and to precipitate flakes (solids).
4. *Meal Processing* involved the removal of hexane by contracting the flakes; inactivate urease and trypsin inhibitor enzymes and lowering the beans to a final moisture content of 12%. Flakes were then grounded and stored for shipment.
5. *Oil Recovery* used multiple effect evaporators to concentrate the miscella and strip the oil.
6. *Solvent Recovery* in this step hexane from vents and hexane/water mixture was placed in a settling tank; the solvent phase was continuously drawn off and pumped back to the extraction area while the water phase was sent to the waste treatment section.
7. *Oil Degumming* involved the removal of phosphatides (gums) and other impurities by mixing oil with hot water. As gums were hydrated they swell and separated from the oil by density difference.
8. *Waste Treatment* ensured that residual hexane was removed and recovered through a steam stripper before discarding of wastewater.

Oil Crushing Facility Assumptions

The conceptual design developed by Sheehan et al. (1998) included a set of underlying assumptions that were subsequently assimilated into the emergy evaluation.

- The facility operated on a continuous basis all year round and had a processing capacity of 1,063,510 metric tons of soybean per year and produced approximately 185 million liters (49.3 million gallons) of unrefined oil and 836,066 metric tons of poultry feed
- The Purdue Oil Crushing Facility used a coal-based boiler and co-generated about 1700 kilo watts (kW) of electricity for on-site use (ORNL, 2006c)

- The industrial boiler was assumed to have 85 percent efficiency.
- The facility was assumed to integrate heat recovery streams into the process; for example, hexane vapor from the meal processing section provided all heat for first stage evaporator in the soybean oil recovery.
- Hexane was used as a solvent to extract the oil from the beans
- Beans were delivered to oil crushing site by truck and the driving distance was assumed to be 80 kilometers (50 miles).
- The moisture level for optimal cracking of beans and storage purposes was 10.5%
- Energy demand of dryers was assumed to be 1940 kcal/kg of removed water.
- Hexane was recovered extensively throughout the plant.

Oil Refining

In this analysis the unrefined “crude” vegetable oil was assumed to be transported from the oil crushing facility located in Chesapeake Virginia to Virginia Biodiesel Refinery located outside of Richmond, Virginia. The refining process for converting crude vegetable oil (soybean or castorbean) to biodiesel employed a process known as transesterification. Although there are other methods to produce biodiesel, transesterifcation is the most widely used process in commercial biodiesel facilities in the US and Europe (Sheehan et al., 1998). Thus in this analysis, it was assumed that this process was used.

The process (Fig. 14) involved the reaction of a simple alcohol with the triglycerides found in the vegetable oil to produce a methyl ester (biodiesel) and glycerol. The refining process involved six steps (Figure 16): alkali refining, transesterification, methyl ester purification, glycerin recovery, methanol recovery and waste treatment. A detailed description on the refining processing is presented below.

Description of Refining Crude Vegetable Oil

1. *Alkali Refining Crude Oil* where caustic soda and hot water were added to the degummed vegetable oil to remove free fatty acids. The crude oil was heated and then mixed with a caustic solution that generates soaps. The hot water wash removed the soaps and the caustic-refined oil was then dried to remove any remaining water.

2. *Transesterification* occurred in a series of reactors where methanol and alkali refined oil were mixed and heated to 60° C. A two-phase (aqueous and oil) product was then sent to the settling tank where the aqueous phase was drawn off from bottom of the tank and sent to the methanol and glycerol recovery section. In this reaction, the theoretical chemical yield was assumed to be 1 kg of biodiesel per 1 kg of crude vegetable (soy or castor) oil; however, losses in the process result on an estimated yield of 96.4% on a per mass basis (Sheehan et. al, 1998).

3. *Methyl Ester Purification.* The oil-rich phase from the transesterification was washed with hot water in a countercurrent wash column to remove any remaining glycerol, methanol, and other water-soluble components to produce 100% biodiesel.

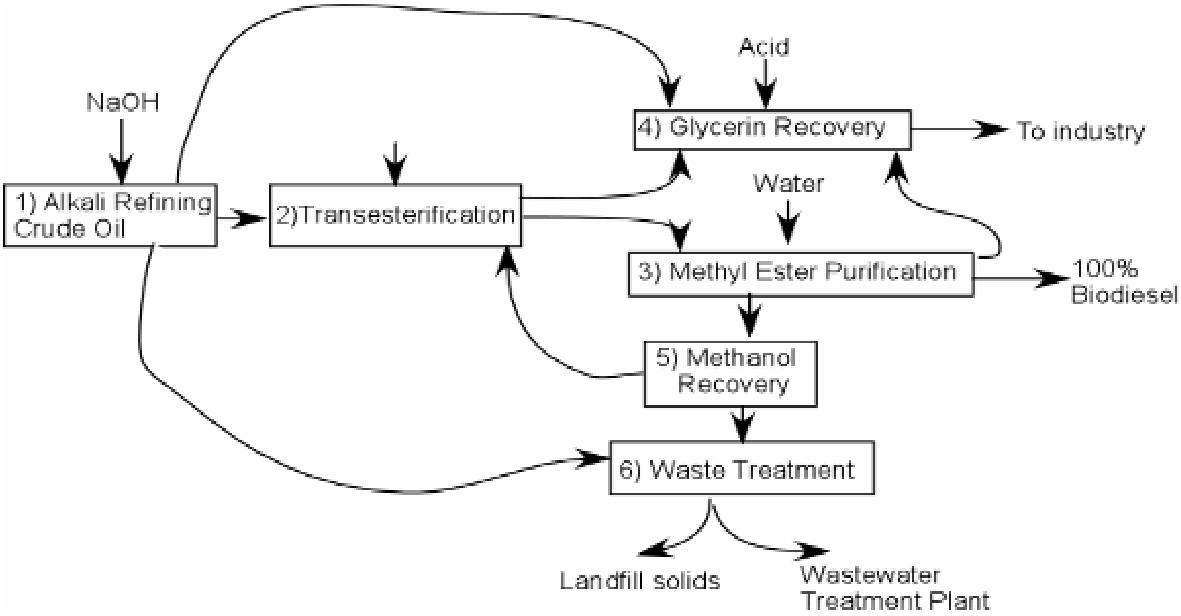

Figure 16. Flow diagram of oil refining.
(Adapted from Sheehan et al., 1998)

4. *Glycerin Recovery.* All glycerin-containing streams from transesterification, purification and alkali refining were collected and heated and fed to a distillation column that yields 80% glycerin by-product.

5. *Methanol Recovery* was where methanol and water vapor from the glycerin column were sent to a second distillation to recover approximately 50% of methanol that was then recycled into the transesterification process.

6. *Wastewater Treatment* wastes from all previous processes were collected and processed for removal of oil and greases. The greases and oil were landfilled while the water was treated and reused.

Oil Refining Facility Assumptions

The underlying assumptions from biodiesel assessment by Sheehan et al. 1998 and local practices in the refining process that were assimilated into the emergy evaluation are described below.

- The truck that delivered the crude vegetable oil to the refining facility was assumed to have a fuel efficiency of 4.25 kilometer per liter (10 miles per gallon) and the transportation distance was assumed to be 80 kilometers (50 miles).

- Because the Virginia facility used an adapted boiler that used recycled motor oil as fuel to produce steam, it was assumed that the facility in this analysis also used heating oil. The heating oil energy was assumed to be 139,000 Btu so the required amount was about 50 liters (13.36 gallons) of heating oil to produce enough steam to refine 1 metric ton of biodiesel.

- The boiler efficiency was assumed to be 75%.

- Estimated energy for steam input was assumed to be 328,000 kcal per metric ton of biodiesel that was produced.

- Electricity requirements were estimated at 28.90 kWh per metric ton of biodiesel produced.

- The biodiesel refinery recycled water.

- Sodium hydroxide was used as a caustic catalyst in the alkali refining step at rate of 24 kg per metric ton of biodiesel produced.

- Sodium methoxide was used as a base catalyst in the transesterification step at a rate of 21.77 kg per metric ton of biodiesel produced.

- Methanol was recovered throughout the process therefore the make-up input was 89.51 kg per metric ton of biodiesel produced.

- Recycled water use was estimated at 356 kg of water per ton of biodiesel produced Shehaan et al. (1998).

- Degummed vegetable oil was transported from crushing facility to refinery via truck.

- The refining cost for 1 gallon of biodiesel was estimated to be \$0.325. (Burton et al., 2002). This cost included insurance, taxes, capital charge, labor, maintenance, overheads and credits for byproducts and investment capital.

Biomass production of hybrid poplar grown using municipal biosolids

Site Description

The study site was located within Prince Georges County, Maryland, in the Washington, D.C. metropolitan area (Figure 17). About six meters of sand and gravel were mined from the site from 1972 to 1983, which left behind mining spoils consisting predominantly of clay. Site morphology consisted of a plateau where the hybrid poplar plantation was located. Steep banks surrounding the plateau were characterized by incised streams and unplanted mixed hardwood forest. The edge of the plateau was bermed to divert runoff to one of four detention ponds. Prior to biosolid application, the reclamation site was representative of abandoned sand and gravel mines in the metropolitan area. Surface hydrology was significantly altered by the mining. The clay spoil layer was 5.0 to 21.3 m thick and overlaid the lower Miocene Calvert Formation, which was a light to medium, olive gray to olive green, micaceous, clayey silt formed from marine shelf deposition (Wilson and Fleck, 1990; Tompkins, 1983).

Site Treatment

Prior to the tree planting rotation for this study the entire site had undergone one complete cycle of deep trenched biosolids application, six year tree growth and complete clear cut. Land was prepared by excavating trenches 76 cm deep and 107 cm wide, which were spaced on 244 cm centers (Figure 18). The trenches were filled with biosolids at a rate of 383,000 kg-dry weight per ha. Upon filling, trenches were covered with 20-30 cm of overburden and the site was leveled using a low-ground pressure bulldozer and disked in preparation for tree planting. The application rate used was similar to experimental trenching conducted by Sikora et al. (1982) on a well-drained, silt loam. The biosolids contained approximately 24% solids, 1.15% total nitrogen, 72% moisture and had a mean pH of 12 due to lime stabilization at the wastewater treatment facility (Buswell et al., 2006).

Figure 17. Location of hybrid poplar tree farm (star) within the metropolitan Washington, D.C. area.

The biosolids remained in a fairly stable anaerobic environment for the months leading up to the Spring planting. All cuttings were from hybrid poplar clones (Felton et al., 2006). Tree plantation management was 'low-intensity' (i.e., there was no irrigation, supplemental fertilization, or pesticide or herbicide applications). However, the understory was mowed for the first two years of the rotation to suppress plant competition.

Figure 18. Excavated trench (foreground) in preparation for biosolids (background).

Experimental Design

Tree stands ranged in age from two to six years. In the fall of 2005, samples were randomly selected from stands planted in years 1999, 2000, 2001, 2002 and 2003. At each stand, five trees were randomly selected for sampling, except for the 2001 stand where a total of 9 samples were selected due to the larger area it covered and only 3 samples were collected from the 2003 stand. If the randomly selected tree was missing or dead, it was excluded from measurements and a new replacement sample was randomly identified.

Data Collection

The diameter at breast height (DBH) of each sample tree was measured with a standard DBH tape at the end of the growing season in September 2005. Each sample tree was felled by cutting it at the ground surface with a chainsaw in October 2005. The height (HT) of felled trees was measured using a 50-meter tape immediately following cutting. In addition, the green weight of the entire tree (GW_{tree}) was obtained by suspending the felled tree from a load cell (National Scale Technology, Huntsville, AL), which was suspended from the bucket of the bulldozer. Two to three centimeter thick disks were then cut from the sample tree every 1.6 m from the bottom, inclusive of the bottom. A minimum of 3 disks per tree were collected. The green weight (GW) of each disk was taken at the site with a scale. The disks were transported to a lab where they were oven dried at 70º C until reaching a constant weight. Drying required from 3 to 5 days. The percent moisture (mass basis) content of each disk (MC_{disk}) was calculated using Equation 2.5.

$$MC_{disk} = (GW_{disk} - DW_{disk})/(DW_{disk}) \times 100 \qquad (2.5)$$

Where GW_{disk} = green weight of tree sample disk (grams)
DW_{disk} = oven-dried weight of tree sample disk (grams)

Sample tree moisture content (MC_{tree}) was determined by taking the average of MC_{disk}, which was then used in Equation 2.6 to determine a tree's above-ground biomass (BA_{tree}).

$$BA_{tree} = (GW_{tree})/(1 + MC_{tree}/100) \qquad (2.6)$$

Where BA_{tree} was in grams dry weight;
GW_{tree} was in grams green weight of sample tree; and
MC_{tree} was estimated percent moisture content of sample tree

Standing above-ground biomass of each stand-age (BA_{stand}) was determined from Equation 2.7.

$$BA_{stand} = s*BA_{tree\text{-}mean} \qquad (2.7)$$

Where s was planted stem density (stems per ha), which was known from planting arrangement (1075 trees/ha), and $BA_{tree\text{-}mean}$ was mean above-ground biomass of sample trees per stand (grams per tree).

Data Analysis

The mean net production of above-ground tree biomass was found by fitting a straight line to BA_{stand} as a function of stand-age. The best fit line was found using simple linear least squares regression.

Allometric relationships predictive of BA_{tree} were determined for DBH and HT using simple linear regression for each metric. Stepwise linear regression was used to explore whether an allometric equation that combined both DBH and HT was a better predictor. SPSS for Windows 10.0 (Chicago, IL) was used for all statistical analysis.

Chapter 3: RESULTS AND DISCUSSION

Emergy Accounting of Production Systems

These emergy evaluations analyses were performed on a per gallon basis to facilitate comparison to other biofuel production studies. The detailed inputs of environmental, energy and financial resources used to produce ethanol from switchgrass are tabulated for agricultural production (Tables 2 and 3), crop transportation (Table 4) and ethanol processing (Table 5). All of the calculations and data sources used to generate the detailed data presented in these tables are given in Appendix B. The emergy evaluations on production of ethanol from hybrid poplar are presented for agricultural production (Tables 12), crop transportation (Table 13) and ethanol processing (Table 14). All of the calculations and data sources used to generate the detailed data on ethanol from hybrid poplar are given in Appendix C. Likewise, detailed inputs of environmental, energy and financial resources used to produce biodiesel from soybean and castorbean are tabulated for agricultural production (Tables 22 and 23, respectively), crop transportation (Tables 24 and 25, respectively), oil crushing (Tables 26 and 27, respectively), Oil transportation (Tables 28), and refining (Table 29). All of the calculations and data sources for biodiesel emergy evaluations are presented in Appendix D.

Since these tables are organized similarly, their structure is explained by using Table 2 as a template. All inputs appear as numbered line items from top to bottom. Line items were arranged according to the source of their input, which included Free Renewable (R), Free Non-renewable (N), Purchased Resources (M), or Purchased Services (S) (Table 2). Additionally, R and N were grouped as Nature's Contribution (I), while M and S were grouped as Purchased (F) (Table 2). Both I and F were subsequently used in calculating traditional emergy indices. Renewable contributions from nature included sun, wind, rain, evaportranspiration. However, to avoid double counting solar emergy of these renewable inputs, only emergy of evapotranspiration was used to measure R. That is, the solar emergy of direct sunlight, rain, and wind were not added to the total solar emergy requirement. The main free non-renewable resource used was soil lost due to erosion and oxidation. Purchased resources (M) accounted for the solar energy embodied in materials, like fertilizers, herbicides, machinery and fuel. Purchased services (S) accounted for the solar energy embodied in human services, which was measured according to dollar payments.

In Table 2, Column A lists the amount of energy, material or money represented by the line item. Column B gives Transformation Ratio as aggregated solar emergy per unit. The Transformation Ratio in Column B was partitioned into its R, $N_{m,}$ N_f, and N_p fractions as described in the methods section and detailed in Appendix A. The R, $N_{m,}$ N_f, and N_p fractions in solar transformity, specific solar emergy of materials, and the solar emergy per dollar are shown in columns C, E, F, and I, respectively. The tranformity fractions were used to convert line values of inputs (column A) expressed as energy (joules), mass (grams) or money ($) to solar emergy by multiplying by the respective R, N_m, N_f, and $N_{p.}$ The emergy input into the system, product of column A and columns C, E, F, and I, respectively, in giga-sej (E09) per gallon for R, N_m, N_f, and N_p are shown in columns D, F, H, and J, respectively. For example the environmental emergy of potash (line item 9, Column D in Table 2) was 1 giga-sej per gallon, but its mineral emergy (line item 9, Column F in Table 2) was 11 giga-sej per gallon, while its petroleum fraction was

.03 giga-sej per gallon. The total emergy of each input is given in Column K, which was the sum of Columns D, F, H, and J.

Switchgrass to Ethanol

The total emergy used during establishment and reseeding was 1659 giga-sej per gallon (Table 2). Since switchgrass is a perennial crop, the line items for establishment and reseeding were prorated for an 11 year cycle (i.e., stand life was 10 years plus one year for reseeding). Whereas Table 2 included only the inputs required for establishment and reseeding, Table 3 columns D, F, H, and J summarized the total amount of resources required for agricultural production (i.e., these included the prorated inputs for line items shown in Table 2). The total emergy required to produce a crop of switchgrass that could be used to generate one gallon of ethanol amounted to 5727 giga-sej (Table 3). The single largest input came from water used in evapotranspiration (Table 3). The three largest purchased inputs were lime, nitrogen fertilizer and operating cost (Table 3).

The emergy analysis for the transportation of the switchgrass crop to the ethanol processing facility is given in Table 4**.** The emergy contributed from steel embodied in manufacturing of truck was estimated to be 13 giga-sej/gallon and fuel for transportation contributed 152 giga-sej per gallon. Emergy from labor services contributed 47 giga-sej per gallon, while emergy from fuel services contributed 18 giga-sej per gallon. In Table 4, the total emergy required in the transport of switchgrass from the field to ethanol processing plant to generate one gallon of ethanol was 230 giga-sej. The solar emergy of the diesel fuel was the largest portion of the total.

Table 5 contains the estimated amount of emergy required to convert switchgrass into ethanol, including the biomass feedstock from the field (line item 1) and the emergy of transportation (line items 15 and 27). The conversion of switchgrass biomass to ethanol required 8915 giga-sej per gallon of ethanol produced (Table 5). After the switchgrass biomass, the two largest inputs came from the operating costs and gasoline. Lime and ammonia were also large inputs to the conversion process.

Table 2: Solar emergy required to establish and re-seed switchgrass (Panicum virgatum L.) based on Iowa 2001 production standards (per gallon of ethanol)

Index	Item	Input (A)	Unit	Solar Emergy per Unit (B)	*Env. Fraction R &N_o (C)	*Env. Emergy E09 sej/gallon (D)	Mineral Fraction N_m (E)	*Mineral Emergy E09 sej/gallon (F)	Coal & Nat.gas Fraction N_f (G)	*Coal & Nat. gas Emergy E09 sej/gallon (H)	Petroleum Fraction N_p (I)	*Petroleum Emergy E09 sej/gallon (J)	*Total Emergy E09 sej/gallon K=D+F+H+J
	Nature Contribution (I)												
	Free Renewable Inputs (R)												
1	Sun	6.73E+10	J	1	1	6	0	0	0	0	0	0	6
2	Wind	3.63E+08	J	2513	2513	83	0	0	0	0	0	0	83
3	Water, rain	6.49E+07	J	30576	30576	180	0	0	0	0	0	0	180
4	Evapotranspiration	5.43E+07	J	30576	30576	151	0	0	0	0	0	0	151
	Free Non-renewable (N)												
5	Net topsoil loss	2.44E+07	J	73800	73800	164	0	0	0	0	0	0	164
	Purchased (F)												
	Feedback from economy Resources (M)												
6	Herbicide	1.91E+06	J	1.10E+05	0	0	0	0	0	0	1.10E+05	19	19
7	Nitrogen (NH_3)	0.0E+00	g	2.87E+09	0	0	0	0	0	0	0	0	0
8	Phosphate (P_2O_5)	54	g	6.55E+09	0	0	1.68E+09	8	4.56E+09	23	3.11E+08	2	32
9	Potash (K_2O_5)	72	g	1.85E+09	1.06E+08	1	1.68E+09	11	5.97E+07	0	4.59E+06	0.030	12
10	Lime	7239	g	1.73E+09	9.80E+06	6	1.68E+09	1106	2.06E+07	14	1.96E+07	13	1138
11	Machinery	19	g	1.30E+10	0	0	1.68E+09	3	9.55E+09	17	1.77E+09	3	22
12	Fuel	2.08E+06	J	1.1E+05	0	0	0	0	0	0	1.1E+05	21	21
	Feedback from economy in Services (S)												
13	Herbicide	0.03	$	1.10E+12	1.32E+11	0	9.90E+10	0.25	4.51E+11	1	4.18E+11	1	3
14	Fertilizers	0.07	$	1.10E+12	1.32E+11	1	9.90E+10	0.62	4.51E+11	3	4.18E+11	3	7
15	Lime	0.09	$	1.10E+12	1.32E+11	1	9.90E+10	0.83	4.51E+11	4	4.18E+11	3	9
16	Labor	0.07	$	1.10E+12	1.32E+11	1	9.90E+10	0.63	4.51E+11	3	4.18E+11	3	7
17	Fuel	0.02	$	1.10E+12	1.3E+11	0.21	9.90E+10	0.16	4.51E+11	1	4.18E+11	1	2
18	Operating costs	0.71	$	1.10E+12	1.32E+11	9	9.90E+10	6.39	4.51E+11	29	4.18E+11	27	71
19	**Total Emergy**												**1659**

*Prorated to 11 year cycle

Lines 1, 2, and 3 Excluded from Total (line 21) to avoid double counting

Table 3: Solar emergy required for crop production of switchgrass (Panicum virgatum L.) based on Iowa 2001 production standards (per gallon of ethanol)

Index	Item	Input (A)	Unit	Solar Emergy per Unit (B)	*Env. Fraction R &N_o (C)	*Env. Emergy E09 sej/gallon (D)	Mineral Fraction N_m (E)	*Mineral Emergy E09 sej/gallon (F)	Coal & Nat.gas Fraction N_f (G)	*Coal & Nat. gas Emergy E09 sej/gallon (H)	Petroleum Fraction N_p (I)	*Petroleum Emergy E09 sej/gallon (J)	*Total Emergy E09 sej/gallon K=D+F+H+J
	Nature Contribution (I)												
	Free Renewable Inputs (R)												
1	Sun	6.73E+10	J	1	1	73	0	0	0	0	0	0	73
2	Wind	3.63E+08	J	2513	2513	995	0	0	0	0	0	0	995
3	Water, rain	6.49E+07	J	30576	30576	2165	0	0	0	0	0	0	2165
4	Evapotranspiration	5.43E+07	J	30576	30576	1810	0	0	0	0	0	0	1810
	Free Non-renewable (N)												
5	Net topsoil loss	2.73E+05	J	73800	73800	184	0	0	0	0	0	0	184
	Purchased (F)												
	Feedback from economy Resources (M)												
6	Herbicide	1.53E+06	J	1.10E+05	0	0	0	0	0	0	1.10E+05	188	188
7	Nitrogen (NH_3)	181	g	2.87E+09	0	0	0	0	2.87E+09	520	0	0	520
8	Phosphate (P_2O_5)	14	g	6.55E+09	0	0	1.68E+09	32	4.56E+09	87	3.11E+08	6	124
9	Potash (K_2O_5)	137	g	1.85E+09	1.06E+08	15	1.68E+09	242	5.97E+07	9	4.59E+06	1	266
10	Lime	0	g	1.73E+09	9.80E+06	6	1.68E+09	1106	2.06E+07	14	1.96E+07	13	1138
11	Machinery	9	g	1.30E+10	0	0	1.68E+09	19	9.55E+09	107	1.77E+09	20	146
12	Fuel	1.6E+06	J	1.11E+05	0	0	0	0	0	0	1.11E+05	203	203
	Feedback from economy in Services (S)												
13	Herbicide	0.03	$	1.10E+12	1.32E+11	4	9.90E+10	3	4.51E+11	13	4.18E+11	12	33
14	Fertilizers	0.08	$	1.10E+12	1.32E+11	11	9.90E+10	8	4.51E+11	38	4.18E+11	35	92
15	Lime	0.008	$	1.10E+12	1.32E+11	2	9.90E+10	1	4.51E+11	7	4.18E+11	6	16
16	Labor	0.05	$	1.10E+12	1.32E+11	7	9.90E+10	5	4.51E+11	23	4.18E+11	21	56
17	Fuel	0	$	1.10E+12	1.32E+11	1	9.90E+10	1	4.51E+11	4	4.18E+11	3	9
18	Operating costs	0.46	$	1.10E+12	1.32E+11	62	9.90E+10	46	4.51E+11	211	4.18E+11	196	516
21	**Total Emergy**												**5727**
22	Yield biomass	13817	g										
23	Energy biomass	2.66E08	J										
24	Emergy/mass (sej/g)			4.15E+08									
25	Transformity (sej/J)			2.15E+04									

**Include values from Table 3 Establishment and Reseeding prorated to 11 year cycle. Lines 1, 2, and 3 Excluded from Total (line 21) to avoid double counting

Table 4: Solar emergy required to transport switchgrass from field to ethanol processing plant (per gallon of ethanol)

Index	Item	Input (A)	Unit	Solar Emergy per Unit (B)	Env Fraction R&N_o (C)	Env. Emergy E09 sej/gallon (D)	Mineral Fraction N_o (E)	Mineral Emergy E09 sej/gallon (F)	Coal and Nat. gas Fraction N_f (G)	Coal and Nat. gas Emergy E09 sej/gallon (H)	Petroleum Fraction N_p (I)	Petroleum Emergy E09 sej/gallon (J)	Emergy E09 sej/gallon K=D+F+H+J
Purchased (F)													
Feedback from economy Resources (M)													
1	Machinery	1	g	1.30E+10	0	0	1.68E+09	2	9.55E+09	10	1.77E+09	2	13
3	Diesel	1.37E+06	J	1.1E+05	0	0	0	0	0	0	1.1E+05	152	152
Feedback from economy in Services (S)													
2	labor	0.043	$	1.10E+12	1.32E+11	6	9.90E+10	4	4.51E+11	19	4.18E+11	18	47
4	Fuels	0.016	$	1.10E+12	1.32E+11	2	9.9E+10	2	4.51E+11	7	4.18E+11	7	18
5	**Total Emergy**												**230**

Table 5: Solar emergy required to produce ethanol from switchgrass biomass based on 2000 data (per gallon of ethanol)

#	Item	Input (A)	Unit	Solar Emergy per Unit (B)	Env Fraction R&N_o (C)	Env. Emergy E09 sej/gallon (D)	Mineral Fraction N_m (E)	Mineral Emergy E09 sej/gallon (F)	Coal and Nat. gas Fraction N_f (G)	Coal and Nat. Gas Emergy E09 sej/gallon (H)	Petroleum Fraction N_p (I)	Petroleum Emergy E09 sej/gallon (J)	Emergy E09 sej/gallon K=D+F+H+J
1	Biomass Input	13837	g	4.15E+08	1.56E+08	2154	1.09E+08	1501	8.73E+07	1206	6.26E+07	866	5727
Purchased (F)													
Feedback from economy Resources (M)													
2	lime	291	g	1.73E+09	9.80E+06	3	1.68E+09	488	2.06E+07	6	1.96E+07	6	503
3	Ammonia	159	g	2.87E+09	0	0	0	0	2.87E+09	455	0	0	455
4	Corn Steep Liquor	2269	g	5.54E+05	1.55E+05	0	4.99E+04	0	2.05E+05	0	1.44E+05	0	1
5	Nutrients	354	g	1.94E+04	7.37E+03	0	1.75E+03	0	4.85E+03	0	5.43E+03	0	0
6	Antifoam (corn oil)	748	g	5.54E+05	1.55E+05	0	4.99E+04	0	2.05E+05	0	1.44E+05	0	0.41
7	Ammonium Sulfate	19	g	2.87E+09	0.00E+00	0	0.00E+00	0	2.87E+09	55	0.00E+00	0	55
8	BFW chemicals	11	g	9.86E+09	0	0	1.68E+09	18	4.83E+09	52	3.35E+09	36	107
9	Equipment Steel	1.2	g	1.30E+10	0	0	1.68E+09	2	9.55E+09	11	1.77E+09	2	15
10	Buildings Steel	2.65	g	6.97E+09	0	0	1.68E+09	4	9.53E+08	3	4.34E+09	11	18
11	Cement	3	g	3.33E+09	0	0	1.68E+09	5	1.56E+09	5	8.23E+07	0	10
12	Water make up	9.6E+04	J	3.14E+05	8.48E+04	8	1.29E+05	12	8.17E+04	8	1.88E+04	2	30
13	Gasoline	6.54E+06	J	1.11E+05	0	0	0	0	0		1.11E+05	726	726
14	Propane	9.82E+04	J	1.11E+05	0	0	0	0	1.11E+05	11	0	0	11
15	*Transportation Emergy From TABLE 4*				0	0	0	*2*		*10*		*154*	165
Feedback from economy in Services (S)													
16	Sulfuric Acid	0.01	$	1.10E+12	1.32E+11	1	9.90E+10	1	4.51E+11	5	4.18E+11	5	12
17	Lime	0.02	$	1.10E+12	1.32E+11	3	9.90E+10	2	4.51E+11	10	4.18E+11	9	25
18	Ammonia	0.04	$	1.10E+12	1.32E+11	6	9.90E+10	4	4.51E+11	19	4.18E+11	18	47
19	Corn Steep Liquor	0.03	$	1.10E+12	1.32E+11	4	9.90E+10	3	4.51E+11	13	4.18E+11	12	31
20	Nutrients	0.008	$	1.10E+12	1.32E+11	1	9.90E+10	1	4.51E+11	4	4.18E+11	3	9
21	Antifoam	0.02	$	1.10E+12	1.32E+11	3	9.90E+10	2	4.51E+11	9	4.18E+11	8	22
22	Amm.Sulfate	0.003	$	1.10E+12	1.32E+11	0	9.90E+10	0	4.51E+11	1	4.18E+11	1	3
23	Water	0.01	$	1.10E+12	1.32E+11	1	9.90E+10	1	4.51E+11	3	4.18E+11	2	6
24	Gasoline	0.05	$	1.10E+12	1.32E+11	7	9.90E+10	5	4.51E+11	23	4.18E+11	21	55
25	Propane	0.000010	$	1.10E+12	1.32E+11	0	9.90E+10	0	4.51E+11	0	4.18E+11	0	0
26	Operating cost	0.74	$	1.10E+12	1.32E+11	98	9.90E+10	73	4.51E+11	335	4.18E+11	310	816
27	*Transportation Emergy From TABLE 4*				*1.32E+11*	*8*	*9.90E+10*	*6*	*4.51E+11*	*27*	*4.18E+11*	*25*	*65*
28	**Total Emergy**												**8915**

Table 5: Continued

29	Yield ethanol mass	2.71E+03	g	
30	Energy in ethanol	8.02E+07	J	
31	Emergy/mass (sej/g)			3.29E+09
32	Transformity (sej/J)			1.11E+05

Emergy Inputs to Switchgrass Ethanol

Figure 19 is a ranking of the largest input items to the entire process chain. Unlike more traditional energy analyses of biofuels (e.g., Farrell et al., 2006; Pimentel and Patzek, 2005), which excluded human, soil and water from rain inputs, this emergy evaluation included them and found they were some of the most important inputs. In fact operating costs (human services) and water of evapotranspiration were the two largest single inputs (Figure 19) with costs and water contributing 28% and 22%, respectively, of the total emergy required. Another environmental input that was important in agricultural systems was the use of organic matter in soil. Depending on slopes and soil types, switchgrass has been used to control erosion (Wolf and Fisk, 1995). Studies on marginal lands have shown that the root system in switchgrass improves soil by adding organic matter and increasing soil water infiltration and nutrient-holding capacity (ORNL, 2006a).

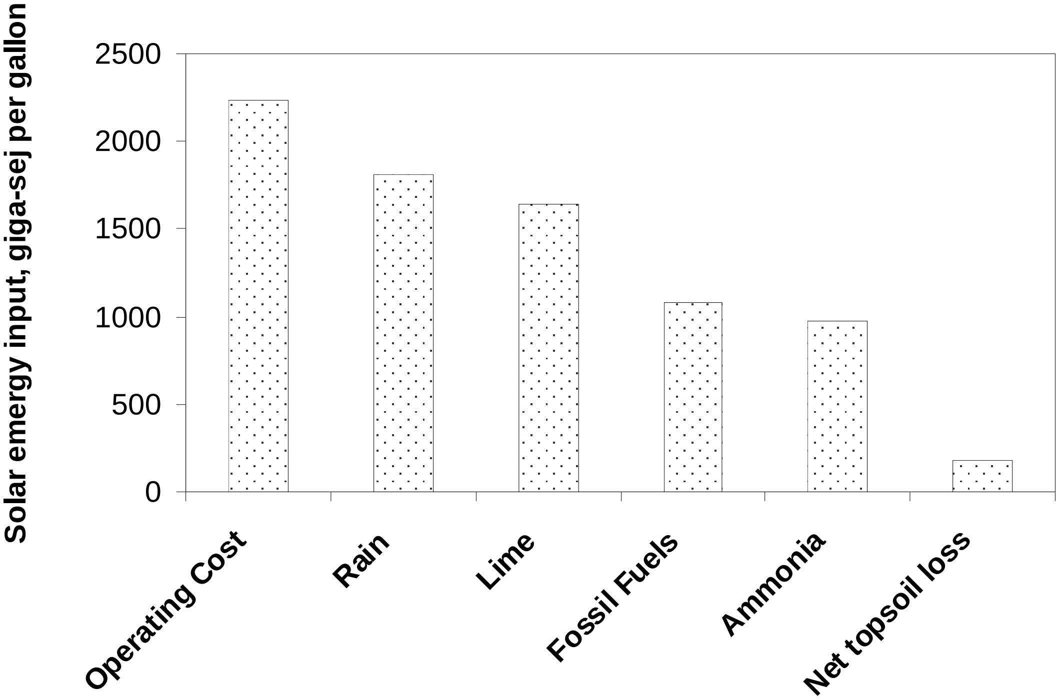

Figure 19. Top inputs required to produce ethanol from switchgrass.

During agricultural production of switchgrass, the top soil loss in establishment and reseeding year (Table 2) was high at 155 giga-sej per gallon because the root system was not well established yet. In the production years, the root system was assumed to be well established so topsoil loss was lower at about 21 giga-sej per gallon (difference between Table 2 and Table 3). Moreover, since the initial topsoil loss in establishment and reseeding (Table 2) was spread over the 11 year lifetime of the stand, the overall impact of switchgrass production on top soil loss was not as severe as in other crop systems. Overall, the total soil erosion represented 2% of the emergy input. Other important inputs included the use of lime and fertilizers in the agriculture stage that together represented 25% of the total emergy required for the production of switchgrass-ethanol. Petroleum-based fuels used in the chain process and processed chemicals used in the industrial conversion of switchgrass to ethanol were both estimated at 12% or the total emergy.

Conventional Emergy Analysis

The conventional emergy inflows to the overall production of ethanol from switchgrass are summarized in Table 6. These flows were used to compute conventional emergy indices for the agricultural and industrial phases. Emergy indices are summarized in Table 7. A limitation with using the conventional emergy flows to estimate the relevant indices was that the environmental inputs were almost solely accounted for within the agricultural production phase, and were not explicitly determined for the indirect pathways. Consequently the industrial processing of switchgrass to ethanol was mainly categorized as imported inputs. In effect, traditional emergy indices were too aggregated to meet the study’s goals.

Table 6: Summary of conventional emergy flows (Giga-sej/gallon)

	Switchgrass Crop	*Switchgrass Ethanol*
Local renewable Inputs (R)	1810	0
Locally nonrenewable inputs (No)	184	0
Imported inputs (F)	3733	3188
Total Emergy inputs (Y)	5651	8915

Table 7: Summary of conventional emergy indicators for ethanol production from switchgrass

	Switchgrass Crop	*Switchgrass Ethanol*
Conventional Emergy Indices		
Specific Emergy (giga-sej/gram)	0.43	3.29
Transformity of Switchgrass (sej/joule)	21,500	110,000
Emergy Yield Ratio= Y/ F	1.53	1.30
Environmental Loading Ratio=(N+ F)/R	2.16	3.92
Emergy Investment Ratio= F/(N+R)	1.87	3.47
Emergy Sustainability Index= (EYR)/(ELR)	0.71	0.33
Percent Renewable = (Y/R)*100	35	20

Conventional Emergy Indicators

Table 7 presents the results on conventional emergy indices for both agricultural production and industrial conversion of switchgrass to ethanol. The transformity of switchgrass production was estimated to be 21,500 sej/joule while the transformity for switchgrass ethanol was 110,000 sej/joule. This result was expected since at every step of the transformation more resources are fed into the process. However, since the EYR also decreased from 1.53 to 1.30, this indicated that most of the resources added during the industrial transformation of switchgrass to ethanol were purchased from the economy.

Based on conventional emergy indices can switchgrass-to-ethanol be a primary energy source? Under the most optimistic assumptions concerning conversion efficiencies, price of inputs, and waste recycling the emergy yield ratio of switchgrass-ethanol was 1.30-to-1 (Table 7), which was a small net positive, but much less than our present source of liquid fuel which has an EYR greater than 5-to-1 (Odum, 1996). To serve as a ‘primary’ fuel source the EYR likely needs to be at least greater than 3-to-1. Thus, the viability of switchgrass-to-ethanol as a major source of fuel is highly questionable.

The environmental loading ratio (ELR) of agricultural production of switchgrass (2.16) was higher than forage crops (1.45), but lower than food crops like rice (2.86), wheat (3.38), corn (5.63), and sugar beat (7.33) (Ugliati et al., 1994), which indicated that switchgrass crop production used less purchased inputs from the economy relative to its use of ‘free’ environmental inputs from renewable and non-renewable sources. However, once the ethanol processing step was taken into account the ELR nearly doubled to 3.92. Compared to other fuels like bio-ethanol produced in Brazil (7.7), corn-ethanol produced in Italy (17.65), and crude oil in Alaska (1429.3), switchgrass ethanol had a lower potential impact on the environment (Ulgiati et al., 1993; Ulgiati, 2001; Brown and Ulgiati, 1997). The ELR of switchgrass-ethanol was comparable to a large-scale hydroelectric power plant proposed for the Mekong River in Thailand (3.3) (Brown and McClanahan, 1996).

The emergy investment ratio (EIR) of switchgrass crop was estimated to be 1.87, meaning that 1.87 units of emergy were purchased from the economy and matched to 1 unit of free environmental energy. This indicated the production of switchgrass crop is more competitive than intensive agriculture systems like Italian rice (2.7), Ecuadorian shrimp aquaculture (3.4), Italian olives (4.1), Indian silk (6.9), Texas cotton (9.6), Brazilian sugarcane (7.0), and Italian sunflowers (26.3) (Odum and Odum, 1984; Odum et al., 1987; Odum and Arding, 1991; Ulgiati et al., 1993; Tilley, 1999), because nature was contributing a larger proportion of energy in the switchgrass-ethanol system than the portion that was purchased from the economy. However, the switchgrass crop was less competitive than forestry or basic sectors of the wood products industry where there was a much higher contribution from nature. For example tropical forests have an EIR of 1.12 while the EIR of logging in North Carolina was estimated at 0.27 (Odum, 1995; Tilley, 1999).

In the conversion of switchgrass to ethanol the EIR increased to 3.47, meaning that 3.47 unit of energy from the economy were needed to match 1 unit of free environmental energy. This indicated that the production of ethanol from switchgrass was less competitive than other fuels like hydroelectricity (0.10), crude oil production in Alaska (0.07), and Brazilian bio-ethanol (1.00), but that it was more competitive than Italian corn-ethanol (12.06) (Brown and McClanahan, 1996; Brown and Ulgiati, 1997; Ulgiati et. al., 1993; Ulgiati, 2001). It also indicated that switchgrass ethanol was not a primary source of energy like Alaskan crude oil, because a primary source of energy will likely have an EIR much less than 1.0.

Refined Emergy Partitioning

Table 8: Summary of emergy flows partitioned according to source and aggregated as direct and indirect inputs to the switchgrass ethanol production system (giga-sej/gallon)

		SOURCE					
		R	N_o	N_m	N_f	N_p	*Total by Category*
CATEGORY	D_I	1810	184	0	0	0	1995
	D_F	0	0	0	11	1081	1092
	I_G	33	0	1930	1340	287	3590
	I_S	269	0	202	918	851	2239
Total by Source		**2112**	**184**	**2132**	**2269**	**2218**	**8915**

Table 8 shows the summary of the refined partitioning of the inputs into their ultimate source type (R, N_o, N_m, N_f, or N_p) and their ‘route’ through the ecological-economic system (i.e., direct or indirect) to the production system. Of these partitions, the largest ultimate source of solar emergy came from non-petroleum fossil fuel (N_f), at 2269 giga-sej per gallon of which only a small amount (11 giga-sej) was from direct consumption, while the remainder was embodied in the indirect consumption of goods (1340 giga-sej) and services (918 giga-sej) (Table 8). Petroleum (N_p), environmental(R) and mineral sources (N_m), closely followed (Table 8).

Integrating the environmental, energy and financial resource inputs required throughout the switchgrass ethanol production chain revealed that 45% (Row: D_I D_F I_G Column: R, N_o and N_m) came from the environment, 30% (Row: D_I D_F I_G Column: N_f and N_p) came from fossil energy sources and the remaining 25% (Row I_S Column: R, N_o, N_m, N_f and N_p) was financial resources as paid human services (Table 8). Of the environmental resources used, water (from rain) for crop growth was the largest, while loss of soil due to erosion made up the remainder.

Indirect inputs were a major source of total emergy requirements, outweighing direct inputs (Table 8). The indirect use of emergy in production of ethanol accounted for 65% ((3590+2239)/8915) of the total consumption. This indirect emergy came from energy embodied in financial services, and from energy embodied in goods like manufactured machinery, fertilizers, and infrastructure. The majority of the indirect emergy came from non-petroleum fossil fuel, non-renewable minerals and petroleum. The major reliance on indirect inputs indicated that the production system enjoyed a hidden energy-subsidy that was provided by the larger economy. Energy analyses that do not fully account for this subsidy are likely missing a majority of the energy embodied in biofuel production systems.

New emergy Indices based on Refined Partitioning

Table 9 presents the results on the new set of emergy-based indicators that were developed to understand the liquid-to-liquid trade-off inherent in biofuel production systems (i.e., how much petroleum was required to make the ethanol). In addition, the new indices also quantified the amount of non-liquid fossil fuel used per unit of liquid fuel produced (i.e., natural gas plus coal used to make ethanol), and discriminated between whether sources were direct and indirect inputs. Table 9 summarizes how each new indicator was calculated.

Table 9: Indices for assessing the viability of producing ethanol from cellulose-switchgrass

Indices	**(A) Optimistic Baseline Scenario**	**(B) Conservative Scenario**
Emergy content of ethanol: Y_{eth} = (84.2 megajoules per gallon ethanol)X(1.1E05 sej per joule) (giga-sej/gallon)	9,267	9,267
Total emergy used: $U=R+N_o+N_m+N_f+N_p$	8915	19,427
Net liquid fuel available beyond production (Y_{eth} -N_p) (giga-sej/gallon)	7048	5475
Liquid produced to total emergy used: Y_{eth}/U	1.04	0.48
Liquid produced to petroleum used: (Y_{eth} /(N_p)	4.2	2.4
Yield of net liquid produced to petroleum emergy used (Y_{eth} -N_p /(N_p)	3.2	1.4
Net Liquid Yield Ratio, EYR_P: (Y_{eth}- N_p)/($R+N_o+N_m+N_f$)	1.05	0.35
Liquid produced to fossil emergy used: Y_{eth} /(N_f+N_p)	2.09	0.79
Ratio of liquid available per non-petroleum fossil emergy used (EYR_f) (Y_{eth} / N_f)	4.2	1.17
Yield ratio of net liquid available per fossil emergy used (EYR_f) ((Y_{eth} -N_p) / N_f)	3.1	0.70
Percent from Renewable sources (R/U)	23%	19%
Percent from free-environmental sources: ($R+N_o+N_m$)/ U	47%	40%
Percent from liquid fuels: N_p/U	25%	20%
Percent from fossil fuels: (N_p+N_f)/U	50%	60%
Percent from Indirect Sources (I_G+I_S)/U	65%	57%
Percent from Direct Sources (D_I + D_f)/U	35%	43%

Note that in calculating the new emergy indices, the solar emergy value of the ethanol yielded from the system (Y_{eth} = 9267 giga-sej per gallon) was the available energy of ethanol (84.2 megajoules per gallon, USDOE, 2006) multiplied by the solar transformity of petroleum products (110,000 sej/joule, Odum, 1996). Under the baseline scenario, the total solar emergy required to produce a gallon was slightly less than emergy value of ethanol (9267) at 8915 giga-sej per gallon.

Baseline Scenario

Is switchgrass-to-ethanol a primary energy source? Considering a primary source of energy as one that is capable of producing extensively more energy than what is required to make it, then the 1.04 ratio of ethanol yield to emergy used (Table 9) under the Optimistic Baseline Scenario indicated that switchgrass ethanol was not a primary source of energy and can not compete with present primary sources of energy.

Can switchgrass-to-ethanol replace petroleum? The switchgrass to ethanol process produced 4.2 gallons of ethanol for each gallon of petroleum used (Y_{eth} / N_p). However, once a credit was made against the ethanol yield to account for the petroleum required in processing, the net yield of ethanol was 3.2 units of liquid fuel emergy per each unit of petroleum fuel emergy used. Both of these indices suggested that there was more liquid fuel produced than consumed.

How much of the ethanol net liquid energy was available for use by other sector of the economy? Here the argument was extended to include the energy that would be required for the distribution of ethanol to its end-markets, something that was not part of this analysis. Since most ethanol refineries are currently located in the Midwest, ethanol will need to be transported to markets throughout the U.S. A study on ethanol transportation showed that transportation by truck is limited by cost to about 300 miles with an average delivery capacity of 8000 gallons (Reynolds, 2000). Moreover, ethanol has lower energy density than petroleum fuels like gasoline and diesel (e.g., denatured ethanol has 38.3 MJ (36,300 Btu) less per gallon than gasoline). Therefore, replacing gasoline in the transportation sector with a lower energy density fuel like ethanol lowers the automobile fuel mileage (National Ethanol Vehicle Coalition, 2006). Studies to date have shown that E85 mixtures (85% ethanol and 15% gasoline), achieve from 5% to 15% lower fuel economy than when operated with pure gasoline (National Ethanol Vehicle Coalition, 2006).

These two factors are important to determine the total amount of crop-ethanol that can ultimately be available to replace petroleum. Assuming truck transportation for 300 mile radius, this represented an additional input of 1340 giga-sej/gallon beyond the emergy of switchgrass-ethanol estimated in this analysis. Moreover, the 15% less fuel economy meant that cars required more ethanol by volume to substitute for gasoline. Combining these two factors showed that only 4852 giga-sej/gallon of the net liquid at the plant door (7048 giga-sej/gallon, Table 9) were available for vehicle consumption. In other words, less than one gallon in of ethanol in emergy equivalent (4852/9267, Table 9) was available for automobile consumption.

What was the net yield of ethanol if petroleum was completely substituted during production? By completely eliminating the petroleum (N_p) input from calculations, the net yield of liquid per unit of total input assuming that petroleum (N_p) required in the production was derived from the ethanol production system was calculated. The Net

Liquid Yield Ratio (Table 9) indicated that there was 5% more liquid emergy produced (i.e., ethanol) than total emergy consumed to make it.

How much fossil fuel was used in the production of ethanol? Now if one considered the net output of liquid fuel in terms of total fossil fuel energy used $[Y_{eth}/(N_f+N_p)]$, switchgrass-to-ethanol provided a gain of 2.07 solar emergy joules of liquid fuel for each solar emergy joule of fossil energy used under the Optimistic Baseline Scenario assumptions, indicating that it could be a competitive process for converting fossil fuels into ethanol. The liquid yield per non-petroleum emergy (N_f) used was 4.2. However, if some of the ethanol yield were returned to the complete chain of processes in place of gasoline, diesel and other petroleum products, then the net liquid yield per non-petroleum emergy used was reduced to 3.11 (Table 9). In other words, the process yielded 3.11 units of liquid fuel per unit of coal and natural gas used. These 3.11 gallons were available for use in other sectors of the economy, suggesting that it may be a competitive process for generating liquid fuel from solid and gaseous sources, under the Optimistic Baseline Scenario. However, it also highlighted the fact that fossil fuel inputs (N_f) were critical to producing ethanol from switchgrass, and confirmed that the process is a technical conversion of non-liquid fossil fuel to liquid fuel.

Is switchgrass-to-ethanol a 'renewable' source of liquid energy? Defining a 'renewable' energy source as one that relied highly on sources of energy that were replaced within human lifetimes (~80 yr), then producing ethanol from a feedstock of switchgrass was not 'renewable' because only 23% of the total emergy consumption was derived from renewable sources, and about half (50%) came from fossil fuels (Table 9). In other words, over three-fourths of the energy used to make ethanol from cellulose came from non-renewable resources (Table 9). The heavy reliance on fossil fuels indicated that switchgrass-to-ethanol was not a ‘renewable’ source of energy as often touted by analysts, politicians and the popular press, but rather it was a process for converting solid and gaseous fossil fuels (i.e., coal and natural gas) into liquid fuel, which agreed with the view espoused by Graboski (2002) and Farrell et al. (2006).

What is the significance of indirect inputs? Indirect sources of emergy made up 65% of total inputs, while direct inputs accounted for 35% under the Optimistic Baseline Scenario (Table 9). First, this indicated that energy embodied in indirect sources was more important than direct inputs. Secondly, it indicated that energy accounting methods that exclude or partially account for the energy embodied in indirect goods, capital and services miss the vast majority of energy required to produce ethanol from biomass, and likely would lead to faulty decisions regarding the viability of ‘biofuels’.

How much of each input was required to make enough ethanol to drive a mid-size vehicle an average 15,000 miles per year based on the Baseline Optimistic Scenario. Here it was assumed that a car travels 15,000 miles per year (American Public Transportation Association, 2005). It was also assumed that a mid-size car has an energy efficiency of 24 miles per gallon (mpg), based on average of highway (27 mpg) and city (21 mpg) driving (USEPA, 1999). The amount of gasoline required per year was calculated to be 625 gallons; however, since ethanol has about 35% lower energy per volume content than gasoline, the ultimate amount of ethanol required to replace the use of gasoline in a mid-size car for one year would be 972 gallons of ethanol gasoline equivalent. Table 10 presents a summary of the major categories of inputs required to supply annual demand of ethanol for a mid-size car in America.

Table 10: Summary of major inputs required to produce 972 gallon of ethanol from switchgrass under Baseline Optimistic Scenario

Input Resource	**Unit**	**Amount Required per 972 gallons of ethanol (A)**	**Amount to substitute 10% gasoline US demand (B)**
Water	gallons	3,373,372	6.68E+13
Top Soil	lbs	84,760	1.68E+12
Land	acres	4	7.69E+07
Nitrogen (NH3)	lbs	388	7.69E+09
Phosphate (P2O5)	lbs	308	6.11E+09
Potash (K2O5)	lbs	41	8.06E+08
Lime	lbs	1411	2.79E+10
Herbicides	lbs	11	2.10E+08
Electricity On-site	kWh	2820	5.58E+10
Direct			
Petroleum-based fuels	gal	73	1.44E+09
Non-Petroleum Fossil	ft^3	104	2.06E+09
Indirect			
Petroleum-based fuels	gal	77	1.52E+09
Non-Petroleum Fossil	ft^3	18,689	3.70E+11
Direct			
Costs	$	1979	3.92E+10
Direct + Indirect			
Emdollar-costs	$	7814	1.55E+11

To produce enough ethanol to supply a mid-size car its average annual demand of 625 gallons of petroleum-fuel with 972 gallons of ethanol, required more than 3.3 million gallons of water consumed in plant transpiration. This is equal to the amount of water used by 124 single family homes annually (American Water Works Association, 2006). The soil lost was 84,760 lbs. The amount of fertilizer required was 388 lbs of nitrogen, 308 lbs of phosphate, 41 lbs of potassium, and 1411 lbs of lime. The total petroleum-based fuel required directly was 73 gallons, while the indirect consumption of petroleum-based products was 77 gallons. The total direct input of the non-petroleum fuels was 104 cubic feet of natural gas equivalent, while the indirect consumption was 18, 689 cubic feet of natural gas equivalent.

The analysis was extended to assess the input requirements to replace 10% of US annual gasoline demand with switchgrass-ethanol. Table 10 column B summarizes the major categories of inputs required to supply 10% of US gasoline demand with 19 billion gallons of ethanol energy equivalent (EIA, 2004b) under the Optimistic Baseline Case Scenario. The amount of land needed to produce 10% of the nation's liquid from switchgrass-ethanol was 77 million acres, which is equivalent to 9% of US cropland. If 100% of gasoline consumption was replaced with switchgrass-ethanol, then the nation would need to divert 770 million acres from current use to switchgrass production.

In addition, the agricultural production of switchgrass to supply the 10% US gasoline demand with ethanol required a higher use of agricultural commercial fertilizers relative to fertilizer used in crop production in 2003 (USDA, 2006e). For example, nitrogen consumption in 2003 was estimated at 26 billion pounds, while producing enough switchgrass to replace 10% of gasoline demand required 7.6 billion pounds of nitrogen or about 25% of the nitrogen used by all crops in 2003.

Sensitivity to Input Prices, Conversion Efficiencies and In-house Electricity Production

The emergy analysis of the Optimistic Baseline Scenario (Table 9) used input prices from the year 2000. As is clear to many, prices for many of these inputs rose sharply by 2006. For example, the national average cost of diesel nearly doubled from $1.40 per gallon in 2001 to $2.56 per gallon in early 2006 (EIA, 2006c), and the U.S. Agricultural Department estimated that fertilizer prices increased by 12% in a single year between 2005 and 2006 because of higher prices for natural gas, electricity and transport (USDA, 2006e). In addition to determining how sensitive switchgrass-ethanol was to price changes and since hurdles for the commercial scale production of lignocellulose ethanol still remain (Iogen, 2006), the sensitivity to technical assumptions concerning cellulose-to-ethanol conversion yields and internal recycling of lignin for electricity generation was also evaluated. The available enzymatic conversion yields for enzymatic hydrolysis and fermentation to ethanol were values determined from lab scale studies, which may be overly optimistic for larger scale commercial applications. Therefore, the analysis on the sensitivity of ethanol production to these types of economic and technical factors was performed by modifying the Optimistic Base Case Scenario to 1) reflect early 2006 prices for fertilizers and fuels and other inputs, 2) represent a less efficient yield for the enzymatic conversion of cellulose/hemicellulose to ethanol (i.e., 51% rather than 85%) and 3) replace on-site electricity production from recycled lignin waste with purchased electricity (included in Appendix B). Results for this Conservative Scenario are shown in Table 9 and Figure 20.

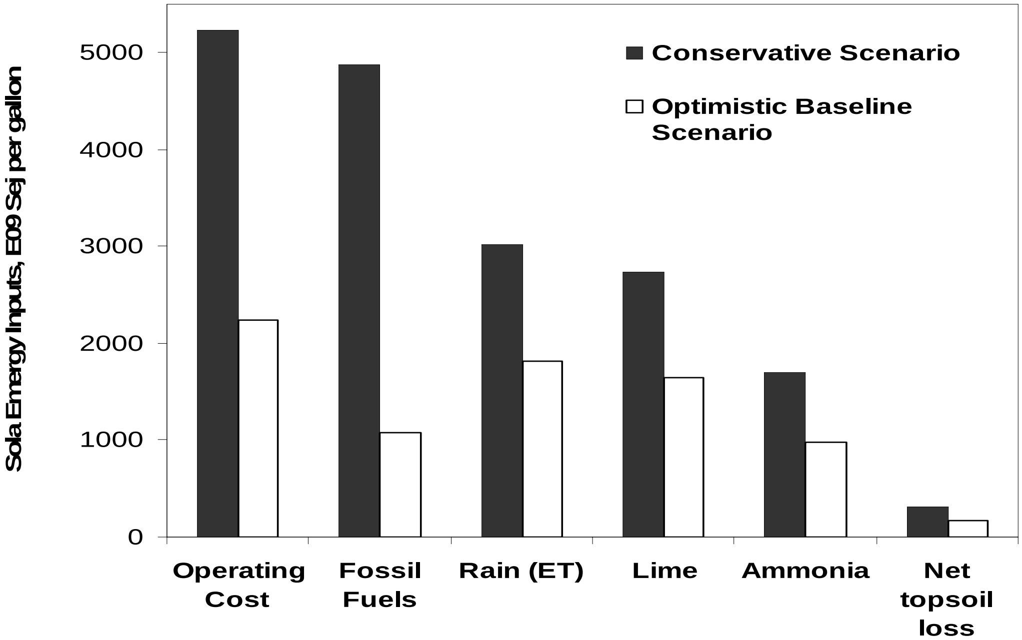

Figure 20. Comparison of direct major inputs to switchgrass ethanol production for Baseline optimistic scenario and a Conservative scenario that reflects early 2006 prices, less efficient enzymatic conversion of cellulose/hemicellulose to ethanol and purchased electricity.

Figure 20 compares the major inputs for the Baseline Optimistic and the Conservative Scenarios. The operating costs more than doubled when the cost of gasoline and fertilizers were updated to 2006 prices and electricity cost was added. Lowering the enzymatic conversion rate of crop switchgrass to ethanol from 85% to 51% meant reducing the output of ethanol by 60% (to 41.6 million gallons) when using the same amount of switchgrass as in the Baseline Optimistic Scenario. As a result on a per gallon basis, the fossil fuel inputs increased from 1081 to 4872 giga-sej per gallon (Fig. 20). The solar emergy from water in rain nearly doubled from 1810 to 3015 sej per gallon; lime and ammonia consumption in a per gallon basis also increased by more than 50%. The comparison indicated that the energy embodied in crop-ethanol is highly sensitive to technical assumptions and the cost of inputs.

Figure 21 compares the differences in input requirements between the two scenarios according to partitioned categories. Like in the Baseline Scenario, the largest source of solar emergy to the switchgrass-to-ethanol production system was from non-petroleum fossil fuel (N_f) (Fig. 21). However, the value of N_f more than tripled to 7923 giga-sej per gallon. This increase was primarily the result of eliminating onsite electricity production and purchasing coal-generated electricity from the grid.

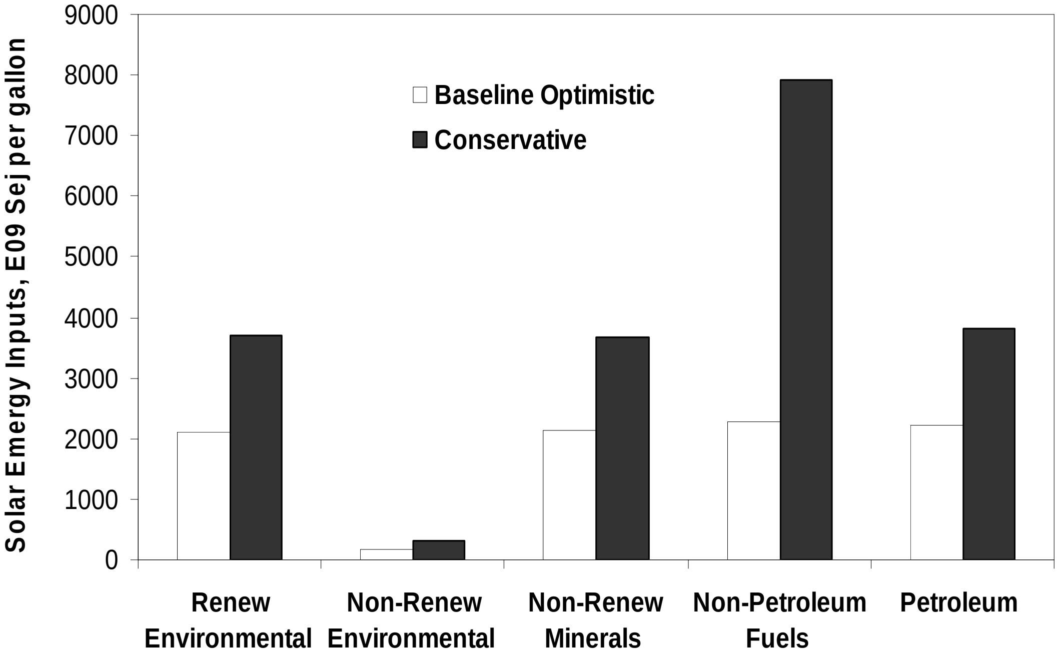

Figure 21. Comparison between the Baseline Optimistic and Conservative scenarios for switchgrass-ethanol according to the partitioned categories for the ultimate sources of solar emergy.

In Figure 22, a summary of emergy flows partitioned according their 'route' (i.e., direct or indirect) through the ecological-economic system to the production system for both the Baseline Optimistic and Conservative scenarios is presented. Direct inputs more than double from 3087 in the Baseline Optimistic to 8194 giga-sej per gallon for the Conservative Scenario. Indirect inputs increased from 5829 in the Baseline Optimistic to 11233 giga-sej per gallon for the Conservative Scenario. This increase can be attributed to expenses related to purchasing electricity as well as from paying more for fuels, fertilizer and herbicides (Fig. 22).

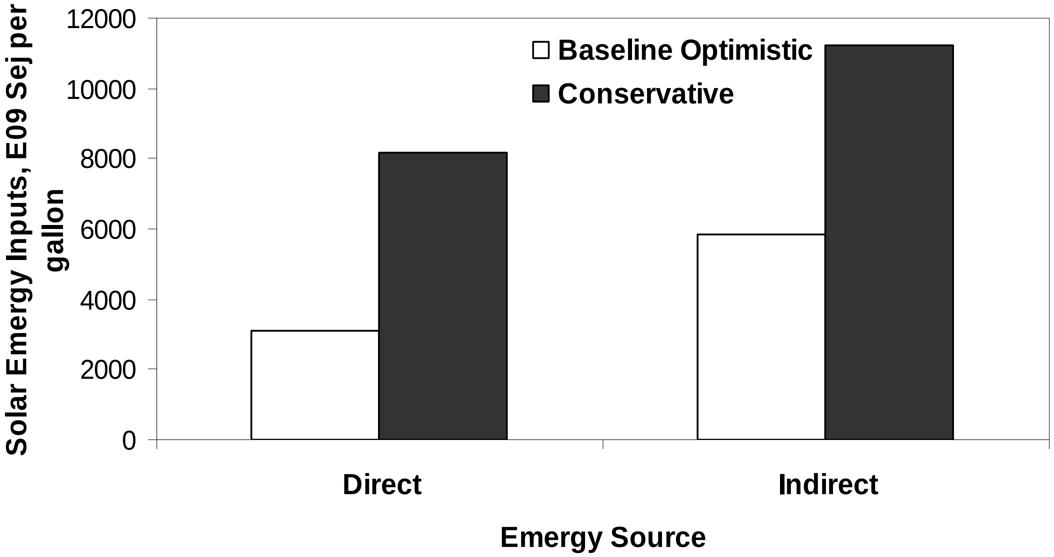

Figure 22. Comparison between the Baseline Optimistic and Conservative scenarios for switchgrass-ethanol according to whether the path of an input was direct or indirect.

How important was on-site electricity production? Under the baseline scenario, it was assumed that the recycling of by-products was highly efficient and led to an excess generation of electricity which was assumed sold to the electric power grid. This was credited in the emergy accounting. The on-site production of electricity from the use of recycled lignin meant that less coal and natural gas were needed as direct inputs (D_f) than if the electricity was purchased. In the baseline scenario, lignin, a solid waste from the process, and captured methane from on-site wastewater treatment were used to fuel a boiler to produce steam. Consequently, the excess steam produced by the boiler was used to co-generate electricity. The electricity generated on-site was used to power the switchgrass-to-ethanol processing and excess electricity sold to the grid. Once the on-site electricity production was eliminated under the Conservative Scenario, the use of coal-generated electricity was the major factor that increased direct energy consumption from

3087 to 8194 giga-sej per gallon (Fig. 22), indicating that on-site electricity production was critical if switchgrass-ethanol was to have a positive net emergy yield.

Sensitivity of Refined Emergy Indices

The refined emergy indices for the Conservative Scenario are given along side the Optimistic Scenario in Table 9. Overall, the total amount of solar emergy used to make ethanol increased from 8,915 giga-sej per gallon in the Baseline Optimistic Scenario to 19,427 giga-sej per gallon under the conservative assumptions (Table 9).

The new indicators showed that under the Conservative Scenario the ratio of liquid produced to total emergy used declined from 1.04 to 0.48 (Table 9), indicating that the production of switchgrass-ethanol ultimately consumed more emergy than it produced. The ratio of liquid energy produced per input of fossil fuel emergy decreased from 2.09 to 0.79, suggesting that the switchgrass-ethanol production process required more fossil fuel energy than it provided. Similarly, the higher input prices and conservative technical assumptions lowered the expected amount of liquid fuel produced per emergy input of petroleum from 4.2 to 2.4 (Table 9). In addition, the Net Liquid Yield Ratio dropped from 1.05 to 0.35 and the yield ratio of net liquid to non-petroleum fossil inputs decreased from 3.11 to 0.70, indicating that on the whole the process used more solid and gaseous fossil fuels than liquid energy produced. Under the Conservative Scenario the fraction of the ethanol derived from renewable sources decreased to a meager 19%, highlighting the fact that it was not a renewable fuel (Table 9). Rather, since 81% of the input requirements were from non-renewable sources (Table 9), switchgrass-ethanol was also a non-renewable resource.

Hybrid Poplar

The first step in the hybrid poplar-ethanol analysis involved the quantification of standing above-grown biomass grown on trenched biosolids at a hybrid poplar plantation. These measurements were used in the emergy evaluation as estimate of biomass production. Therefore, hybrid poplar results were divided into two parts, the first part presents the productivity estimates and the second gives the emergy analysis of producing ethanol from hybrid-poplar.

Analysis on Hybrid Poplar Biomass Productivity

After six years of growth on trenched biosolids the hybrid poplar plantation appeared healthy with a developing canopy and full understory (Figure 23).

Figure 23. Hybrid poplar standing biomass after six years of growth on trenched municipal biosolids.

As shown in Table 11 the mean tree dry weight increased with stand age, except for the 2001 planting, which suffered from heavy deer grazing and drought conditions during its first year of growth. Mean tree height and DBH also increased with stand age, with the 2001 planting again the exception. After six years of growth, trees weighed an average of 20.5 kg, were 974 cm tall and had diameters of 11.7 cm (Table 11).

Table 11: Weight, height and diameter of hybrid poplar trees grown on trenched municipal biosolids in Maryland (USA).(SD – standard deviation)

Year of	Age	Dry Weight (kg)		Height (cm)		DBH (cm)		Moisture Content (%)		Samples
Planting	Years	Mean	SD	Mean	SD	Mean	SD	Mean	SD	n
2003	2	0.3	0.2	225	47	1.3	0.7	104	6	4
2002	3	4.6	4.5	494	188	5.0	2.7	116	8	10
2001	4	3.0	1.9	442	106	4.2	1.5	114	8	9
2000	5	14.9	6.7	844	91	9.5	2.5	117	5	5
1999	6	20.5	2.9	974	66	11.7	1.0	125	5	5

Allometric Models

Field inventory of the wood biomass of a hybrid poplar plantation, such as the one studied here, requires allometric models that are precise with easy to measure field variables. In this study the efficacy of models that were based either on tree height or DBH were tested. Diameter at breast height (r^2=0.974, P<0.01) and height (r^2=0.932, P<0.01) were strongly predictive of above ground tree biomass (Figure 24).

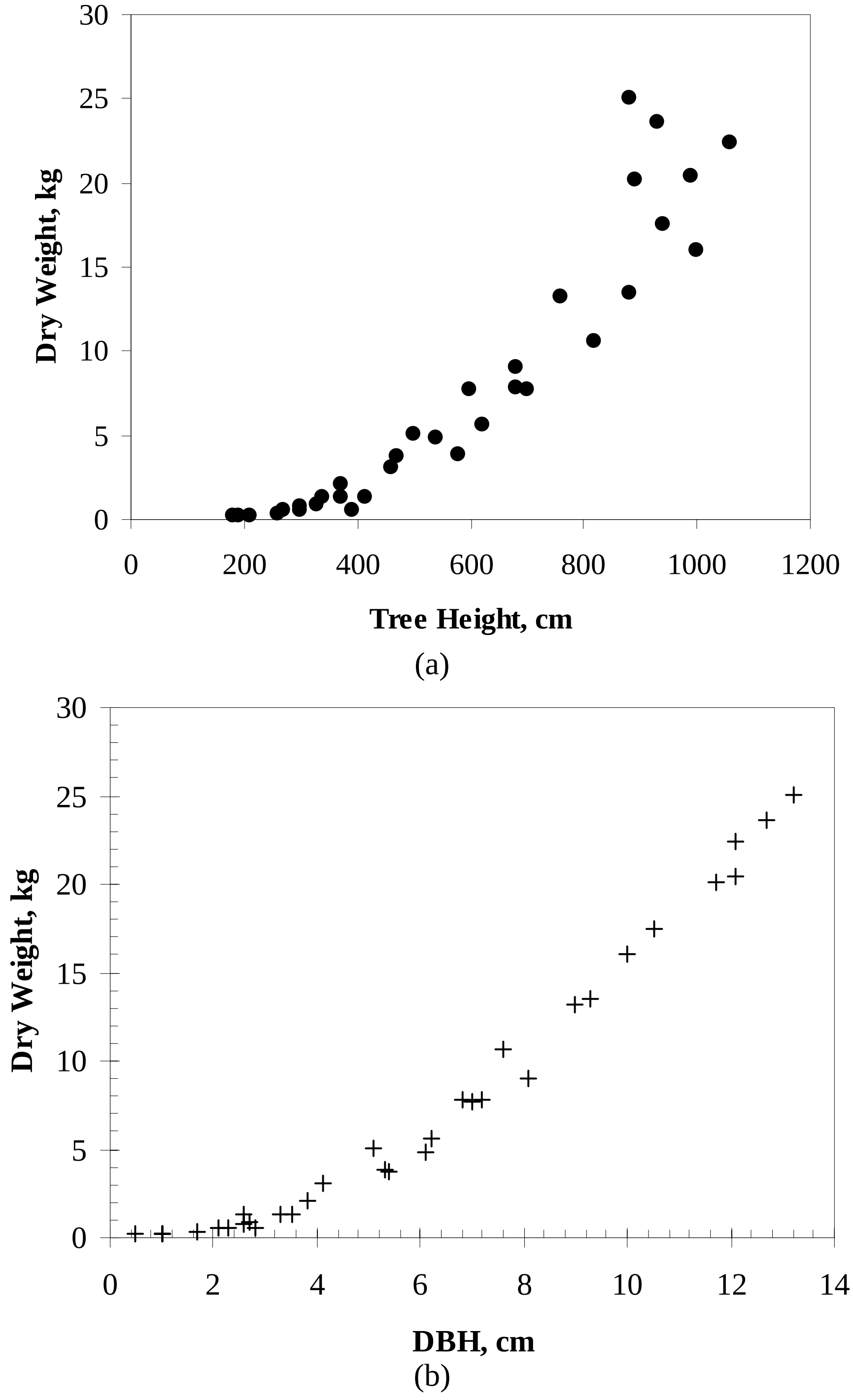

Figure 24. Dry weight of hybrid poplar trees as a function of (a) tree height and (b) diameter at breast height (DBH) during their first six years of growth on trenched municipal biosolids near Washington, D.C.

From the regression analysis it was found that tree height (HT) to be a strong estimator of above ground tree biomass (WB_{tree}) using Equation 3.1:

$$WB_{tree} = 0.0274 * HT - 8.1 \quad (3.1)$$

Where WB_{tree} was in kg and HT was tree height in cm.

Also, Equation 3.2 estimated WB_{tree} as a function of DBH:

$$WB_{tree} = 2.0 * DBH - 4.64 \quad (3.2)$$

Where DBH was diameter at breast height in cm.

The relationship between tree biomass and DBH was not quite linear because of an apparent inflection point at a DBH of 4 cm (Figure 24). To improve the precision of the DBH allometric model, the data was divided into two sets based on whether DBH was greater or less than 4 cm. This division resulted in different model coefficients for the two data sets as shown in Equations 3.3 and 3.4.

$$WB_{tree} = 2.6 * DBH - 9.64 \quad (3.3)$$

When DBH was greater than 4 cm

$$WB_{tree} = 0.5 * DBH - 0.35 \quad (3.4)$$

When DBH was less than 4 cm

Equation 3.3 provided slightly better predictability of tree biomass (r^2=0.98; P<0.001) than Eq. 3.2. If a plantation owner were more interested in estimating the biomass of large rather than small trees, then Eq. 3.3 would be more appropriate than Eq. 3.2 and it would provide a slightly better estimate. Equation 3.4, on the other hand, did not offer as much precision (r^2=0.78; P<0.001) as Eq. 3.2, and it would not be of use for estimating the biomass of large trees.

While it was tempting to build an allometric model that combined DBH and height to estimate tree biomass, strong correlation between these two metrics (r^2= 0.970, P<0.01) indicated they were not independent of each other. Combining these types of collinear variables in a regression model typically overestimates fitness and builds an unstable model.

Net Wood Productivity

To estimate the net wood productivity of the hybrid poplar plantation, three types of curves (i.e., linear, exponential and power) were evaluated to see how well they fit the plot of standing tree biomass as a function of age (Figure 25). As explained above, the 2001-age class had less standing wood than the 2002-age class due to a summer drought and heavy deer grazing during its planting year. Since there were only five years of data, this single year strongly influenced the regression analysis.

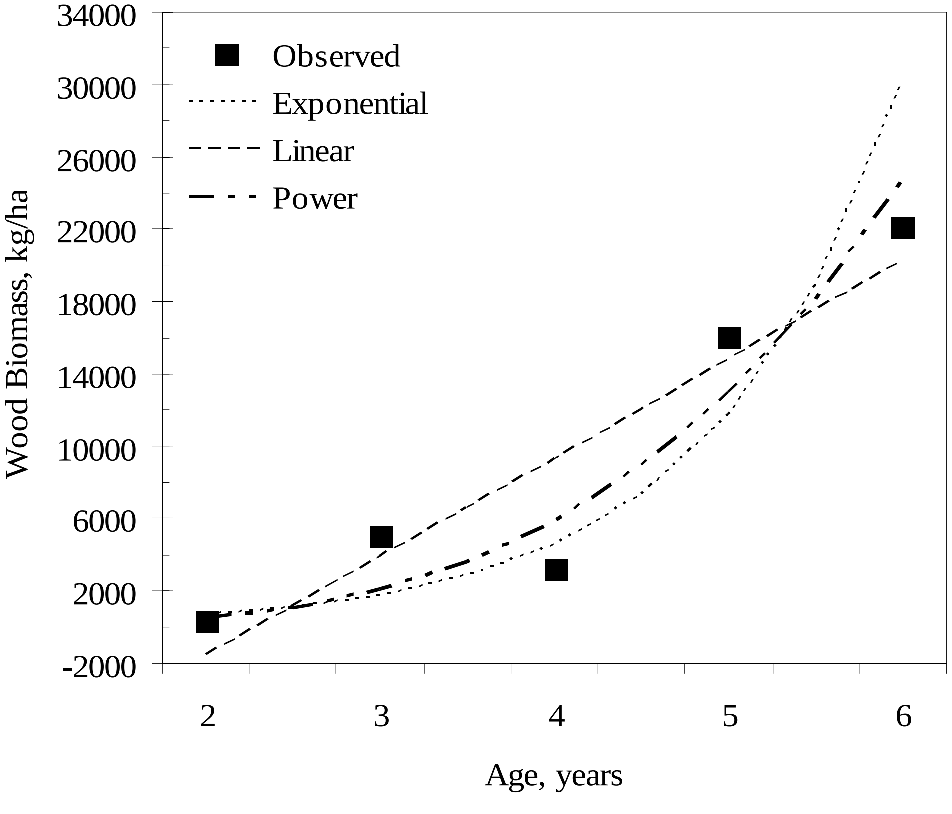

Figure 25. Standing wood biomass of hybrid poplar grown on trenched municipal biosolids for stand ages from 2 to 6 years with exponential, linear and power models fitted to observed data.

When the 2001-age class was included the in the regression analysis, all three models explained more than 83% of the variation in stand wood biomass (all $P<0.05$). When the 2001-age class was excluded from the regression, the linear model was much superior ($r^2=0.998$; $P<0.001$) to the exponential ($r^2=0.84$; not significant) and power ($r^2=0.922$; $P<0.05$) models. In addition, the estimate of net wood productivity taken as the slope of the linear model (Figure 25) was 5450 kg/ha/y whether the 2001-age class was included or excluded in the regression. Only the y-intercept and coefficient of determination were changed.

Hybrid Poplar to Ethanol

Table 12 line item 18 "Scenario 1," shows the total emergy used in 6-year rotational crop production of hybrid poplar grown using municipal biosolids, excluding the emergy from biosolids. As mentioned above, Scenario 1 assumed the forest is grown without the biosolids. Thus, Scenario 1 did not include the emergy from biosolids. The total emergy required to produce a crop of hybrid poplar biomass with "free biosolids" that could be used to generate one gallon of ethanol amounted to 12,794 giga-sej per gallon (line item 18, Table 12). The single largest input came from labor. The largest environmental renewable resource used was water for evapotranspiration.

Alternatively, Scenario 2, as explained above, assumed that the energy embodied in municipal biosolids were necessary for wood production and therefore must be accounted for in the environmental accounting analysis. In this case, the total emergy used in a 6-year rotational crop production of hybrid poplar (line item 19, Table 12) amounted to 575,909 giga-sej per gallon (line item 19, Table 12), which was over an order of magnitude greater than under Scenario 1. In Scenario 2, the single largest input came from emergy in municipal biosolids, totaling 96% of the total emergy required to produce 1 gallon of ethanol using hybrid poplar biomass. Other important inputs included labor services and gasoline.

Scenario 3 assumed that the only emergy contributed by the biosolids was from its nutrient additions (i.e., nitrogen, phosphorous and water). The total emergy used in a 6-year rotational crop production of hybrid poplar in Scenario 3 was calculated to be 39,179 giga-sej per gallon (line item 20, Table 12), which was slightly more than Scenario 1, but vastly less than Scenario 2. In Scenario 3, the single largest emergy input came from lime closely fallowed by phosphorous and nitrogen.

The emergy analysis for the transportation of the biomass crop to the ethanol processing facility is given in Table 13**.** The emergy contributed from steel embodied in manufacturing of truck was estimated to be 8 giga-sej/gallon and fuel for transportation contributed 218 giga-sej per gallon. Emergy from services contributed 63 giga-sej per gallon from labor and 24 giga-sej per gallon from fuel. In Table 13, the total emergy required in the transport of hybrid poplar from the field to ethanol processing plant to generate one gallon of ethanol was 314 giga-sej. The solar emergy of diesel fuel was the largest portion of the transportation requirement.

Table 14 contains the estimated amount of emergy required to convert hybrid poplar grown with trenched municipal biosolids into ethanol for each of the Scenarios that were considered in this study. Line items 1, 2, 3 (Table 14) show the emergy associated with the hybrid poplar feedstock for Scenarios 1, 2 and 3, respectively. The emergy associated with transportation of biomass feedstock to the ethanol plant was also included (line items 17 and 29). The total emergy required to produce 1 gallon of ethanol under each of the scenarios are summarized in lines 30, 31 and 32 (Table 14). The conversion of hybrid poplar biomass to ethanol under Scenario 1 (excluding the emergy in biosolids) required 17,187 giga-sej per gallon of ethanol produced (line item 30 Table 14). The conversion of hybrid poplar biomass to ethanol under Scenario 2, including the emergy in biosolids, required 580,301 giga-sej per gallon of ethanol produced (line item 32, Table 14). The conversion of hybrid poplar biomass to ethanol under Scenario 3 required 43,572 giga-sej per gallon of ethanol produced (line item 33, Table 14). After the hybrid poplar biomass, the two largest inputs for all scenarios came from gasoline and operating costs. Lime and ammonia were also large inputs to the conversion process.

Table 12: Solar emergy required for crop production of hybrid poplar using municipal biosolids for 6-year rotation (per gallon of ethanol)

Index	Item	Input (A)	Unit	Solar Emergy per Unit (B)	Env Fraction R&N_o (C)	Env Emergy E09 sej/gallon (D)	Mineral Fraction N_m (E)	Mineral Emergy E09 sej/gallon (F)	Coal & Nat. gas Fraction N_f (G)	Coal & Nat. gas Emergy E09 sej/gallon (H)	Petroleum Fraction N_p (I)	Petroleum Emergy E09 sej/gallon (J)	Sum of all Emergy E09 sej/gallon K=D+F+H+J
Nature Contribution (I)													
Free Renewable Inputs (R)													
1	Sun		J	1	1	104	0	0	0	0	0	0	104
2	Water, rain		J	30576	30576	4051	0	0	0	0	0	0	4051
3	Evapotranspiration		J	30576	30576	2995	0	0	0	0	0	0	2995
Free Non-renewable (N)													
4	Net topsoil loss		J	73800	73800	61	0	0	0	0	0	0	61
Purchased (F)													
Feedback from economy Resources (M)													
5	Biosolid		g	3.41E+09	3.4E+08	56311	5.1E+08	84467	1.70E+09	281557	8.5E+08	140779	563114
6	Nitrogen (N)		g	2.87E+09	0.0E+00	0	0.0E+00	0	2.87E+09	5458	0.0E+00	0	5458
7	Phosphorous (P)		g	6.55E+09	0.0E+00	0	1.7E+09	2334	4.56E+09	6333	3.1E+08	432	9098
8	Water-Irrigated		J	2.79E+05	2.23E+05	139	0	0	5.58E+04	35	0	0	173
9	Lime		g	1.73E+09	9.8E+06	66	1.7E+09	11318	2.06E+07	139	2.0E+07	132	11655
10	Machinery		g	1.30E+10	0	0	1.68E+09	10	9.55E+09	55	1.77E+09	10	75
11	Diesel		J	1.11E+05	0	0	0	0	0	0	1.11E+05	1069	1069
12	Gasoline		J	1.11E+05	0	0	0	0	0	0	1.11E+05	302	302
13	Electricity		J	3.36E+05	0	0	0	0	3.36E+05	23	0	0	23
Feedback from economy in Services (S)													
14	Utilities	0.01	$	1.10E+12	1.32E+11	0	9.90E+10	0	4.51E+11	0	4.18E+11	0	0
15	Labor	7	$	1.10E+12	1.32E+11	1	9.90E+10	1	4.51E+11	5	4.18E+11	4	11
16	Fuels	0.15	$	1.10E+12	1.32E+11	926	9.90E+10	695	4.51E+11	3165	4.18E+11	2934	7720
17	Operational cost	0.34	$	1.10E+12	1.32E+11	19	9.90E+10	14	4.51E+11	66	4.18E+11	61	160
18	**Total Emergy Scenario 1 (excluding lines 5,6,7, 8 and 9)**												**12794**
19	**Total Emergy Scenario 2 (excluding lines 6,7, 8 and 9)**												**575909**
20	**Total Emergy Scenario 3 (excluding line 5)**												**39179**
21	Yield biomass	9.54E+03	g										
22	Energy biomass	1.84E+08	J										
	Emergy/mass												
23	Scenario 1 (sej/g)			1.34E+09									
24	Scenario 2 (sej/g)			6.04E+10									
25	Scenario 3 (sej/g)			4.11E+09									

Table 12: Continued.

	Transformity	
26	Scenario 1 (sej/J)	6.95E+04
27	Scenario 2 (sej/J)	3.13E+06
28	Scenario 3 (sej/J)	2.1E+05

Lines items 1 and 2. Excluded from Total (line items 18, 19, 20) to avoid double counting

Table 13: Solar emergy required to transport hybrid poplar from field to ethanol processing plant (per gallon of ethanol)

Index	Item	Input (A)	Unit	Solar Emergy per Unit (B)	Env Fraction R&N_o (C)	Env. Emergy E09 sej/gallon (D)	Mineral Fraction N_o (E)	Mineral Emergy E09 sej/gallon (F)	Coal & Nat. gas Fraction N_f (G)	Coal & Nat. gas Emergy E09 sej/gallon (H)	Petroleum Fraction N_p (I)	Petroleum Emergy E09 sej/gallon (J)	Emergy E09 sej/gallon K=D+F+H+J
Purchased (F)													
Feedback from economy Resources (M)													
1	Machinery	0.62	g	1.30E+10	0	0	1.68E+09	1	9.55E+09	6	1.77E+09	1	8
2	Diesel	1.97E+06	J	1.1E+05	0	0	0	0	0	0	1.1E+05	218	218
Feedback from economy in Services (S)													
3	labor	0.058	$	1.10E+12	1.32E+11	8	9.90E+10	6	4.51E+11	26	4.18E+11	24	63
4	Fuels	0.022	$	1.10E+12	1.32E+11	3	9.9E+10	2	4.51E+11	10	4.18E+11	9	24
5	**Total Emergy**												**314**

Table 14: Solar emergy required to produce ethanol from hybrid poplar biomass grown with municipal biosolid based on 2000 data (per gallon of ethanol)

#	Item	Input (A)	Unit	Solar Emergy per Unit (B)	Env Fraction R&N_o (C)	Env. Emergy E09 sej/gallon (D)	Mineral Fraction N_m (E)	Mineral Emergy E09 sej/gallon (F)	Coal & Nat. gas Fraction N_f (G)	Coal & Nat. Gas Emergy E09 sej/gallon (H)	Petroleum Fraction N_p (I)	Petroleum Emergy E09 sej/gallon (J)	Emergy E09 sej/gallon K=D+F+H+J
Biomass Input													
1	Scenario 1	9542	g	1.34E+09	4.24E+08	4048	7.90E+07	754	3.63E+08	3468	4.74E+08	4524	12794
2	Scenario 2	9542	g	6.04E+10	6.33E+09	60360	8.93E+09	85221	2.99E+10	285025	1.52E+10	145302	575909
3	Scenario 3	9542	g	4.11E+09	4.46E+08	4253	1.51E+09	14406	1.62E+09	15433	5.33E+08	5087	39179
Purchased (F)													
Feedback from economy Resources (M)													
4	lime	291	g	1.73E+09	9.80E+06	3	1.68E+09	488	2.06E+07	6	1.96E+07	6	503
5	Ammonia	159	g	2.87E+09	0	0	0	0	2.87E+09	455	0	0	455
6	Corn Steep Liquor	2269	J	5.54E+05	1.55E+05	0	4.99E+04	0	2.05E+05	0	1.44E+05	0	1
7	Nutrients	354	J	1.94E+04	7.37E+03	0	1.75E+03	0	4.85E+03	0	5.43E+03	0	0
8	Antifoam	207	J	5.54E+05	1.55E+05	0	4.99E+04	0	2.05E+05	0	1.44E+05	0	0.11
9	Amm.Sulfate	19	g	2.87E+09	0.00E+00	0	0.00E+00	0	2.87E+09	55	0.00E+00	0	55
10	BFW chemicals	11	g	9.86E+09	0	0	1.68E+09	18	4.83E+09	52	3.35E+09	36	107
11	Equipment	1.2	g	1.30E+10	0	0	1.68E+09	2	9.55E+09	11	1.77E+09	2	15
12	Buildings	2.65	g	6.97E+09	0	0	1.68E+09	4	9.53E+08	3	4.34E+09	11	18
13	Cement	32	g	3.33E+09	0	0	1.68E+09	53	1.56E+09	49	8.23E+07	3	105
14	Water make up	9.6E+04	J	3.14E+05	8.48E+04	8	1.29E+05	12	8.17E+04	8	1.88E+04	2	30
15	Gasoline	6.54E+06	J	1.11E+05	0	0	0	0	0		1.11E+05	726	726
16	Propane	9.82E+04	J	1.11E+05	0	0	0	0	1.11E+05	11	0	0	11
17	*Transportation Emergy From TABLE 13*				*0*	*0*	*0*	*1*		*6*		*213*	226
Feedback from economy in Services (S)													
18	Sulfuric Acid	0.011	$	1.10E+12	1.32E+11	1	9.90E+10	1	4.51E+11	5	4.18E+11	5	12
19	Lime	0.02	$	1.10E+12	1.32E+11	3	9.90E+10	2	4.51E+11	10	4.18E+11	9	25
20	Ammonia	0.04	$	1.10E+12	1.32E+11	6	9.90E+10	4	4.51E+11	19	4.18E+11	18	47
21	Corn Steep Liquor	0.03	$	1.10E+12	1.32E+11	4	9.90E+10	3	4.51E+11	13	4.18E+11	12	31
22	Nutrients	0.008	$	1.10E+12	1.32E+11	1	9.90E+10	1	4.51E+11	4	4.18E+11	3	9
23	Antifoam	0.02	$	1.10E+12	1.32E+11	3	9.90E+10	2	4.51E+11	9	4.18E+11	8	22
24	Amm. Sulfate	0.003	$	1.10E+12	1.32E+11	0	9.90E+10	0	4.51E+11	1	4.18E+11	1	3
25	Water	0.006	$	1.10E+12	1.32E+11	1	9.90E+10	1	4.51E+11	3	4.18E+11	2	6
26	Gasoline	0.05	$	1.10E+12	1.32E+11	7	9.90E+10	5	4.51E+11	23	4.18E+11	21	55
27	Propane	0.000010	$	1.10E+12	1.32E+11	0	9.90E+10	0	4.51E+11	0	4.18E+11	0	0

Table 14. Continued.

28	Operating cost	0.74	$	1.10E+12	1.32E+11	98	9.90E+10	73	4.51E+11	335	4.18E+11	310	816
29	*Transportation Emergy From TABLE 13*				*1.32E+11*	*10*	*9.90E+10*	*8*	*4.51E+11*	*36*	*4.18E+11*	*33*	*87*
	Total Emergy												
30	**Scenario 1**												**17,187**
31	**Scenario 2**												**580,301**
32	**Scenario 3**												**43,572**
33	Yield Ethanol mass			2707	g								
34	Energy Ethanol			8.02E+07	J								
35	Emergy/mass Scenario 1 (sej/g)				6.35E+09								
36	Transformity Scenario 1 (sej/J)				2.14E+05								
37	Emergy/mass Scenario 2 (sej/g)				2.14E+11								
38	Transformity Scenario 2 (sej/J)				7.2E+06								
39	Emergy/mass Scenario 3 (sej/g)				1.61E+10								
40	Transformity Scenario 3 (sej/J)				5.4E+05								

Conventional Emergy Analysis

The conventional categories for emergy flows are summarized in Table 15. These flows were used to compute conventional emergy indices for the recycling benefit of biosolids, agricultural production of hybrid poplar and industrial phases for conversion of hybrid poplar to ethanol. Emergy indices are summarized in Table 16.

Table 15: Summary of conventional emergy flows (giga-sej/gallon)

	Agricultural Production		
	Scenario 1	***Scenario 2***	***Scenario 3***
Local renewable Inputs (R)	2995	2995	2995
Locally nonrenewable inputs (N_o)	61	61	61
Imported inputs (F)	9738	572853	36123
Total Emergy inputs (Y)	12794	575909	39179

	Ethanol Conversion		
	Scenario 1	***Scenario 2***	***Scenario 3***
Local renewable Inputs (R)	2995	2995	2995
Locally nonrenewable inputs (N_o)	61	61	61
Imported inputs (F)	14131	577246	40516
Total Emergy inputs (Y)	17187	580301	43572

Table 16: Summary of emergy indicators for recycling of biosolids in hybrid poplar farm

Indices	
Landfill Recycle Ratio (LRR)	1.78
Recycling Yield Ratio (RYR)	59

Recycle Emergy Indices

Table 16 shows the LRR and RYR for biosolids recycling results that measured and compared the benefit of recycling biosolids and using them in the tree farm to burying the biosloids at a landfill. The emergy required to landfill biosolids was calculated from Buranakarn (1998). The LRR for biosolids was calculated to be 1.78, meaning that it took 1.78 units of emergy to landfill biosolids per 1 unit of emergy required to recycle biosolids at the tree farm. This indicated that 56% less emergy was used to process the biosolids in the hybrid poplar farm than to burry them in a landfill; as a result there was more benefit to society in recycling biosolids at the tree farm than on sending them to a landfill. The LRR of recycling biosolids at the tree farm was comparable to recycling concrete (1.7) and lumber (1.4) (Buranakarn, 1998). The RYR for recycling biosolids in the hybrid poplar tree farm was estimated at 59. The RYR indicated that overall there was a net benefit to society in recycling biosolids because there was a small investment needed in recycling relative to the emergy embodied in biosolids. The RYR of recycle biosolids was comparable to recycle aluminum (44.7) (Buranakarn, 1998). Both of these indices, LRR and RYR, indicated that the recycling of biosolids in the tree farm provided more benefits than to burying the biosolids at landfill.

Table 17: Summary of conventional emergy indicators for ethanol production from hybrid poplar

	Agricultural			*Ethanol*		
Scenario	***1***	***2***	***3***	***1***	***2***	***3***
Conventional Emergy Indices						
Specific Emergy (giga-sej/gram)	1.34	60	4.1	6.4	214	16
Transformity (sej/joule)	6.9E04	3.13E06	2.13E05	2.14E05	7.24E06	5.43E05
Emergy Yield Ratio= Y/ F	1.31	1.01	1.08	1.22	1.01	1.08
Environmental Loading Ratio=(N+ F)/R	3.3	191	12.1	4.7	193	13.5
Emergy Investment Ratio = F/(N+R)	3.2	188	11.8	4.6	190	13.3
Emergy Sustainability Index= (Y/ F) /((N+ F)/R)	0.41	0.01	0.09	0.26	0.01	0.08
Percent Renewable = (Y/ R)*100	23%	0.52%	8%	17%	0.52%	7%

Conventional emergy indicators

Table 17 presents the results on conventional emergy indices for both the agricultural production and the industrial conversion hybrid poplar to ethanol for the three scenarios. The transformity for the production of hybrid poplar biomass under scenario 1 (“free emergy” in biosolid) was calculated to be 69,500 sej/joule while the transformity for hybrid poplar, this was a bit higher than values observed in natural forest growth in North Carolina (21,000) (Tilley, 1999). Once the biosolid embodied emergy was accounted for, the transformity of hybrid poplar biomass increased by factor of 45 to 3,130,000. The transformity for hybrid poplar under Scenario 3 was 213,000 sej per joule. The transformity for the conversion of hybrid poplar to ethanol for scenarios 1, 2 and 3 was 214,000, 7,240,000 and 543,000 sej/joule, respectively. The transformity for hybrid poplar ethanol in Scenario 1 was comparable to production of paper wood (2.4E05) from natural forest biomass (Tilley, 1999) and sugarcane-ethanol produced in a micro-distillery in “Fazenda Jardim” in Brazil (2.6E05) (Ortega et al., 2006). On the other hand, the transformity of hybrid poplar-to-ethanol in Scenarios 2 is more comparable to transformity of methanol from wood (2.6E06) (Giampietro & Ulgiati, 2005).

Based on conventional emergy indices can hybrid poplar-to-ethanol be a primary energy source? The emergy yield ratio of hybrid poplar-ethanol ranged from was 1.01 to 1.22 (Table 19), which was a marginal net positive values and much less than our present source of liquid fuel (i.e., petroleum) with an estimated EYR greater than 5-to-1 (Odum, 1996). To serve as a ‘primary’ fuel source the EYR likely needs to be at least greater than 3-to-1. Thus, the viability of hybrid poplar-to-ethanol as a major source of fuel is highly questionable.

The environmental loading ratio (ELR) for the agricultural production of hybrid poplar biomass varied depending on assumptions. For example under Scenario 1, considering the biosolid’s embodied energy as “free”, the ELR was 3.3. Once the emergy embodied in municipal biosolids was accounted for, the ELR was dramatically higher at 191. These values were much higher than for agricultural production of other energy crops like switchgrass (2.12) which indicated that hybrid poplar production used more purchased inputs from the economy relative to its use of ‘free’ environmental inputs from renewable and non-renewable sources.

Once the ethanol processing step was taken into account the ELR changed slightly for each of the scenarios to 4.7, 193 and 13.5 for Scenario 1, 2 and 3 respectively. These results indicated that a large fraction of emergy from purchased inputs was embedded in the agricultural production of hybrid poplar. Compared to switchgrass-to-ethanol (3.88), hybrid poplar-ethanol has a higher impact on the environment. Under Scenario 1, the environmental impact of hybrid poplar-ethanol was less than a Texas Cotton Field (9.6) (Odum et al., 1987). In Scenario 3, the environmental impact of hybrid poplar-to-ethanol was more comparable to corn-ethanol in Italy (17.65) (Ulgiati, 2001). However, even under Scenario 2 (194), the environmental impact of hybrid poplar-to-ethanol was 10 times lower than crude oil in Alaska (1429.3) (Brown and Ulgiati, 1997).

The emergy investment ratio (EIR) of hybrid poplar crop was estimated to be between 3.2, 188 and 11.8 for scenarios 1, 2 and 3 respectively. For example under scenarios 1, this meant that 3.2 units of energy were purchased from the economy and matched to 1 unit of free environmental energy. This indicated that the production of wood using municipal biosolids is less competitive than other wood production systems like tropical forests with an EIR of 1.12, and temperate montane forest (0.27) (Odum, 1995; Tilley, 1999). This was due to nature contributing a small proportion of resources in the hybrid poplar plantation system relative to the inputs purchased from the economy.

In the conversion of hybrid poplar to ethanol the EIR increased slightly for scenario 1 from 3.2 to 4.6, in scenario 2 from 188 to 190 and in scenario 3 from 11.8 to 13.3. These results indicated that in scenario 1, 4.6 units of energy from the economy were needed to match 1 unit of free environmental energy whereas in scenario 2, 190 units of energy from the economy were needed to match 1 unit of free environmental energy. Compared to the production of ethanol from switchgrass, hybrid poplar-ethanol less competitive than switchgrass ethanol where 3.43 units of energy from the economy were used to match 1 unit of free environmental energy. However, under scenarios 1, hybrid poplar-to-ethanol was more competitive than Italian corn-ethanol (12.06) (Ulgiati, 2001). These results also indicated that the use of hybrid poplar to produce ethanol was not a viable alternative since the ethanol produced in this manner was not a primary source of energy like Alaskan crude oil production with EIR of 0.07, because a primary source of energy will have an EIR much less than 1.0.

Refined Emergy Partitioning

Tables 18, 19 and 20 show the summary on refined partitioning of the inputs into their ultimate source type (R, N_o, N_m, N_f, or N_p) and their ‘route’ through the ecological-economic system (i.e., direct or indirect) to the production system for each of the alternative scenarios. Of these partitions, the largest ultimate source of solar emergy in Scenarios 2 and 3 came from non-petroleum fossil fuel (N_f) and in Scenario 1 came from petroleum fuel (N_p) (Tables 18, 19 and 20).

Table 18: Summary of emergy flows partitioned according to source and aggregated as direct and indirect inputs to the hybrid poplar production system (giga-sej/gallon) Scenario 1

		SOURCE					
		R	N_o	N_m	N_f	N_p	*Total by Category*
CATEGORY	D_I	2995	61	0	0	0	3056
	D_F	0	0	0	33	2315	2349
	I_G	11	0	589	700	71	1372
	I_S	1249	0	937	4268	3956	10410
Total by Source		**4256**	**61**	**1526**	**5002**	**6343**	**17187**

Under Scenario 1 the largest ultimate source of solar emergy came from petroleum sources (N_p), which was 6,343 giga-sej per gallon (Table 18). About one-third of the emergy from N_p entered the system through direct pathways (2315 giga-sej) while the remainder came from indirect pathways embodied largely in services (3,956 giga-sej) and to lesser extent energy embodied in goods (71 giga-sej).

Table 19: Summary of emergy flows partitioned according to source and aggregated as direct and indirect inputs to the hybrid poplar production system (giga-sej/gallon) Scenario 2

		SOURCE					
		R	**N_o**	**N_m**	**N_f**	**N_p**	***Total by Category***
CATEGORY	**D_I**	2995	61	0	0	0	3056
	D_F	0	0	0	33	2315	2349
	I_G	56323	0	85056	282257	140850	564487
	I_S	1249	0	937	4268	3956	10410
Total by Source		**60567**	**61**	**85993**	**286559**	**147121**	**580301**

Under Scenario 2, once the energy embodied in biosolids was accounted in the production of hybrid poplar-ethanol, the largest ultimate source of solar emergy came from non-petroleum fossil fuel (N_f), (286,559 giga-sej per gallon, Table 19). Most of the non-petroleum fossil fuel amount entered the system through indirect pathway (I_G and I_S); however, in this particular case 98% of the emergy was embodied in goods (282,257 giga-sej) (Table 19).

Table 20: Summary of emergy flows partitioned according to source and aggregated as direct and indirect inputs to the hybrid poplar production system (giga-sej/gallon) Scenario 3

		SOURCE					
		R	N_o	N_m	N_f	N_p	*Total by Category*
CATEGORY	D_I	2995	61	0	0	0	3056
	D_F	0	0	0	33	2315	2349
	I_G	216	0	14241	12665	635	27757
	I_S	1249	0	937	4268	3956	10410
Total by Source		**4460**	**61**	**15178**	**16966**	**6906**	**43572**

Under Scenario 3 the largest ultimate source of solar emergy also came from non-petroleum fossil fuel (N_f), (16,966), closely followed by emergy in non-renewable minerals N_m (15,178) (Table 20). Like Scenarios 1 and 2, most of the total emergy entered the system through indirect pathway as emergy embodied in goods and services (I_G and I_S).

Integrating the environmental, energy and financial resource inputs required throughout the chain of processes needed for making ethanol from cellulosic hybrid poplar biomass revealed that 21% (Row: D_I D_F I_G Column: R, N_o and N_m) of embodied solar energy came from the environment, 18% (Row: D_I D_F I_G Column: N_f and N_p) came from fossil energy sources and the remaining 61% (Row: I_S Column: R, N_o, N_m, N_f and N_p) was financial resources in paid human services under Scenario 1 (Table 18). Once the emergy embodied in municipal biosolids was accounted for under Scenario 2 (Table 19), the ethanol from cellulosic hybrid poplar biomass required 25% of its embodied solar energy from the environment, 73% from fossil energy sources, and only 2% was financial resources in paid human services. Under Scenario 3 (Table 20) environmental sources contributed 40%, fossil energy 36% and financial resources 24%. Of the environmental resources used in each of the scenarios water (from rain) for crop growth was the largest. Regardless of the assumptions, in all scenarios the largest input from financial sources to the overall production chain came from labor costs during the agricultural phase

New emergy Indices based on Refined Partitioning

Table 21 presents a new set of emergy-based indicators developed in this study. These indicators were calculated based on the solar emergy value of the ethanol yielded from the system, Y_{eth} = 9267 giga-sej per gallon, which was calculated by multiplying the available energy of ethanol (84.2 megajoules per gallon) by the solar transformity of petroleum products (110,000 sej/joule) used throughout the production systems.

Table 21: Indices assessing the viability of producing ethanol from Hybrid Poplar

Indices	**Values**		
	Scenario 1	**Scenario 2**	**Scenario 3**
Emergy content of ethanol: Y_{eth}= (84.2E06 Joules)X(1.1E05 sej per Joule) (giga-sej/gallon)	9,267	9,267	9,267
Total emergy used: $U=R+ N_o+N_m+N_f+N_p$	17,187	580,301	43,572
Net liquid fuel available beyond production (Y_{eth} -N_p) (giga-sej/gallon)	2,924	(137,855)	2,360
Liquid produced to total emergy used: Y_{eth}/U	0.54	0.02	0.21
Liquid produced to petroleum used: (Y_{eth} /(N_p)	1.5	0.06	1.3
Yield of net liquid produced to petroleum emergy used (Y_{eth} -N_p /(N_p)	0.5	(0.94)	0.3
Net Liquid Yield Ratio, EYR_P: (Y_{eth}-N_p)/($R+N_o+N_m+N_f$)	0.3	(0.3)	0.15
Liquid produced to fossil emergy used: Y_{eth} /(N_f+N_p)	0.82	0.02	0.39
Ratio of liquid available per non-petroleum fossil emergy used (Y_{eth} / N_f)	1.85	0.03	0.55
Yield ratio of net liquid available per fossil emergy used (EYR_f) ((Y_{eth} -N_p) / N_f)	0.58	(1.60)	0.14
Percent from Renewable sources (R/U)	25%	10%	10%
Percent from free-environmental sources: ($R+N_o+N_m$)/ U	34%	25%	43%
Percent from liquid fuels: Np/U	37%	25%	16%
Percent from fossil fuels: (Np+Nf)/U	66%	75%	55%
Percent from Indirect Sources (I_G+I_S)/U	69%	99%	88%
Percent from Direct Sources (D_I + D_f)/U	31%	1%	12%

Is hybrid poplar-to-ethanol a primary energy source? Under each Scenario, more emergy was used to make ethanol than the ethanol produced. The ratio of liquid yield to total emergy used was 0.54, 0.02 and 0.21 for Scenarios 1, 2 and 3, respectively (Table 20). These results indicated that hybrid poplar-ethanol was not a primary source and can not compete with present primary sources of energy.

Can hybrid poplar-to-ethanol replace petroleum? Under Scenarios 1 and 3, the hybrid poplar-to-ethanol yielded 1.5 and 1.3 gallons of ethanol for each gallon of petroleum used (Y_{eth} /N_p) respectively. However, once a credit was made against the ethanol yield to account for the petroleum required in processing, the net yield of ethanol in scenarios 1 and 3 was less than 1 unit of liquid fuel emergy per each unit of petroleum fuel emergy used. If the petroleum input (N_p) was completely eliminated the Net Liquid Yield Ratio (Table 21) indicated that there was far less than 1 unit of emergy produced (in form of ethanol) than emergy consumed to make it. Both of these indices suggested that there was no net yield from the process.

In scenario 1, the liquid yield per non-petroleum emergy (N_f) used, had the highest yield at 1.85 units of liquid fuel emergy per each unit of non-petroleum emergy used. However, if some of the produced ethanol yield was returned to complete the chain of processes in place of gasoline, diesel and other petroleum products, then the net liquid yield per non-petroleum emergy used was reduced to 0.58 (Table 21). In other words, more fossil fuel (coal and natural gas) emergy units went into the process than the units of emergy produced as liquid ethanol fuel. This result indicated that this was not a competitive process for converting non-petroleum fossil fuels into liquid form.

The ratio of ethanol yield to total fossil energy used [Yeth/(Nf+Np)], which was a metric analogous to more traditional energy analyses, showed that hybrid poplar-ethanol did not have a net energy balance (0.82 for Scenario 1, 0.02 for Scenario 2 and 0.39 for

Scenario 3). However, for a waste recycling operation the transformation of biosolids into biomass required large contributions from financial resources in the form of human services relative to other energy crop systems. As a result, the production of biomass form recycle systems was less emergy efficient than other ethanol feedstock. Improving the efficiency in the production of hybrid poplar biomass to reduce human services inputs can contribute to enhance the net energy balance of hybrid poplar-ethanol. As of now, the emergy embodied in the biomass being produced at the farm was relatively high compare to the emergy that was yielded from its conversion to ethanol.

Producing ethanol from a feedstock of hybrid poplar grown with trenched municipal biosolids was not 'renewable' because the total emergy derived from renewable sources was only between 10% to 25%, depending on assumptions. In other words, for the assumptions with highest renewable percentage (Scenario 1) about 75% of the energy used to make ethanol came from non-renewable resources (Table 21).

What is the significance of indirect inputs? Indirect inputs of emergy were high for each of the scenarios, ranging from 69% up to 99% of the total inputs. Primarily, this indicated that energy embodied in indirect sources was more important than direct inputs. Secondly, it indicated that energy accounting methods that exclude or partially account for the energy embodied in indirect goods, capital and services miss the vast majority of energy required to produce ethanol from biomass, and likely would lead to faulty decisions regarding the viability of 'biofuels'.

Biodiesel

In Table 22 columns D, F, H, and J summarized the total amount of resources required for agricultural production of soybean in Virginia. The total emergy required to produce a crop of soybean in Virginia that could be used to generate one gallon of biodiesel was estimated at 17,903 giga-sej (line 18, Column K, Table 22). The largest input came from evaportranspiration (Table 22). The three largest purchased inputs were evaportranspiration of rain, organic matter contributed from soil and non-labor production costs (Table 22).

In Table 23 columns D, F, H, and J summarized the total amount of resources required for agricultural production of castorbean in Texas. The total emergy required to produce a crop of castorbean in Texas that could be used to generate one gallon of biodiesel was 21,521 giga-sej (line 14, Column K, Table 23). The single largest input came from groundwater used for crop irrigation, which was followed by purchased input (Table 23). Electricity, rain and organic matter contributed from soil were also among the top contributors (Table 23).

The emergy analysis for the transportation of the soybean crop to the oil crushing processing facility required to produce one gallon of biodiesel is given in Table 24**.** The emergy contributed from steel embodied in manufacturing of truck was estimated to be 20 giga-sej/gallon. The emergy in fuel used for transportation contributed 238 giga-sej per gallon. Emergy from services in labor contributed 194 giga-sej per gallon while emergy in fuel services contributed 27 giga-sej per gallon. The total emergy required to transport soybean from the field to the oil crushing plant to generate one gallon of biodiesel was estimated at 480 giga-sej. The solar emergy of the diesel fuel was the largest portion of the total emergy required but labor services was a close second (Table 24).

The emergy analysis for the transportation of the castorbean crop to the oil crushing processing facility required to produce one gallon of biodiesel is given in Table 25**.** The emergy contributed from steel embodied in the manufacturing of a truck was estimated to be 61 giga-sej/gallon. The emergy of fuel for transportation contributed 72 giga-sej per gallon. Emergy embodied in labor services was 22 giga-sej per gallon while the emergy embodied in services embodied in fuel contributed 8 giga-sej per gallon. The total emergy required in the transport of castorbean to generate one gallon of biodiesel was 164 giga-sej. The transportation emergy for castorbean per gallon of biodiesel produced was less than soybean due to the difference in oil content between the two crop systems; i.e. castorbean is estimated at 50% oil content whereas soybean has around 18%.

Table 26 contains the estimated amount of emergy required to produce “crude” vegetable oil from soybeans and castorbean feedstock from the field (line item 1 and 2) and emergy of transportation (line items 9 and 15). Likewise, Table 27 presents the estimated amount of emergy required to produce “crude” vegetable oil from castorbeans, including the castorbean feedstock from the field (line item 1) and transportation (line items 9 and 15). The production of crude vegetable oil needed to produce one gallon of biodiesel from soybean required 23,888 giga-sej per gallon (Table 26). The production of crude vegetable oil needed to produce one gallon of biodiesel from castorbean required 24,088 giga-sej per gallon (Table 27). The two largest inputs in oil crushing processing of either castorbean and soybean, after the feedstock input (line 1 Table 26 and 27), came from using coal to produce heat needed to dry the beans and electricity demand for dehulling, grinding and extracting the oil from castorbean and soybean.

The emergy analysis for the transportation of “crude” vegetable oil from either castorbean or soybean from the crushing processing facility to the refining facility is given in Table 28. The total emergy required in the transport of “crude” vegetable oil to generate one gallon of biodiesel was 88 giga-sej. The largest emergy contribution was from fuels used at 33 sej per gallon.

Table 29 shows the estimated amount of emergy required to refine “crude” vegetable oil from unrefined soy oil (line item 1) or castor oil (line item 2) into biodiesel, including the transportation of “crude” oil (lines 13 and 17). Biodiesel produced from soybean required 26,631giga-sej per gallon (line 18, Table 29). The production of biodiesel from castorbean required 26,831 giga-sej per gallon (line 19, Table 28). The three largest inputs were methanol, operating costs and hydrochloric acid.

Table 22: Solar emergy required for agricultural production of soybean (Glycine max.) *based on Virginia 2003 production standards (per gal of biodiesel)*

Index	Item	Input (A)	Unit	Solar Emergy per Unit (B)	Env Fraction R&N_o (C)	Env Emergy E09 sej/gallon (D)	Mineral Fraction N_m (E)	Mineral Emergy E09 sej/gallon (F)	Coal & Nat. gas Fraction N_f (G)	Coal & Nat. gas Emergy E09 sej/gallon (H)	Petroleum Fraction N_p (I)	Petroleum Emergy E09 sej/gallon (J)	Sum of all Emergy E09 sej/gallon (K=D+F+H+J)
Nature Contribution (I)													
Free Renewable Inputs (R)													
1	Sun	4.04E+11	J	1	1	404	0	0	0	0	0	0	404
2	Water, rain	4.53E+08	J	30576	30576	13846	0	0	0	0	0	0	13846
3	Evapotranspiration	1.75E+08	J	30576	30576	5360	0	0	0	0	0	0	5360
Free Non-renewable (N)													
4	Net topsoil loss	5.89E+07	J	73800	73800	4348	0	0	0	0	0	0	4348
Purchased (F)													
Feedback from economy as Resources (M)													
5	Herbicide	2.25E+06	J	1.11E+05	0	0	0	0	0	0	1.11E+05	249	249
6	Nitrogen (NH_3)	69	g	2.87E+09	0	0	0	0	2.87E+09	198	0	0	198
7	Phosphorus (P_2O_5)	68	g	6.55E+09	0	0	1.68E+09	114	4.56E+09	310	3.11E+08	21	446
8	Potassium	353	g	1.85E+09	1.06E+08	37	1.68E+09	593	5.97E+07	21	4.59E+06	2	653
9	Machinery	18	g	1.30E+10	0	0	1.68E+09	30	9.55E+09	173	1.77E+09	32	235
10	Diesel	5.37E+06	J	1.11E+05	0	0	0	0	0	0	1.11E+05	595	595
11	Gasoline	3.18E+06	J	1.11E+05	0	0	0	0	0	0	1.11E+05	353	353
12	Electricity	5.11E+04	J	3.36E+05	0	0	0	0	3.36E+05	17	0	0	17
Feedback from economy in Services (S)													
6	Herbicide	0.339	$	1.10E+12	1.32E+11	45	9.90E+10	34	4.51E+11	153	4.18E+11	142	373
10	Fertilizers	0.25	$	1.10E+12	1.32E+11	33	9.90E+10	24	4.51E+11	111	4.18E+11	103	271
12	Labor	1.54	$	1.10E+12	1.32E+11	203	9.90E+10	152	4.51E+11	695	4.18E+11	644	1694
16	Fuels	0.22	$	1.10E+12	1.32E+11	29	9.90E+10	22	4.51E+11	98	4.18E+11	91	239
17	Production costs	2.94	$	1.10E+12	1.32E+11	388	9.90E+10	291	4.51E+11	1327	4.18E+11	1230	3237
18	**Total Emergy**												**18269**
19	Yield biomass	2.15E+04	g										
20	Energy biomassi	3.45E+08	J										
21	Emergy/mass (sej/g)			8.49E+08									
22	Transformity (sej/J)			5.30E+04									

Lines 1 and 2 Excluded from Total (line 18) to avoid double counting

Table 23: Solar emergy required for agricultural production of castorbean (Ricinus comunis) based on Texas production standards in the 1960s (per gal basis)

Index	Item	Input (A)	Units	Solar Emergy per Unit (B)	Env Fraction R&N_o (C)	Env Emergy E09 sej/gallon (D)	Mineral Fraction N_m (E)	Mineral Emergy E09 sej/gallon (F)	Coal & Nat. gas Fraction N_f (G)	Coal & Nat. gas Emergy E09 sej/gallon (H)	Petroleum Fraction N_p (I)	Petroleum Emergy E09 sej/gallon (J)	Sum of all Emergy E09 sej/gallon K=D+F+H+J
Nature Contribution (I)													
Free Renewable Inputs (R)													
1	Sun	1.27E+11	J	1	1	112	0	0	0	0	0	0	112
2	Wind	9.78E+08	J	2513	2513	2169	0	0	0	0	0	0	2169
3	Water, rain	9.69E+07	J	30576	30576	2615	0	0	0	0	0	0	2615
Free Non-renewable (N)													
4	Net topsoil loss	3.02E+07	J	73800	73800	2229	0	0	0	0	0	0	2229
5	Water Irrigation	2.57E+07	J	278880	223104	5738	0	0	55776	1435	0	0	7173
Purchased (F)													
Feedback from economy Resources (M)													
6	Nitrogen (NH3)	268	g	2.87E+09	0	0	0	0	2.87E+09	768	0	0	768
7	Phosphate (P2O5)	138	g	6.55E+09	0	0	1.68E+09	232	4.56E+09	631	3.11E+08	43	906
8	Potassium (K2O5)	51	g	1.85E+09	1.06E+08	5	1.68E+09	85	5.97E+07	3	4.59E+06	0	94
9	Machinery	8	g	1.30E+10	0	0	1.68E+09	14	9.55E+09	78	1.77E+09	14	106
10	Diesel	3.28E+06	J	1.11E+05	0	0	0	0	0	0	111000	364	364
11	Electricity	8.29E+06	J	3.36E+05	0	0	0	0	3.36E+05	2786	0	0	2786
Feedback from economy in Services (S)													
12	Seeds	0.005	$	1.27E+13	1.52E+12	7	1.14E+12	5	5.21E+12	25	4.83E+12	23	61
13	Production costs	0.39	$	1.27E+13	1.52E+12	588	1.14E+12	441	5.21E+12	2008	4.83E+12	1861	4898
14	**Total Emergy**												**21999**
15	Yield biomass	6391	g										
16	Energy biomassi	2.41E+08	J										
17	Emergy/mass (sej/g)			3.44E+09									
18	Transformity (sej/J)			9.14E+04									

Lines 1 and 2 Excluded from Total (line 14) to avoid double counting

Table 24: Solar emergy required for transportation of soybean crop to crushing facility in 2000 (per gallon of biodiesel)

Index	**Item**	**Input (A)**	**Unit**	**Solar Emergy per Unit (B)**	**Env Fraction R&N$_o$ (C)**	**Env Emergy E09 sej/gallon (D)**	**Mineral Fraction N$_m$ (E)**	**Mineral Emergy E09 sej/gallon (F)**	**Coal & Nat. gas Fraction N$_f$ (G)**	**Coal & Nat. gas Emergy E09 sej/gallon (H)**	**Petroleum Fraction N$_p$ (I)**	**Petroleum Emergy E09 sej/gallon (J)**	**Sum of all Emergy E09 sej/gallon (K=D+F+H+J)**
Purchased (F)													
Feedback from economy Resources (M)													
1	Machinery	2	g	1.30E+10	0	0	1.68E+09	3	9.55E+09	15	1.77E+09	3	20
2	Diesel	2.14E+06	J	1.11E+05	0	0	0	0	0	0	1.11E+05	238	238
Feedback from economy in Services (S)													
3	Fuels	0.025	$	1.10E+12	1.32E+11	3	9.9E+10	2	4.51E+11	11	4.2E+11	10	27
4	Services labor	0.18	$	1.10E+12	1.32E+11	23	9.90E+10	17	4.51E+11	80	4.18E+11	74	194
5	**Total Emergy**												**480**

Table 25: Solar emergy required for transportation of castorbean crop to crushing facility in 2000 (per gallon of biodiesel))

Index	**Item**	**Input (A)**	**Unit**	**Solar Emergy per Unit (B)**	**Env Fraction $R\&N_o$ (C)**	**Env Emergy E09 sej/gallon (D)**	**Mineral Fraction N_m (E)**	**Mineral Emergy E09 sej/gallon (F)**	**Coal & Nat. gas Fraction N_f (G)**	**Coal & Nat. gas Emergy E09 sej/gallon (H)**	**Petroleum Fraction N_p (I)**	**Petroleum Emergy E09 sej/gallon (J)**	**Sum of all Emergy E09 sej/gallon K=D+F+H+J**
Purchased (F)													
Feedback from economy Resources (M)													
1	Machinery		g	1.30E+10	0	0	1.68E+09	8	9.55E+09	45	1.77E+09	8	61
2	Diesel		J	1.11E+05	0	0	0	0	0	0	1.11E+05	72	72
Feedback from economy in Services (S)													
3	Fuels	0.020	$	1.10E+12	1.32E+11	3	9.90E+10	2	4.51E+11	9	4.18E+11	8	22
4	Services labor	0.008	$	1.10E+12	1.32E+11	1	9.90E+10	1	4.51E+11	3	4.18E+11	3	8
5	**Total Emergy**												**164**

Table 26: Solar emergy required for soybean oil crushing in 2000 (per gallon of biodiesel)

Index	Item	Input (A)	Unit	Solar Emergy per Unit (B)	Env Fraction $R\&N_o$ (C)	Env Emergy E09 sej/gallon (D)	Mineral Fraction N_m (E)	Mineral Emergy E09 sej/gallon (F)	Coal & Nat. gas Fraction N_f (G)	Coal & Nat. gas Emergy E09 sej/gallon (H)	Petroleum Fraction N_p (I)	Petroleum Emergy E09 sej/gallon (J)	Sum of all Emergy E09 sej/gallon K=D+F+H+J
1	Biomass Input	21521	g	*8.49E+08*	*4.85E+08*	*10443*	*5.86E+07*	*1261*	*1.44E+08*	*3103*	*1.61E+08*	*3462*	*18269*
Purchased (F)													
Feedback from economy Resources (M)													
2	Hexane		J	1.11E+05	0	0	0	0	0	0	1.11E+05	240	240
3	Steel Equip.		g	1.30E+10	0	0	1.68E+09	1	9.55E+09	7	1.77E+09	1	9
4	Buildings Steel		g	6.94E+09	0	0	1.68E+09	3	9.53E+08	2	4.34E+09	7	11
5	Concrete		g	3.33E+09	0	0	1.68E+09	5	1.56E+09	5	8.23E+07	0.24	10
6	Water		J	3.14E+05	8.48E+04	0.03	1.29E+05	0.04	8.17E+04	0.03	1.88E+04	0.01	0.1
7	Coal		J	6.69E+04	0	0	0	0	6.69E+04	3157	0	0	3157
8	Electricity		J	3.36E+05		0		0	3.36E+05	1546	0	0	1546
9	*Transportation (Table 24)*				0	0		3		15		241	*258*
Feedback from economy in Services (S)													
10	Hexane		$	1.10E+12	1.32E+11	0.42	9.90E+10	0.31	4.51E+11	1	4.18E+11	1	3
11	Water		$	1.10E+12	1.32E+11	0.31	9.90E+10	0.23	4.51E+11	1	4.18E+11	1	3
12	Coal		$	1.10E+12	1.32E+11	8	9.90E+10	6	4.51E+11	29	4.18E+11	26	70
13	Electricity		$	1.10E+12	1.32E+11	0.46	9.90E+10	0.34	4.51E+11	2	4.18E+11	1	4
14	Operating cost		$	1.10E+12	1.32E+11	54	9.90E+10	41	4.51E+11	186	4.18E+11	172	453
15	*Transportation (Table 24)*					27		20		91		84	222
16	**Total Emergy**												**24254**
17	Yield oil, mass	3385	g										
18	Energy in oil	1.25E+08	J										
19	Emergy/mass (sej/g)			7.17E+09									
20	Transformity (sej/J)			1.94E+05									

Table 27: Solar emergy required for castorbean oil crushing in 2000 (per gallon of biodiesel)

Index	Item	Input (A)	Unit	Solar Emergy per Unit (B)	Env Fraction R&N_o (C)	Env Emergy E09 sej/gallon (D)	Mineral Fraction N_m (E)	Mineral Emergy E09 sej/gallon (F)	Coal & Nat. gas Fraction N_f (G)	Coal & Nat. gas Emergy E09 sej/gallon (H)	Petroleum Fraction N_p (I)	Petroleum Emergy E09 sej/gallon (J)	Sum of all Emergy E09 sej/gallon K=D+F+H+J
1	Biomass Input	21521	g	3.44E+09	1.7E+09	11183	1.2E+08	777	1.2E+09	7734	3.6E+08	2306	21999
Purchased (F)													
Feedback from economy Resources (M)													
2	Hexane		J	1.10E+05	0	0	0	0	0	0	1.10E+05	98	98
3	Steel Equip.		g	1.30E+10	0	0	1.68E+09	0.50	9.55E+09	3	1.77E+09	0.53	4
4	Buildings Steel		g	6.97E+09	0	0	1.68E+09	1.09	9.53E+08	1	4.34E+09	2.82	5
5	Concrete		g	3.33E+09	0	0	1.68E+09	4.84	1.56E+09	5	8.23E+07	0.24	10
6	Water		J	3.14E+05	84823	0.01	1.29E+05	0.02	8.17E+04	0	1.88E+04	0.00	0.04
7	Coal		J	6.69E+04	0	0	0	0	0	0	6.69E+04	1166	1166
8	Electricity		J	3.36E+05	0	0	0	0	3.36E+05	636	0	0	636
9	*Transportation (Table 24)*					0		8		45		81	134
Feedback from economy in Services (S)													
10	Hexane		$	1.10E+12	1.32E+11	0.17	9.90E+10	0.13	4.51E+11	1	4.18E+11	1	1
11	Water		$	1.10E+12	1.32E+11	0.13	9.90E+10	0.10	4.51E+11	0	4.18E+11	0	1
12	Coal		$	1.10E+12	1.32E+11	3.43	9.90E+10	2.58	4.51E+11	12	4.18E+11	11	29
13	Electricity		$	1.10E+12	1.32E+11	0.19	9.90E+10	0.14	4.51E+11	1	4.18E+11	1	2
14	Operating cost		$	1.10E+12	1.32E+11	54.38	9.90E+10	40.79	4.51E+11	186	4.18E+11	172	453
15	*Transportation (Table 24)*					4		3		12		12	*30*
16	**Total Emergy**												**24566**
17	Yield oil, mass	3385	g										
18	Energy in oil	1.25E+08	J										
19	Emergy/mass (sej/g)			7.26E+09									
20	Transformity (sej/J)			1.96E+05									

Table 28: Solar emergy required for transportation of crude oil to refining facility in 2000 (per gallon of biodiesel)

Index	**Item**	**Input (A)**	**Unit**	**Solar Emergy per Unit (B)**	**Env Fraction R&N_o (C)**	**Env Emergy E09 sej/gallon (D)**	**Mineral Fraction N_m (E)**	**Mineral Emergy E09 sej/gallon (F)**	**Coal & Nat. gas Fraction N_f (G)**	**Coal & Nat. gas Emergy E09 sej/gallon (H)**	**Petroleum Fraction N_p (I)**	**Petroleum Emergy E09 sej/gallon (J)**	**Sum of all Emergy E09 sej/gallon K=D+F+H+J**
Purchased (F)													
Feedback from economy Resources (M)													
1	Machinery	2	g	1.30E+10	0	0	1.68E+09	4	9.55E+09	20	1.77E+09	4	28
2	Diesel	2.95E+05	J	1.11E+05	0	0	0	0	0	0	1.11E+05	33	33
Feedback from economy in Services (S)													
3	Fuels	0.003	$	1.10E+12	1.32E+11	0	9.9E+10	0	4.5E+11	2	4.2E+11	1	4
4	Services labor	0.021	$	1.10E+12	1.32E+11	3	9.90E+10	2	4.51E+11	10	4.18E+11	9	23
5	**Total Emergy**												**88**

Table 29: Solar emergy required for oil refining from soy or castor to biodiesel in 2003 (per gallon of biodiesel)

Index	**Item**	**Input (A)**	**Unit**	**Solar Emergy per Unit (B)**	**Env Fraction E (R&N$_o$) (C)**	**Env Emergy E09 sej/gallon (D)**	**Mineral Fraction N$_m$ (E)**	**Mineral Emergy E09 sej/gallon (F)**	**Coal and Nat. gas Fraction N$_f$ (G)**	**Coal & Nat. Gas Emergy E09 sej/gallon (H)**	**Petroleum Fraction N$_p$ (I)**	**Petroleum Emergy E09 sej/gallon (J)**	**Sum of all Emergy E09 sej/gallon K=D+F+H+J**
1	Soy Oil (Table 26)	3385	g	*7.17E+09*	*3.1E+09*	*10534*	*3.96E+08*	*1340*	*2.4E+09*	*8144*	*1.3E+09*	*4237*	*24254*
2	Castor oil (Table 27)	3385	g	*7.26E+09*	*3.32E+09*	*11245*	*2.48E+08*	*838*	*2.6E+09*	*8634*	*1.1E+09*	*3850*	*24566*
Purchased (F)													
Feedback from economy Resources (M)													
3	Methanol	6.44E+06	J	1.11E+05	0	0	0	0	0	0	1.11E+05	714	714
4	Sodium Methoxide	1.57E+06	J	1.11E+05	0	0	0	0	0	0	1.11E+05	174	174
5	Sodium Hydroxide	81	g	1.85E+09	1.06E+08	9	1.68E+09	137	5.97E+07	5	4.59E+06	0.37	151
6	Hydrochloric Acid	26	g	9.86E+09	0	0	1.68E+09	43	4.83E+09	123	3.35E+09	86	252
7	Steel Equipment	5	g	1.30E+10	0	0	1.68E+09	8	9.55E+09	46	1.77E+09	8	62
8	Steel Building	2	g	6.97E+09	0	0	1.68E+09	4	9.53E+08	2	4.34E+09	9	15
9	Cement	1	g	3.33E+09	0	0	1.68E+09	1	1.56E+09	1	8.23E+07	0	2
10	Water Recycled	5030	J	3.14E+05	8.48E+04	0	1.29E+05	1	8.17E+04	0	1.44E+05	0.72	2
11	Recycle Oil	6.18E+06	J	1.11E+05	0	0	0	0	0	0	1.11E+05	686	686
12	Electricity	3.52E+05	J	3.36E+05	0	0	0	0	336000	118	0	0	118
13	*Transportation (Table 28)*					*0*		*4*		*20*		*36*	*61*
Feedback from economy in Services (S)													
14	Chemicals		$	1.10E+12	1.32E+11	12	9.90E+10	9	4.51E+11	42	4.18E+11	39	103
15	Utilities		$	1.10E+12	1.32E+11	2	9.90E+10	2	4.51E+11	8	4.18E+11	7	20
16	Operating cost		$	1.10E+12	1.32E+11	43	9.90E+10	32	4.51E+11	147	4.18E+11	136	358
17	*Transportation (Table 28)*					*3*		*2*		*11*		*10*	*27*
18	**Total Emergy Soybean-Biodiesel (excluding line 2)**												**26997**
19	**Total Emergy Castrobean-Biodiesel (excluding line 1)**												**27309**

Table 29: Continued

20	Yield Oil, mass	3.26E+03	g	
21	Energy in oil	1.24E+08	J	
Soybean				
22	Emergy/mass (sej/g)			8.27E+09
23	Transformity (sej/J)			2.19E+05
Castorbean				
24	Emergy/mass (sej/g)			8.37E+09
25	Transformity (sej/J)			2.21E+05

Emergy Inputs to Biodiesel from Soybean and Castorbean

Ranking of the largest input items to the entire process chain are summarized in Figure 26.

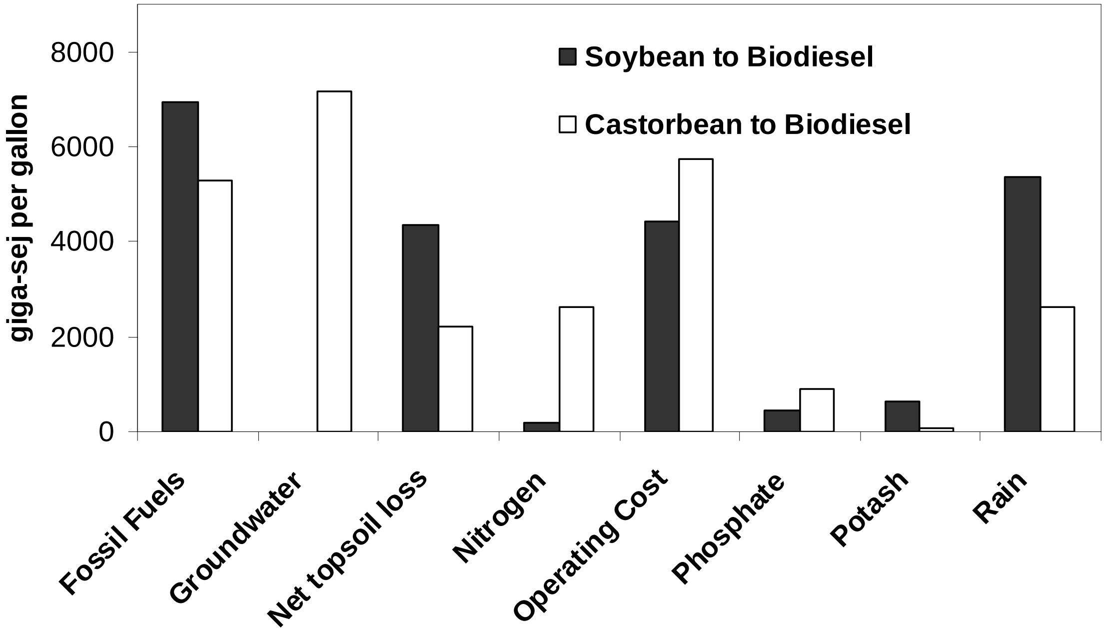

Figure 26. Comparison of main inputs required to produce biodiesel from castorbean and soybean sorted by alphabetical order of input source.

Unlike other energy analyses of biofuels (e.g., Farrell et al., 2006; Pimentel and Patzek, 2005), that excluded inputs from humans and the environment (i.e., soil and rainwater), this emergy evaluation included them and found they were some of the most important inputs. In fact operating costs (human services) was the third largest single input (Fig. 26) for both soybean and castorbean biodiesel. The highest input in the production of biodiesel from soybean came from fossil fuels followed closely by water (rain). Like soybean biodiesel, inputs from fossil fuel and operating cost were also larger contributors in the production of castorbean biodiesel (Fig. 26). However, the highest input in castorbean-to-biodiesel was groundwater extracted from an aquifer for irrigation during agricultural production that contributed 26% of the total emergy. A key difference in agricultural phase between the two oil-crop systems was that soybean relied more on organic matter from soil whereas castorbean relied heavily on groundwater resources for irrigation.

Conventional Emergy Analysis

The conventional emergy flows to the overall production of biodiesel from soybean and castorbean are summarized in Table 30. These flows were used to compute conventional emergy indices in agricultural and industrial phases (Table 31).

Table 30: Summary of conventional emergy flows (Giga-sej/gallon)

	Soybean Crop	***Soybean Biodiesel***	***Castor Crop***	***Castor Biodiesel***
Local renewable Inputs (R)	5360	0	2615	0
Locally nonrenewable inputs (No)	4348	0	9401	0
Imported inputs (F)	8561	8728	9982	5310
Total Emergy inputs (Y)	18269	26997	21999	27309

Table 31: Summary of conventional emergy indicators for biodiesel production from soybean & castorbean

	Soybean Crop	***Soybean Biodiesel***	***Castor Crop***	***Castor Biodiesel***
Conventional Emergy Indices				
Specific Emergy (sej/gram)	0.85	8.3	3.4	8.3
Transformity (sej/joule)	5.3E04	2.19E05	9.14E04	2.21E05
Emergy Yield Ratio= Y/ F	2.1	1.6	2.2	1.80
Environmental Loading Ratio=(N+ F)/R	2.4	4	7.4	10
Emergy Investment Ratio= F/(N+R)	0.88	1.8	0.83	1.3
Emergy Sustainability Index= (EYR) /(ELR)	0.90	0.40	0.30	0.17
Percent Renewable = (R/Y)	30	20	12	10

Conventional Emergy Indicators

Table 31 presents the results on conventional emergy indices for both agricultural production and industrial conversion of soybean and castorbean to biodiesel. The transformity of soybean was estimated to be 53,000 sej/joule. The transformity of castorbean was 91,400 sej/joule. A substantial difference in crop production practice that increased the solar transformity of castorbean was in the use of groundwater in crop irrigation. The use of irrigation alone contributed around 60% of the total emergy used in the production of castorbean. The transformity for biodiesel from both soybean and castorbean was fairly similar, 219,000 sej/joules and 221,000 sej per joule respectively.

The emergy yield ratio was for the production of castorbean was 2.2 and soybean followed closely at 2.1. In both cases the EYR for the conversion of soybean and castorbean to biodiesel decreased. In the case of soybean-to-biodiesel, it went from 2.1 to 1.6. In castorbean-to-diesel, it decreased from 2.2 to 1.8. These results indicated that in the industrial production phase purchased resources superseded that of “free” environment inputs.

Based on conventional emergy indices can oil crop-to-biodiesel be a primary energy source? The EYR was 1.60-to-1 in soybean-to-biodiesel which was a small net positive but much less than our present source of liquid fuel which has an EYR greater than 5-to-1 (Odum, 1996). The EYR of castorbean-to-biodiesel was higher at 1.8-to-1 but to serve as a ‘primary’ fuel source the EYR likely needs to be at least greater than 3-to-1. Thus, the viability of biodiesel from soybean and castorbean as a major source of fuel is questionable. On the other hand, the EYR for biodiesel from castorbean was slightly higher, indicating that castorbean was a better feedstock for biodiesel production.

The environmental loading ratio (ELR) of agricultural production of soybean (2.4) was much lower than the agricultural production of castorbean (7.4). These results indicated that castorbean crop production used more purchased inputs from the economy relative to its use of ‘free’ environmental inputs from renewable and non-renewable sources when compared to soybean. This indicated that soybean was a more competitive crop than castorbean. The ELR for the entire biodiesel chain production for soybean double to 4, while the ELR for biodiesel from castorbean increased to 10. These results indicated that soybean biodiesel production system had a lower potential impact on the environment than the production of biodiesel from castorbean.

The emergy investment ratio (EIR) of soybean crop was estimated to be 0.88, meaning that 0.88 units of energy were purchased from the economy and matched to 1 unit of free environmental energy. The EIR for castorbean crop was estimated to be 0.83. This indicated that the U.S. production of castorbean and soybean crops were more economically competitive than soybean produced in Brazil (2.28) (Cavalett et al., 2006). The small EIR obtained for castorbean reflects the greater contribution made by two free-renewable sources, soil and groundwater, as result nature is contributing a larger proportion of energy than the portion that is purchased from the economy. In the case of soybean large environmental contributions came from water (rain) and soil organic matter.

The EIR for the conversion crude vegetable oil to biodiesel increased from 0.88 to 1.8 in soybean and 0.79 to 1.3 in castorbean. This indicated that biodiesel from soybean or castorbean was not a primary source of energy like hydroelectricity (0.10) or crude oil production in Alaska (0.07), (Brown and McClanahan, 1996; Brown and Ulgiati, 1997) because a primary source of energy will have an EIR much less than 1.0.

Refined Emergy Partition

Tables 32 and 33 show the summary of refined partitioning of inputs into their ultimate source type (R, N_o, N_m, N_f, or N_p) and their 'route' through the ecological-economic system (i.e., direct or indirect) to the production system. This analysis indicated that the largest ultimate source of solar emergy in soybean biodiesel came from non-petroleum fossil fuel (N_f), which was 8668 giga-sej per gallon (Table 32). A large amount (4838 giga-sej) of that was from direct consumption, while the remainder was embodied in the indirect consumption of goods (928 giga-sej) and services (2901 giga-sej) (Table 32).

Table 32: Summary of emergy flows partitioned according to source and aggregated as direct and indirect inputs for the production soybean biodiesel (giga-sej/gallon).

		SOURCE					
		R	N_o	N_m	N_f	N_p	*Total by Category*
CATEGORY	D_I	5360	4348	0	0	0	9708
	D_F	0	0	0	4838	1904	6742
	I_G	46	0	945	928	1551	3471
	I_S	849	0	637	2901	2689	7076
Total by Source		**6255**	**4348**	**1582**	**8668**	**6144**	**26997**

In the production process of castorbean biodiesel, the largest ultimate source of solar emergy was also from non-petroleum fossil fuel (N_f), which was 9158 giga-sej per gallon (Table 33). However only about 2/5th of the total non-petroleum fossil fuel amount (3540 giga-sej) was from direct consumption while the remainder entered the system through indirect pathways embodied in consumption of goods (3166 giga-sej) and services (2453 giga-sej) (Table 33).

Table 33: Summary of emergy flows partitioned according to source and aggregated as direct and indirect inputs for the production of castorbean biodiesel (giga-sej/gallon).

		SOURCE					
		R	N_o	N_m	N_f	N_p	*Total by Category*
CATEGORY	D_I	2615	7967	0	0	0	10582
	D_F	0	0	0	3540	1154	4694
	I_G	14	0	542	3166	2330	6051
	I_S	718	0	538	2453	2273	5982
Total by Source		**3348**	**7967**	**1080**	**9158**	**5757**	**27309**

Integrating the environmental, energy and financial resource inputs required throughout the chain of processes needed for making biodiesel from soybean (Table 32) revealed that 40% (Row: D_I D_F I_G Column: R, N_o and N_m) came from the environment, 34% came from fossil energy sources and the remaining 26% (Row: D_I D_F I_G Column: N_f and N_p) was financial resources in paid human services (Row I_S Column: R, N_o, N_m, N_f and N_p). Of the environment sources in the soybean biodiesel production, about 70% was from non-renewable sources in loss of soil due to erosion for crop growth. On the other hand, the environmental, energy and financial resource inputs required for making biodiesel from castorbean (Table 33) showed that 41% was from environment, 37% came from fossil energy sources and the remaining 22% was financial resources in paid human services. Almost half of castorbean biodiesel is derived from environment sources, of which about 76% is from non-renewable sources (groundwater, soil, and mineral).

Indirect inputs were a major source of total emergy requirements (Table 32 and 33). The indirect use of emergy in the production of biodiesel accounted for 39% in the soybean production system and 44% of the total consumption in castorbean to biodiesel. This indirect emergy came from energy embodied in financial services and from energy embodied in imported goods like manufactured machinery, fertilizers, and infrastructure. The major reliance on indirect inputs indicated that the production system enjoyed a hidden energy-subsidy that was provided by the larger economy. Energy analyses that do not fully account for this subsidy are likely missing a majority of the energy embodied in biofuel production systems.

New Emergy Indices based on Refined Partitioning

Table 34, presents a new set of emergy-based indicators that were developed based on emergy flows from Tables 32 and 32. Note that in calculating the new emergy indices presented in Table 34, the solar emergy value of the biodiesel yielded from the production system (Y_{biod} = 15,087 giga-sej per gallon) was the available energy of ethanol (137 megajoules per gallon, USDOE, 2006) multiplied by the solar transformity of petroleum products (110,000 sej/joule, Odum, 1996).

Table 34: Indices for assessing the viability of producing biodiesel from soybean and castorbean

Indices	**(A) Soybean Biodiesel**	**(B) Castorbean biodiesel**
Emergy content of biodiesel Y_{biod}= (137E06 Joules)X(1.1E05 sej per Joules) (giga-sej/gallon)	15,087	15,087
Total emergy used: $U=R+N_o+N_m+N_f+N_p$	26,997	27,309
Net liquid fuel available beyond production (Y_{biod} -N_p) (giga-sej/gallon)	8,942	9,329
Liquid produced to total emergy used: Y_{biod}/U	0.55	0.55
Liquid produced to petroleum used: (Y_{biod} /(N_p)	4.4	2.6
Yield of net liquid produced to petroleum emergy used (Y_{biod} - N_p /(N_p)	1.74	1.63
Net Liquid Yield Ratio, EYR_P: (Y_{biod}- N_p)/($E+N_o+N_m+N_f$)	0.43	0.43
Liquid produced to fossil emergy used: Y_{biod} /(N_f+N_p)	1.82	1.01
Ratio of liquid available per non-petroleum fossil emergy used (EYR_f) (Y_{biod} / N_f)	1.74	1.65
Yield ratio of net liquid available per fossil emergy used (EYR_f) ((Y_{eth} -N_p) / N_f)	1.03	1.02
Percent from Renewable sources (R/U)	23%	12%
Percent from free-environmental sources: ($R+N_o+N_m$)/ U	45%	45%
Percent from liquid fuels: N_p/U	23%	21%
Percent from fossil fuels: (N_p+N_f)/U	55%	55%
Percent from Indirect Sources (I_G+I_S)/U	39%	44%
Percent from Direct Sources (D_I + D_f)/U	61%	56%

Is oil crop-to-biodiesel a primary energy source? The ratio of biodiesel yield to emergy used for both soybean and castorbean (Table 34) was less than 1. This indicated that biodiesel production from either soybean or castorbean consumed more emergy than it produced. As a result biodiesel from either of these sources was not a primary energy source and can not compete with present primary sources of energy.

Can oil crop-to-biodiesel replace petroleum diesel? The oil crop to biodiesel process for soybean produced 4.4 gallons of biodiesel for each gallon of petroleum used, conversely 2.6 gallons of biodiesel were produced per each gallon of petroleum used in castorbean process (Y_{biod} /N_p) (Table 34). However, the "net" yield was reduced to 1.74 units for soybean and 1.63 units for castorbean. These results suggested that there was a net yield of liquid fuel for both soybean and castorbean biodiesel.

What was the net yield of biodiesel if petroleum was completely substituted during production? By completely eliminating the petroleum (N_p) input from calculations the net yield of liquid produced per unit of total input was calculated, assuming a true substitution where all petroleum (N_p) required in the production was derived from the biodiesel production system itself. The Net Liquid Yield Ratio (Table 34) was less than 1 this indicated that processing soybean or castorbean into biodiesel consumed more emergy than the emergy content of biodiesel produced.

How much fossil fuel was used in the production of biodiesel? Now if one considered the net output of liquid fuel in terms of total fossil fuel emergy used [$Y_{biod}/(N_f+N_p)$], oil crop-to-biodiesel provided a gain of 1.82 solar emergy joules of liquid fuel for each solar emergy joule of fossil used under the soybean production process, indicating that it could be a competitive process for converting non-petroleum fossil fuels (coal and natural gas) into liquid form. However, in the production of biodiesel from castorbean the net output of liquid fuel in terms of total non-petroleum fossil fuels used was slightly over 1 indicating that the castorbean biodiesel is not a competitive process for converting non-liquid fossil fuel into liquid form.

The liquid yield per non-petroleum emergy (N_f) used for soybean biodiesel was 1.74 of liquid fuel emergy were produced per each unit of non-petroleum emergy used. The liquid yield per non-petroleum emergy (N_f) used for castorbean biodiesel was 1.65 of liquid fuel emergy were produced per each unit of non-petroleum emergy used. However, if some of the produced biodiesel yield were returned to the complete chain of processes in place of gasoline, diesel and other petroleum products, then the net liquid yield per non-petroleum emergy used was reduced to 1.03 and 1.02 for soybean and castorbean respectively (Table 34). In other words, the soybean-to-biodiesel process yielded between 1.03 and 1.02 units of liquid fuel emergy per each unit coal and natural gas emergy used. These 1.03 and 1.02 gallons from soybean and castorbean biodiesel, respectively, were available for use in the transportation sector to replace diesel.

Is oil crop-to-biodiesel a 'renewable' source of liquid energy? Since over 88% of the energy of the total emergy consumption (Table 34) in the production of biodiesel from a feedstock of soybean or castorbean was from non-renewable then biodiesel from castorbean or soybean is not 'renewable' because only between 12% and 23% of the energy came from renewable sources.

What is the significance of indirect inputs? Indirect sources of emergy were significant, making up between 39% to 44% of total inputs in biodiesel (Table 34) while direct inputs were between 56% to 61%. These results indicated that energy accounting methods that exclude or partially account for the energy embodied in indirect goods, capital and services miss the vast majority of energy required to produce biodiesel from oil crops, and likely would lead to faulty decisions regarding the viability of 'biofuels'.

Chapter 4: CONCLUSIONS

- Integrating the environmental, energy and financial resource inputs required throughout the process chain needed for making ethanol from cellulosic feedstock and biodiesel from oil-crops revealed that between 21% to 44% came from the environment, 18% to 73% came from fossil energy sources and the remaining 2% to 61% was paid human services.
- Rainwater for crop growth was the largest environmental resource input in switchgrass, hybrid poplar and soybean crops closely followed by topsoil loss.
- Groundwater used for irrigation was the largest environmental input to castorbean crop production followed by rainwater for crop growth and topsoil loss.
- Biosolids recycling indices indicated that there was a benefit of recycling biosolids to the hybrid poplar tree farm. The Landfill Recycle Ratio (LLR) indicated that it would require society to devote 1.78 as much emergy to landfill the biosolids as to recycle them to the poplar farm.
- The Recycle Yield Ratio (RYR) indicated that the overall net benefit to society in recycling biosolids to the tree farm was comparable to the benefits of recycling aluminum. One of the most direct benefits attained in the use of biosolids at the farm is the return of organic matter to soil to transform depleted land into a more ecologically productive landscape that provides ecosystem services such as wildlife habitat and aesthetic improvements.
- The new refined approach for partitioning solar emergy according to its ultimate source showed that the consumption of non-petroleum fossil fuels was greater than

petroleum, financial resources in human service, mineral or renewable emergy for the production of biodiesel from castorbean and soybean.

- The new refined approach for partitioning of solar emergy according to its ultimate source showed that the largest source of energy for the production of ethanol was from non-petroleum fossil fuel except in the case of hybrid poplar-ethanol under the assumption that biosolids were "free," in which petroleum fuel sources was the largest source.
- Between 0.06 and 4.2 gallons of ethanol were produced per gallon of petroleum consumed depending on feedstock.
- Between 2.6 and 4.4 gallons of biodiesel were produced per gallon of petroleum used in castorbean biodiesel and soybean biodiesel, respectively.
- Under a Baseline Scenario, which assumed high conversion yields for switchgrass-to-ethanol and low input prices, there was a net energy yield of 5% after accounting for petroleum replacement with ethanol along the process chain. In contrast, less optimistic assumptions showed that more energy was consumed than energy produced.
- There was no net energy yield for hybrid poplar-ethanol or biodiesel, indicating that these were not viable processes for replacing liquid petroleum demand.
- The amount of non-renewable resources used to produce cellulosic ethanol was between 75% and 90% of total inputs depending on feedstock and, in the case of recycling biosolids to the poplar farm, assumptions about how to account for the solar emergy of the biosolids.

- The amount of non-renewable resources used to produce biodiesel from soybean was 76% and from castorbean 87% of total resource requirements.
- The heavy reliance on non-renewable energy inputs indicated that neither lignocellulosic ethanol nor biodiesel were ‘renewable’ sources of energy.
- The largest non-renewable inputs were petroleum, coal and natural gas.
- Energy use ‘hidden’ in monetary flows ranged from 2% to 61% of total requirement for lignocellulosic ethanol and 22% to 26% for biodiesel.
- Indirect energy consumption ranged from 65% to 99% of total requirements for lignocellulosic ethanol and 39% to 44% for biodiesel. This indicated that both were highly dependent on inexpensive economic goods and services and extremely sensitive to price fluctuations of inputs. It also highlighted the importance of accounting for indirect sources of energy.
- The net energy yield of switchgrass-ethanol was sensitive to input prices, due to the high reliance on ‘hidden energy flows’, which indicated that energy analysts must account for financial inputs to fully assess net energy questions.
- The net energy yield of switchgrass-ethanol was also highly dependent on technical assumptions about conversion efficiencies. This indicated that the viability of cellulosic-ethanol depends on achieving the high conversion yields attained in lab-scale systems.
- The net energy yield of switchgrass-ethanol was also highly dependent on whether processing facilities generated their own electricity on-site from process by-products.

Policy Implications

In recent years U.S. policy makers have focused on promoting lignocellulose sources for ethanol production because these feedstocks are perceived to be more promising than corn-ethanol. It is contended that a cellulosic feedstock such as switchgrass can be planted for an 11 year cycle and harvested on a short cycle, yielding at least 2 crops each year, which makes it more productive than corn This type of crop system, in turn, would make biomass feedstock more cost-effective and less resource intense than corn ethanol. However, in the analysis reported in this thesis, making the most optimistic assumptions about operating a switchgrass-ethanol system proved that growing, harvesting and converting biomass to ethanol required 1) extensive use of fertilizers, pesticides and energy inputs and 2) energy-dense fossil fuels to breakdown the structural biomass to facilitate the fermentation process. As a result, the high energy intensity of the cellulose-to-ethanol process ultimately limits its energetic output and thus its ability to replace gasoline.

Recent studies have shown that the productivity of switchgrass is high when grown in fertile soil with lots of fertilizer, pesticide and energy inputs (Tilman et al., 2006). Therefore to grow enough switchgrass to produce substantive amount of ethanol to replace gasoline would require vast amount of fertile cropland. This thesis showed that to produce enough switchgrass to replace 10% of the nation’s liquid petroleum fuel demand required 77 million acres, which is equivalent to 9% of US cropland. To put this into perspective, according to the USDA (2002), 303 million acres of cropland were harvested in 2002. However, replacing 100% of gasoline consumption with switchgrass-ethanol would require 770 million acres. As a result, all of the US cropland, 434 million acres, and most of the 385 million acres of grassland would need to be dedicated to the production of switchgrass. This analyis showed that growing enough switchgrass feedstock to replace 10% of the current U.S. consumption would also require about 7.7 billion pounds of nitrogen or about 25% of the nitrogen used by all crops in 2003. Moreover, because nitrogen fertilizer is mainly produced from natural gas and since over half of the nitrogen fertilizer is produced from foreign natural gas, the production of switchgrass-ethanol would merely shift our reliance from foreign oil to foreign natural gas. This study also showed that production of switchgrass-ethanol was highly sensitive to the prices of inputs, indicating that its viability depended on cheap fertilizers and fossil fuels.

Comparing switchgrass-ethanol to Ulgiati's (2001) corn-ethanol production analysis (Table 35) showed that the emergy yield ratio for switchgrass was only marginally better than corn ethanol and not the promising prospect that many promote. With such marginal energy gains, it would seem that government efforts supporting cellulosic ethanol are not worthwile.

Table 35. Comparison of emergy indices for switchgrass-ethanol and corn-ethanol*

Index	*Agricultural Production*		*Industrial Ethanol Processing*	
	Switchgrass	Corn*	Switchgrass	Corn*
Specific Emergy (1E6 sej/gram)	409	618	5030	4660
Transformity (sej/joule)	22,100	42,200	170,000	176,000
Emergy Yield Ratio	1.55	1.20	1.30	1.08
Environmental Load Ratio	2.2	7.42	3.9	17.65
Emergy Investment Ratio	1.83	4.89	3.4	12.06
Emergy Sustainability Index	0.73	0.16	0.3	0.06
Percent Renewable	35	12	20	5.4

*Ulgiati, 2001

Overall, the role for biofuels as a substitute for fossil fuels was limited because their production relied heavily upon the use of fossil fuels. This was in part because large amounts of fossil energy embodied in transportation fuels, electricity, fertilizers, peticides and human labor were used during both agricultural production and the biomass-to-liquid-fuel conversion process. As a result, biofuels provided a small amount of net energy, if any at all, which was well below the net energy of fossil fuels used today.

While an economic analysis addresses only the costs of biofuel production, an energy accounting provides a framework to assess the energetic vaiability of the production process. Emergy-based energy analyses broaden the spectrum and provide the means to integrate energetic, economic and environmental tradeoffs of proposed alternative energies. In this particular case, the emergy analysis showed that envriomental inputs, like freshwater used during agricultural production were important to the biofuel production systems. It also showed that biofuel production relied heavily on indirect energy inputs hidden in purchases of goods and services, indicating that energy accounting methods that exclude or partially account for the energy embodied in indirect goods, capital and services miss the vast majority of energy required to produce biofuels and likely would lead to faulty decisions regarding the viability of ‘biofuels’.

Summary

In summary, it was concluded that neither cellulosic ethanol made from switchgrass nor hybrid poplar feedstock, nor biodiesel made from soybean or castorbean, can be a primary source of liquid fuel that substitutes for petroleum-based fuels. Rather, their production is an energy consuming process that provides a means to convert stocks of water, soil, coal, natural gas, and electricity into a liquid fuel that is highly demanded by Americans for transportation. With marginal to negative net energy yields, the current political push to subsidize “biofuels” like switchgrass ethanol will only accelerate the rate at which the nation depletes its endowment of coal, natural gas and uranium. Like Odum

(1996) pointed out, crude oil and coal production have Emergy Yield Ratios on the order of 3:1 to 12:1, which ‘sets the bar’ for proposed alternatives. If an alternative does not meet this level, then it will not be competitive. It is critical that primary fuels have high yield ratios because they are the foundation of the economy. A low positive yield ratio (less than 2.0) offers little extra energy for use in ‘downstream’ economic sectors. It is not sufficient to just have a positive yield ratio to be of economic value; the yield ratio needs to be large (i.e., likely greater than 3-to-1) to support an extensive web of economic sectors.

Appendix A: Transformity Partitioning

Partitioning Method:

In the refined emergy analysis, the solar emergy of each input was partitioned into five categories that represented the ultimate sources of the input. These five categories were: environmental flows (N_r), environmental non-renewable flows (N_o), non-renewable flows from minerals (N_m), non-renewable flows from coal and natural gas (N_f), and non-renewable flows from petroleum (N_p). Partitioning each input was accomplished by separating the original transformity of the input into 'partial transformities' that corresponded to each of the five categories. Partial transformities were defined as the fraction of an original (total) solar transormity derived from a specific source category. The fractions were obtained by identifying the amount of each source used to calculate the original transformity and then dividing this amount by the sum of all sources.

1. Mineral and material transformities (sej/g) were partitioned by first subtracting the emergy associated with the formation of sedimentary rocks (1.68E+09 sej/g). The reminder of the transformity was then allocated to its corresponding fraction of N_f, N_r and N_p.

2. Energy transformities (sej/J) were partitioned by dividing the input of each of the sources by sum of all sources.

3. For purchased inputs expressed in money the solar emergy to dollar ratio (sej/$) was partitioned based on the fraction that N_r Nm N_f, and N_p, and contributed to the US economy in 2000 (Tilley, 2006). .

Calculations

Tables A1 shows the partial transformities that were estimated from partitioning. Column B is the original solar transformity, which can be thought of as a ‘total’ transformity. Column C gives the units for the solar transformity. Column D is the ‘renewable’ partial transformity. Column E is the ‘non-renewable mineral’ partial transformity. Column F is the ‘non-petroleum fuel’ partial transformity. Column G is the ‘petroleum’ partial transformity.

Table A1: Partitioning of original transformities into renewable (R), non-fuel mineral (N_o), non-petroleum fuel (N_f), and petroleum (N_p) fractions.

Item (A)	Original Transformity (B)	Unit (C)	Nr (D)	Nm (E)	Nf (coal, Nat. gas &Electricity) (F)	Np (petroleum) (G)
1. Ammonia	2.87E+09	sej/gram	0	0	2.87E+09	0
2. Phosphate	6.55E+09	sej/gram	0	1.68E+09	4.56E+09	3.11E+08
3. Potash	1.85E+09	sej/gram	1.06E+08	1.68E+09	5.97E+07	4.59E+06
4. Lime	1.73E+09	sej/gram	9.80E+06	1.68E+09	2.06E+07	1.96E+07
5. Machinery	1.30E+10	sej/gram	0	1.68E+09	9.55E+09	1.77E+09
6. Cement	3.33E+09	sej/gram	0	1.68E+09	1.56E+09	8.23E+07
7. Steel	6.97E+09	sej/gram	0	1.68E+09	9.53E+08	4.34E+09
8. Switchgrass	4.09E+08	sej/gram	1.56E+08	1.07E+08	8.41E+07	6.24E+07
9. Hybrid Poplar						
Scenario 1	1.34E+09	sej/gram	4.24E+08	7.90E+07	3.63E+08	4.74E+08
Scenario 2	6.04E+10	sej/gram	6.33E+09	8.93E+09	2.99E+10	1.52E+10
Scenario 3	4.11E+09	sej/gram	4.46E+08	1.51E+09	1.62E+09	5.33E+08
10. Soybean	8.32E+08	sej/gram	4.85E+08	4.99E+07	1.37E+08	1.60E+08
11. Castorbean	3.37E+09	sej/gram	1.75E+09	1.00E+08	1.16E+09	3.57E+08
12. Soybean “crude oil”	7.06E+09	sej/gram	3.11E+09	3.41E+08	2.36E+09	1.25E+09
13. Castorbean “crude oil”	7.12E+09	sej/gram	3.32E+09	2.08E+08	2.46E+09	1.13E+09
14. Herbicide	1.11E+05	sej/joule	0	0	0	1.11E+05
15. Potable Water	3.14E+05	sej/joule	8.48E+04	1.29E+05	8.17E+04	1.88E+04
16. Processed Food	5.54E+05	sej/joule	1.55E+05	4.99E+04	2.05E+05	1.44E+05
17. Glucose-sugarcane	1.94E+04	sej/joule	7.37E+03	1.75E+03	4.85E+03	5.43E+03
18. Fuel	1.11E+05	sej/joule	0	0	0	1.11E+05
19. Money	1.1E+12	sej/$	1.32E+11	9.9E+10	4.51E+11	4.18E+11

Footnotes Table A1

1. **Ammonia:** Partitioning was calculated in this study based on the process used in Haldor Topsoe plants (Smil,1999) which gives 35.6 MJ-natural gas per kg of nitrogen as the total energy requirement for ammonia production. All of the emergy was allocated to N_f.

2. **Phosphate:** Partitioning was based on Odum's 1996 evaluation of phosphate production in Florida.

3. **Potash:** Partitioning fractions was calculated in this study based on data from Department of Interior at the USGS (DOI, 1997) and CRU International Ltd. (CRU, 2006).

4. **Lime:** Partitioning fractions was calculated in this study based on data from Department of Interior at the USGS (DOI, 1997).

5. **Machinery:** Transformity of Machinery is from Brown and Arding, 1991. Since the original transformity calculation was not available. The partitioning into renewable, mineral, non-petroleum fossil fuel and petroleum was based on the energy consumption of industrial machinery and equipment industry in the US (USDOE, 1994).

6. **Cement:**Partitioning fractions of cement is from Buranakarn, 1998.

7. **Steel:** Partitioning fractions of steel is from Buranakarn, 1998.

8. **Switchgrass:** Partitioning fractions for switchgrass is from this study.

9. **Hybrid Poplar:** Partitioning fractions for hybrid poplar crop is from this study.

10. **Soybean:**Partitioning fractions for soybean crop is from this study.

11. **Castorbean:** Partitioning fractions for castorbean crop is from this study.

12. **Soybean "crude oil":** Partitioning fractions for soybean "crude" oil is from this study

13. **Soybean "crude oil"** Partitioning fractions for castorbean "crude" oil is from this study

14. **Herbicide:** Partitioning fractions for herbicide is from fossil fuel Odum, 1996. This transformity represents the energy embodied by herbicide. Thus, all of the emergy was allocated to and non-renewable flows from petroleum.

15. **Potable Water:** Partitioning fractions for potable water is from Buenfil, 1998.

16. **Processed Food:** Partitioning fractions for processed food is from Johansson, 2005.

17. **Glucose:** Partitioning fractions for sugarcane is from Brandt-Williams, 2000.

18. **Fossil Fuel:** Partitioning fractions for fossil fuel Odum, 1996. This represents the energy embodied in fossil fuel. Thus, all of the emergy was allocated to and non-renewable flows from petroleum.

19. **Money:** Partitioning fractions for money is based in Odum, 1996. The fraction of renewable, mineral, non-petroleum fossil fuel and petroleum was calculated based on total emergy consumed from renewable, mineral, non-petroleum fossil fuel and petroleum in the economy as (Tilley, 2006).

Appendix B: Notes for Emergy Tables for Switchgrass to Ethanol

Footnotes to Table 2. All agricultural inputs were determined on a per hectare basis and divided by the estimated gallons of ethanol that would be produced per hectare of cropland, which equaled 619 gallons per ha. Farmed area was 1 ha. Older transformity values were corrected by factor of 1.68 (Odum et al., 2000). Values given for line items were prorated over 11 year stand cycle therefore the total emergy column reflect the annual inputs.

1. Transformity of sunlight = 1 sej/J by definition (Odum, 1996). Solar insolation was annual average for Iowa (USA) at 42 degrees latitude and 93 degrees longitude. Data: 4.12 kWh/m^2/day; albedo = 0.23 (NASA, 2006). Energy in sunlight = (10000 m^2)X(4.12 kWh/ m^2 /day)X((859.9 kcal per kWh)X(365 days per year)X(1-albedo)X(4186 joules per kcal)/(619 gallons ethanol per ha) = 6.73E10 J

2. Transformity of wind = 2513 sej/J (Odum, 1996). Wind was annual average of three stations in Iowa (USA) (University of Utah, 2006); calculation of geostrophic wind based on fact that observed wind is about 0.6 of geostrophic wind. Data: Drag coefficient = 1.0E-3, dimensionless (Miller, 1964 in Kraus, 1972); wind velocity annual average estimated to be 4.92 meter per second (m/s); air density = 1.3 kg/m^3. Geostrophic wind = (4.92 m/s)/(0.6)=8.2 m/s. Energy in wind = (10000 m^2)X(1.3,kg/m^3)X(1.0E-03,drag coefficient)X(8.2 m/s)^{3}X(3.14E07 seconds/year)X(1 joule / kg m^2/s^2)/(619 gallons ethanol per ha) = 3.63E8 J

3. Transformity of rain = 30576 sej/J (Odum, 1996). Data: annual rainfall of 813 mm per year (Iowa State University, 2006); density of water 1000kg/m^3. Annual Energy = (10000 m^2)X(813 mm)X(0.001 m/mm)X(1000 kg/ m^3)X(4940J/kg)/(619 gallons per ha) = 6.49E07 J

4. Transformity of evapotranspiration (ET) = 30576 sej/J (Odum, 1996). ET averaged from observation of 13 plots of switchgrass (Brown, et. al, 1998). Data: ET=680 mm/year; specific gravity of water = 1.0E06 g/ m^3. Energy in ET = (10000 m^2)X(680 mm/yr)X(0.001 m/mm)X(1E06 g/ m^3)X(4.94J/g)/(619 gallons ethanol per ha) = 5.43E7 J

5. Transformity of topsoil = 73,800 sej/J (Odum, 1996). Estimated annual average soil displacement on cropland in Iowa for more than 26 million acres planted to row crops, small grain, and forages for hay production (Miller et. al, 1998). The energy in the organic soil content was estimated from average of caloric content on the composition of soil organic matter (SOM) materials from composition of SOM (UM, 2006) and energetic value of particulate organic matter (Malone and Swartout, 1969; Currie et al., 2003) and energetic value of decomposed organic material (Chubu Shiryo Co.,Ltd., 2006). The percent organic soil average from Lucas, Wayne, Appanoose and Monroe counties in Iowa. Data: soil erosion 2.44E07 grams per ha; average organic percent in soil 3.85% (Al-Kaisi et al., 2006); energy organic soil 3.84 kcal/gram. Energy in soil = (10000 m^2)X(2.44E07 grams per ha)X(1 ha/10,000 m^2)X(3.84 %)X(3.84 kcal/g)X(4186 J/kcal)/(619 gallons ethanol per ha) = 2.44E07 J

6. Transformity for fuels = 1.1E05 sej/g (Odum, 1996). Data: herbicide requirements for switchgrass establishment and reseeding included a one time application of 3.5 liters per ha (1.5 quart per acre) of atrazine and 1.77 liters per ha (1.5 pint per acre) of 2,4-D, with 25% probability for reapplication (Duffy and Nanhou, 2002). Atrazine density is 1.187g per cm^3; 2,4-D density is 1.56 g per cm^3. The embodied fossil fuel energy in atrazine was estimated at 0.005 liter petroleum per gram (0.584 gallons fuel per lb) and 0.002 liters per gram (0.261 gallons of fuel per lb) of 2,4-D (Helsel, 1992).

- Grams of Atrazine required = (3.5 liters)(1000 cm^3 per liter)(1.187 g per cm^3)=4154.5 grams of Atrazine. However 1038.6 grams (25% of the value) was added to address the probable need for a reapplication.
- Embodied fossil fuel in Atrazine= (4154.5+1038.6 grams Atrazine)(0.005 liter gasoline per gram Atrazine)=26 liters of petroleum equivalent.
- Grams of required 2,4-D=(1.77 liters)(1000 cm^3 per liter)(1.56 g per cm^3)=2761 grams of 2,4-D. However 690 grams (25% of the value) was added to address the probable need for a reapplication.
- Embodied fossil fuel in 2,4-D = (2761+690, grams 2,4-D)(0.002 liter gasoline per gram 2,4-D)=6.9 liters of petroleum equivalent.

Energy in herbicides = (10000 m^2)X(26+6.9, liters of gasoline in herbicide used in 10,000 m2 area)X(3.6E07 joules per liter of petroleum)/(619 gallons ethanol per ha)= 1.9E06 J

7. Mass Transformation Ratio for ammonia = 2.87E09 sej/g calculated in here based in Haldor Topsoe Plants (Smil, 1999). The process uses 35.6 MJ/kg of nitrogen as the total energy for ammonia production. There is **no** nitrogen required for switchgrass during establishment and re-seeding (Duffy and Nanhou, 2002). Mass in nitrogen= (10000 m^2)X(Nitrogen used, kg/m2)X(1000 g/kg)/(619 gallons ethanol per ha) = 0

8. Mass Transformation Ratio for P_2O_5 = 6.55E09 sej/g (Odum, 1996). Data: P_2O_5 requirements for switchgrass estimated at 33.63 kg/ha (Duffy and Nanhou, 2002). Mass of P_2O_5 = (10000 m^2)X(33.63 kg/ha (1ha /10,000 m^2)X(1000, g/kg)/(619 gallon ethanol per ha) = 54 grams

9. Mass Transformation Ratio for potash (K_2O_5) = 1.85E09 sej/g calculated in here based on energy and environmental profile for potash (USDOI, 1997). Data: K_2O_5 requirements for switchgrass estimated at 44.8kg/ha (Duffy and Nanhou, 2002). Mass of potash (K_2O_5) = (10000 m^2)X(44.8 kg/ha)X(1 ha /10,000 m^2)X(1000 g/kg)/(619 gallon ethanol per ha) = 72 grams

10. Mass Transformation Ratio for lime = 1.73E09 sej/g calculated in here based on energy content for surface mining and beneficiation (USDOI, 1997). Data: lime requirements for switchgrass recommendation average about 4.48 metric tons per ha during the life of the strand (Qin et al., 2005). In this analysis lime was accounted for in establishment year and spread over 11 years (Duffy and Nanhou, 2002). Mass in lime= (10000 m^2)X(4.48 metric tons per ha)X(1ha/10, 000 m^2)X(1E06 grams per metric ton)/(619 gallon ethanol per ha)=7239 grams

11. Mass Transformation Ratio of machinery = 1.30E10 sej/g (Odum, 1996). Data: total equipment required for establishment and reseeding weighs about 14102 kg; it was assumed that the equipment was used for 54.07 hrs per ha (21.9 hrs per acre) (Green and Benson, 2006) has a life cycle of 64800 hrs (7.5yr). Rate of equipment used per ha was calculated = (54.07 hrs per ha per year)/(64800 hrs lifetime equipment) = 0.0008 equipment/ha/y. Mass in equipment= (0.0008 equipment/ha/y)X(14102 kilograms)X(1000 grams/kilogram)/(619 gallon ethanol per ha) = 19 grams

12. Tranformity diesel = 1.1E5 sej/J (Odum, 1996). Agricultural activities included: disking, harrowing, mowing, airflow spreader spraying fertilizer. Data: liters of diesel fuel per ha per year was estimated at 35.1 (3.75 gal per acre) (Hanna and Ayres, 2001; Edwards and Smith, 2001). Energy in diesel= (10000, m^2)X(3.75 gallons per acre)X(1 acre / 0.405 ha)X(1 ha /10,000 m^2)X(132000 Btu per gallon diesel)X(1055 joules per Btu)/(619 gallon ethanol per ha) = 2.08E6 J

13. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of services on herbicides $17.16/ha (Duffy and Nanhou, 2002). (10000 m^2)X($17.16 per ha)X(1 ha / 10000 m^2)/(619 gallon ethanol per ha)= $0.03

14. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of services on fertilizers $42.79 /ha, (Duffy and Nanhou, 2002). (10000, m^2)X($ 42.79 per ha (1ha / 10000 m^2)/(gallon ethanol per ha)= $0.07

15. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of services on lime $56.79/ha, (Duffy and Nanhou, 2002). (10000 m^2)X($ 56.79/ per ha) (1 ha/10000 m^2)/(619 gallon ethanol per ha)= $0.09

16. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of services on labor to operate machinery $43.64 /ha, (Duffy and Nanhou, 2002). (10000 m^2)X($ 43.64 per ha)X(1ha/ 10000 m^2)/(619 gallon ethanol per ha)= $0.07

17. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Based on estimate fuel cost of $0.31 per liter ($1.18 per gallon) in Midwest in 2000-2001 (EIA, 2006). Data: cost of services on fuel $10.5 /ha, (Duffy and Nanhou, 2002). (10000 m^2)X($ 10.93 per ha)X(1 ha/ 10000 m^2)/(619 gallon ethanol per ha)= $0.02

18. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: other production cost $439.51 /ha, (Duffy and Nanhou, 2002). (10000 m^2)X($ 439.51 per ha)X(1 ha/10000 m^2)/(619 gallon ethanol per ha)= $0.71

19. Sum of all components except 1, 2 & 3

Footnotes to Table 3. All agricultural inputs were determined on a per hectare basis and divided by the estimated gallons of ethanol that would be produced per hectare of cropland, which equaled 619 gallons per ha. Farmed area was 1 ha. Older transformity values were corrected by factor of 1.68 (Odum et al., 2000)

1. Transformity of sunlight = 1 sej/J by definition (Odum, 1996). Solar insolation was annual average for Iowa (USA) at 42 degrees latitude and 93 degrees longitude. Data: 4.12 kWh/m^2/day; albedo = 0.23 (NASA, 2006). Energy in sunlight = (10000 m^2)X(4.12 kWh/ m^2 /day)X(859.9 kcal per kWh)X(365 days per year)X(1-albedo)X(4186 joules per kcal)/(619 gallons ethanol per ha) = 6.73E10 J

2. Transformity of wind = 2513 sej/J (Odum, 1996). Wind was annual average of three stations in Iowa (USA) (University of Utah, 2006); calculation of geostrophic wind based on fact that observed wind is about 0.6 of geostrophic wind. Data: Drag coefficient = 1.0E-3, dimensionless (Miller, 1964 in Kraus, 1972); wind velocity annual average estimated to be 4.92 meter per second (m/s); air density = 1.3 kg/m^3. Geostrophic wind = (4.92 m/s)/(0.6)=8.2 m/s. Energy in wind = (10000, m^2)X(1.3, kg/m^3)X(1.0E-03,drag coefficient)X(8.2, m/s)^{3}X(3.14E07, seconds/year)X(1 joule / kg m^2/s^2)/(619 gallons ethanol per ha) = 3.63E8 J

3. Transformity of rain = 30576 sej/J (Odum, 1996). Data: annual rainfall of 813 mm per year (Iowa State University, 2006); density of water 1000kg/m^3. Annual Energy = (10000 m^2)X(813, mm)X(0.001 m/mm)X(1000 kg/ m^3)X(4940 J/kg)/(619 gallons ethanol per ha) = 6.49E07 J

4. Transformity of evapotranspiration (ET) = 30576 sej/J (Odum, 1996). ET averaged from observation of 13 plots of switchgrass (Brown, et. al, 1998). Data: ET=680 mm/year; specific gravity of water = 1.0E06 g/ m^3. Energy in ET = (10000 m^2)X(680, mm/yr)X(0.001 m/mm)X(1E06 g/ m^3)X(4.94J/g)/(619 gallons ethanol per ha) = 5.43E7 J

5. Transformity of topsoil = 73,800 sej/J (Odum, 1996). Estimated from average erosion rate for established switchgrass crop under grazing from (Pitts et. al., 1997). The energy in the organic soil content was estimated from average of caloric content on the composition of soil organic matter (SOM) materials from composition of SOM (UM, 2006) and energetic value of particulate organic matter (Malone and Swartout, et. al, 1969, Currie et al., 2003); and energetic value of decomposed organic material (Chubu Shiryo Co., Ltd., 2006). The percent organic soil average from Lucas, Wayne, Appanoose and Monroe counties in Iowa. Data: erosion rate is estimated at 2.75E05 grams/ha/yr; average organic percent in soil 3.85% (Al-Kaisi, et. al., 2006); energy organic soil 3.84 kcal/g. Energy in soil = (10000 m^2)X(2.75E05 grams per ha)X(1 ha/10,000 m^2)X(3.85, O.M. %)X(3.84 kcal/g)X(4186 J/kcal)/(619 gallons ethanol per ha) = 2.73E05 J

6. Transformity for fuels = 1.1E05 sej/g (Odum, 1996). Data: herbicide requirements for switchgrass establishment and reseeding included a one time application of 3.5 liters per ha (1.5 quart per acre) of atrazine and 1.77 liters per ha (1.5 pint per acre) of 2,4 D (Duffy and Nanhou, 2002). Atrazine density is 1.187g per cubic cm^3; 2,4-D density is 1.56 g per cm^3. The embodied fossil fuel energy of atrazine was estimated at 0.005 liter petroleum per gram (0.584 gallons fuel per lb) and 0.002 liters per gram (0.261 gallons of fuel per lb) of 2,4-D (Helsel, 1992).

- Grams of Atrazine required = (3.5 liters)X(1000 cm^3 per liter)X(1.187 g per cm^3)=4154.5 grams of Atrazine.
- Embodied fossil fuel energy in Atrazine= (4154.5 grams)X(0.005 liter gasoline per gram)=20.8 liters of petroleum equivalent.
- Grams of required 2,4-D=(1.77 liters)X(1000 cm^3 per liter)X(1.56 g per cm^3)=2761 grams of 2,4-D.
- Embodied fossil fuel energy in 2,4-D = (2761grams 2,4-D)X(0.002 liter gasoline per gram 2,4-D)=5.52 liters of petroleum equivalent.

Energy in herbicides = (10000, m^2)X(20.8+5.52, liters of gasoline in herbicide used in 10,000 m^2)X(3.6E07 joules per liter of petroleum)/(619 gallons ethanol per ha)= 1.53E06 J

7. Mass Transformation Ratio for ammonia = 2.87E09 sej/g calculated from Haldor Topsoe Plants (Smil, 1999). The process uses 35.6 MJ/kg of nitrogen as the total energy for ammonia production. According to the USDA Fertilizer statistics, most of the fertilizer used to supply nitrogen is in the form of anhydrous ammonia or urea (USDA, 2006). Data: 112 kg per ha (100 lb / acre) of nitrogen required for switchgrass during production (Duffy and Nanhou, 2002). Mass in nitrogen= (10000, m^2)X(112 kg/ha)X(1 ha/10,000 m^2)X(1000, g/kg)/(619 gallon ethanol per ha)= 181 grams

8. Mass Transformation Ratio for P_2O_5 = 6.55E09 sej/g (Odum, 1996). Data: P_2O_5 requirements for switchgrass estimated at 8.7 kg per ha (7.76 lb/ acre) (Duffy and Nanhou, 2002). Mass of P_2O_5 = (10000 m^2)X(8.7 kg/ha)X(1 ha /10000 m^2)X(1000 g/kg)/(619 gallon ethanol per ha)= 14 grams

9. Mass Transformation Ratio for potash (K_2O_5) = 1.85E09 sej/g calculated here based on energy and environmental profile for potash (USDOI, 1997). Data: K_2O_5 requirements for switchgrass estimated at 85 kg per ha (22.8 lb/acre) (Duffy and Nanhou, 2002). Mass of Potash (K_2O_5) = (10000 m^2)X(85 kg/ ha)X(1 ha /10000 m^2)X(1000 g/kg)/(619 gallon ethanol per ha) = 137 grams

10. Mass Transformation Ratio for lime = 1.73E09 sej/g calculated here based on energy content for surface mining and beneficiation (USDOI, 1997). Data: lime requirements for switchgrass estimated at 0 (Duffy and Nanhou, 2002). Energy in lime = 0 grams

11. Mass Transformation Ratio for machinery = 1.30E10 sej/g (Odum, 1996). Data: mass machinery is 2703 kg for spraying equipment; 493kg for mower, 493 kg for rake; baling is 1411kg and loader is 2386 plus bucket 259 kg (Lague and Khelifi, 2001). Equipment use was estimated at 53 hrs per ha per year (Green and Benson, 2006; Patterson et al., 2005). It was assumed that equipment had life cycle of 64800 hrs (7.5yr). Rate of equipment used per ha = (53 hrs per ha per yr)/(64800hrs)= 0.0008 equipment/ha/y. Mass in Equipment = (.0008 equipment/ha/y)X(7.12E6 grams sum of all equipment)/(619 gallon ethanol per ha)= 9 grams

12. Tranformity diesel = 1.1E5 sej/J (Odum, 1996). Agricultural activities include: harvesting, baling, airflow spreader spraying fertilizer. Data: 27.6 liter per ha (2.95 gal per acre) (Duffy and Nanhou, 2002; Hanna and Ayres, 2001). Energy in diesel= (10000 m^2)X(2.95 gal per acre)X(1 acre/.405 ha)X(1 ha/10000 m^2)X(132000 Btu/gallon diesel)X(1055 joules per Btu)/ (619 gallon ethanol per ha) = 1.64E06 J

13. Money Transformation Ratio= 1.1E12 sej/$ (Tilley, 2006). Data: cost of services on herbicides $16.91 /ha, (Duffy and Nanhou, 2002). (10000 m^2)X($ 16.91 per ha)X(1ha/ 10000 m^2)/(619 gallon ethanol per ha)= $0.03

14. Money Transformation Ratio= 1.1E12 sej/$ (Tilley, 2006). Data: cost of services on Nitrogen $51.85 /ha, (Duffy and Nanhou, 2002). (10000 m^2)X($ 51.85/ha)X(1 ha/ 10000 m^2)/(619 gallon ethanol per ha)= $0.08

15. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of services on P_2O_5 $5.19 /ha, (Duffy and Nanhou, 2002). (10000 m^2)X($ 5.19 per ha)X(1 ha/ 10000 m^2)/(619 gallon ethanol per ha)= $0. 008

16. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of services on K_2O_5 $31.53 /acre, (Duffy and Nanhou, 2002). (10000 m^2)X($ 31.53 per ha)X(1 ha / 10000 m^2)/(619 ethanol per ha)= $0.05

17. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of services on lime $0/ha, (Duffy and Nanhou, 2002).

18. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of services on labor to operate machinery $286.16 /ha, (Duffy and Nanhou, 2002). (10000 m^2)X($

286.16 per ha)X(1 ha / 10000 m^2)/(619 gallon ethanol per ha)= $0.46

19. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of services on fuel $8.59/ha, Duffy and Nanhou, 2002). (10000 m^2)X($ 8.59 per ha)X(1 ha / 10000 m^2)/(619 gallon ethanol per ha)= $0.014.

20. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: other production land and insurance cost $188 /ha, (Duffy and Nanhou, 2002). (10000 m^2)X($ 188 per ha)X(1 ha / 10000 m^2)/(619 gallon ethanol per ha)= $0.31

21. Sum of all components except 1, 2 & 3

22. Production of switchgrass crop yielded 9.88E06 grams per ha. Moisture content of switchgrass range from 12% to15% moist; average 13.5%. Estimated dry yield = (9.88E06 grams per ha)X(86.5%) = 8.96E6 g per ha. Gallons pf switchgrass ethanol per ha were 619. Mass of switchgrass per gallon of ethanol = (8.96E06 grams)/(619 gallon ethanol per ha)=1.38E04 grams per gallon

23. The energy content of switchgrass was reported as 19055 joules per gram (8200 Btu/lb). Energy content switchgrass = (1.38E04 grams)X(19055 joules per gram) = 2.66E08 joules per gallon

24. Specific emergy per mass = (Total Emergy, line 21)/(Yield mass, line 22) = (5727E09 sej per gallon)/(1.38E04 grams per gallon) = 4.15E08 sej per gram

25. Transformity of switchgrass = (Total Emergy, line 21)/(Yield energy, line 23) = (5727E09 sej per gallon)/(2.66E08 joules per gallon) = 2.15E04 sej per joule

Footnotes to Table 4. Transportation in hectare basis and divided by the estimated gallons of ethanol that would be produced per hectare of cropland, which equaled 619 gallons per ha. Older transformity values were corrected by factor of 1.68 (Odum et al., 2000).

1. Mass Transformation Ratio for machinery = 1.25E10 sej/g (Odum, 1996). Data: class 8 truck weigh about 4540kg, has a capacity to transport 8 tons of grain, has a life cycle of 7 yr and is driven 103, 266 kilometers (64,000 miles) annually (Lovins et al., 2004). The yield of 1 ha of grains is 9.9 tons (wet) and the trip distance is assumed at 80 kilometers (50 miles) (Urbanchuk and Kapell, 2002). Total truck use estimated = (1 truck)X(1/7 year)X(80, kilometers per trip /103,266 kilometers per year)X(9.9 tons per ha /8 tons per trip) = 0.00014 truck/y. Mass in truck = (0.00014 truck per year)X(4540 kilograms)X(1000 grams/1 kilogram)/(619 gallons ethanol per ha) = 1 gram

2. Tranformity diesel =1.1E05 sej/J (Odum, 1996). Data: a class eight uses an average of 10 mile per gallon (Transportation Business Association, 2006). The grain is transported a distance of 80 kilometers (50 miles) (Urbanchuk and Kapell, 2002). The truck transports 8 tons per trip. 1 ha produces 9.9 tons wet tons of switchgrass grain. Gallons of diesel = (80, kilometers per trip) (9.9 tons per ha / 8 tons per trip) (1/4.25, km per liter) = 23 liters of diesel. Energy in diesel= (23 liters)X(0.264 gallons/ 1 liter)X(132000 Btu/gallon diesel)X(1055 joules per Btu) /(619gallons ethanol per ha) = 1.37E06 J

3. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Cost of services on operating a truck. Data: 1.24 trips/ha, cost for trucker is $0.266 per km ($0.43 per mile) (Heartland Express, 2004). ($0.267/km)X(80 km)X(1.24 trips per ha)/(ethanol per ha) = $0.043

4. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Cost of services on fuels. Data: 2003 Averaged was estimated at $0.425 per liter ($1.62 per gallon) (EIA, 2006). ($0.425/liter)X(23 liters of diesel)/(619 gallons per ha) = $0.016

Footnotes to Table 5. Inputs in kg per hour for facility running 8406 hours annually, and then converted to a per gallon basis by dividing by the volume of ethanol produced annually, which was estimated to be 69.27 million gallons of pure ethanol. Older transformity values were corrected by factor of 1.68 (Odum et al., 2000).

1. Mass Transformation Ratio for switchgrass biomass = 4.09E08 sej/g, calculated here. Data: biomass required for corn stover 12 kg per gallon (McAloon et al., 2000). The average gallons of ethanol per ton for corn stover was 83.5 gal per ton. The average ethanol gallons of ethanol per ton of switchgrass was estimated at 72 gal per ton. The mass was was adjusted by factor of 1.15 based on (83.5/72). Mass in switchgrass= (12,000 kg per gallons ethanol from corn stover)(1000grams per kg)(1.15) =13819 grams

2. Mass Transformation Ratio for lime =1.73E09 sej/g calculated here based on energy content for surface mining and beneficiation (USDOI, 1997). Data: grams calculated from 2395 kilograms per hour. (Aden et. al., 2002). Mass in lime = (2395 kg per hr)X(1000 g/ kg)X(8406 hr per yr)/(69.27E06 gallons ethanol)= 291 grams

3. Mass Transformation Ratio for ammonia = 2.87E09 sej/g based on process by Haldor Topsoe plants (Smil, 1999). Total energy for ammonia production is 35.6 MJ/kg of nitrogen. Data: Average of ammonia use = (689 kg+1811 kg +1419 kg)/3= 1306 kilograms per hour (McAloon et al., 2000; Aden et al., 2002; Wooley et al., 1999). Mass in ammonia = (1306 kg per hr)X(1000 g/ kg)X((8406 hr per yr)/(69.27E06 gallons ethanol) = 159 gram

4. Transformity of corn steep liquor from processed foods = 330000 sej/J (Johansson, 2005). Data: grams calculated from 1306 kilograms per hour. (Aden et al, 2002); energetic value estimated at 342 calories per 100 grams of cornstarch (USDA, 2006). Energy in corn steep liquor = (1306 kg per hr)X(1000 g/ kg)X(8406 hr per yr)X(3.42 calories per gram)X(.186 joules per calorie)/(69.27E06 gallons ethanol) = 2269 J

5. Transformity of nutrients from sugarcane = 1.94E04 sej/J (Brandt-Williams, 2001). Data: assuming that sugar as nutrients energy supplement for anaerobic bacteria; sugar grams estimated at 174 kilograms per hour, carbohydrates have 4 calories per gram. (Aden et al., 2002). Energy in sugarcane = (174 kg per hr)(1000 g/ kg)X((8406 hr per yr)X(4 calories per gram)X(4.186 joules per calorie)/(69.27E06 gallons ethanol) =354 J

6. Transformity of antifoam from processed foods = 330000 sej/J (Johansson, 2005). Data: grams corn oil used as antifoam is estimated at 167 kilograms per hour. (Aden et al., 2002); there are 884 calories per 100 grams of corn oil (USDA, 2006). Energy in antifoam = (167 kg per hr)X(1000 g/ kg)X(8406 hr per yr)X(8.84 calories per gram)X(4.186 joules per calorie) /(69.27E06 gallons ethanol) = 748 J

7. Mass Transformation ratio for nitrogen 2.87E09 sej/g based on process by Haldor Topsoe plants (Smil, 1999). Total energy for ammonia production is 35.6 MJ/kg of nitrogen. Data: grams of Ammonium Sulfate calculated from 158 kilograms per hour.

(McAloon et al., 2000), carbohydrates have 4 calories per gram. Mass in nitrogen = (158 kg per hr)X(1000 g/ kg)X(8406 hr per yr)/(69.27E06 gallons ethanol) = 19 grams

8. Mass Transformation Ratio for BFW chemical used PVC = 9.86E9sej/g (Buranakarn, 1998). Data: grams BWF chemicals calculated from 89 kilograms per hour (Aden et al., 2002). Mass in BFW chemicals = (89 kg per hr)X(1000 g/ kg)X(8406 hr per yr)/(69.27E06 gallons ethanol)=11 grams

9. Mass Transformation Ratio for machinery = 1.30E10sej/g (Brown and Arding, 1991). Data: components estimated based in design in McAloon et al., 2000; equipment lifetime of 15 years; pumps assume 85% steel data (Goulds Pumps, 2006). Vessels assume 100% steel at gauge 12 thickness and 7.9 grams/cm^3 density (Bushman et al, 2004); mixer assume 95% steel data (HC Davis, 2006); heat exchanger assume 95% steel, (Armstrong International, 2006).

Pumps	3.10E+07	g
Vessels	4.50E+08	g
Mixers	2.30E+08	g
Heat exchanger	3.00E+07	g
Other	4.64E+08	g
Total Mass	1.21E+09	g

Mass in machinery = (1.21E09 grams)/ (15 yrs)/(69.27E06 gallons ethanol)=1.2 grams

10. Mass Transformation Ratio for buildings= 6.97E09sej/g (Brown & Buranakarn, 2001). Assume use life of 15 years. Data: Construction materials for 50 million gallon facility (Midwest Grain Processors LLC, 2006) required 1000 tons of reinforced steel and 600 tons of structural steel. Values were adjusted by factor of 1.24 (69.27 million gallon/50 million gallon) to correct for capacity difference in production at the facility. Mass in buildings = (adjustment factor) (total mass of steel)/(life cycle)/(69.26E06 gallons of ethanol)= (1.4)X(1600 tons of steel)X(1E06 grams per ton)/(15 yrs)/(69.27E06 gallons ethanol) = 2.65grams

11. Mass Transformation Ratio for concrete = 3.33E09sej/g (Brown & Buranakarn, 2001). Assume use life of 30 years. Data: 5000 cubic yards of concrete use in 50 million gallon ethanol capacity facility (Midwest Grain Processors, 2006); density of concrete aggregate estimated at 1.13E06 grams per m^3. Mass in concrete = (adjustment factor)(mass of concrete)/(lifetime)/(69.27E06 gallons ethanol) = (1.4)X(5000 cubic yards)X(0.7645 cubic meter to cubic yard)X(1.13E06 grams per m^3)/(30 years)/(69.27E06 gallons of ethanol produced) = 3 grams

12. Transformity of potable water = 3.14E05sej/J (Buenfil, 1998). Data: grams of water 189649 kilograms per hour (McAloon et al., 2000). Energy in water = (1.9E+05 kg/hr)X(8406 hr per yr)X(1000g/kg)X(4.186 joules per gram)/(69.27E06gallon ethanol produced = 9.6E+04 J

13. Transformity gasoline = 1.1E05 sej/J (Odum, 1996). Data: calculated based on 5% gasoline needed to denature a gallon of ethanol. Energy in gasoline = (1 gal ethanol)X(5%) (124000 Btu per gallon)X(1055 joules per Btu) = 9.82+04 J

14. Transformity of petroleum products 1.1E05 sej/J (Odum, 1996). Data: amount required 20 kg of propane per hour (McAloon, et. al., 2000). Energy in propane = (20, kg/year)X(8406, hr per yr)X(m^3/ 584kg)(246 gal/ m^3)X(91000 Btu per gal)X(1055 joules per Btu)/(69.27E6 gallons ethanol) = 1.06E+05 J

15. Transportation Emergy from Table 4.

16. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: Sulfuric acid is produced by capturing the sulfur from stack emissions and recycled as sulfuric acid. Since this is a byproduct, it only account for the cost involved with processing the sulfur into sulfuric acid. Cost of acid input estimated at $0.01 per gallon. (Aden et al., 2002)

17. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: services lime $.02/gallon (Aden et al., 2002)

18. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of ammonia input is $0.040/gallon (Wooley et al., 1999).

19. Money Transformation Ratio =1.1E12 sej/$ (Tilley, 2006). Data: cost of corn steep liquor is $0.03 /gallon (Aden et al., 2002)

20. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: nutrients cost $0.008/gallon (Wooley et al., 1999)

21. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: services antifoam $0.02 /gallon (Wooley et al., 1999)

22. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: services ammonium sulfate $0.003/gallon (Wooley et al., 1999)

23. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: services water: $0.01/ year/gallon (Aden et al., 2002)

24. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: Services gasoline required $0.05/gallon (Wooley et al., 1999)

25. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: services propane required $0.000001/gallon (Aden et al., 2002)

26. Money Transformation Ratio = $1.1E12 (Tilley, 2006). Cost includes insurance, taxes, capital charge, labor, maintenance, overheads and credits electricity sales. Data: operating cost: $0.074/gallon (Wooley et al., 1999 and Aden et al., 2002)

27. Transportation Emergy from Table 4

28. Total Emergy sum of all.

29. The ethanol mass was calculated from density of ethanol, 789 kg per m^3. Mass gallon of ethanol = (1 gallon)X(789 kg per m^3)X(1000 grams 1 gram)X(.0038 m^3 per gallon)X(0.903% ethanol in denatured ethanol)/(619)=2.71E03 grams

30. The energy content of ethanol was reported as 8.02E7 joules per gallon (76,000 Btu/lb).

31. Specific emergy per mass switchgrass ethanol = (Total Emergy, line 28)/(Yield mass, line 29) = (8915E09 sej per gallon)/(2.7E03 grams per gallon) = 3.29E09 sej per gram

33. Transformity of switchgrass ethanol = (Total Emergy, line 28)/(Yield energy, line 30) = (8915E09 sej per gallon)/(8.07E07 joules per gallon) = 1.11E05 sej per joule.

Table B1: Solar emergy required to establish and re-seed switchgrass (Panicum virgatum L.) Conservative Scenario (per gallon of ethanol)

Index	**Item**	**Input (A)**	**Unit**	**Solar Emergy per Unit (B)**	***Env. Fraction R &N_o (C)**	***Env. Emergy E09 sej/gallon (D)**	**Mineral Fraction N_m (E)**	***Mineral Emergy E09 sej/gallon (F)**	**Coal & Nat.gas Fraction N_f (G)**	***Coal & Nat. gas Emergy E09 sej/gallon (H)**	**Petroleum Fraction N_p (I)**	***Petroleum Emergy E09 sej/gallon (J)**	***Total Emergy E09 sej/gallon K=D+F+H+J**
Nature Contribution (I)													
Free Renewable Inputs (R)													
1	Sun	1.1E+11	J	1	1	10	0	0	0	0	0	0	10
2	Wind	6.0E+08	J	2513	2513	138	0	0	0	0	0	0	138
3	Water, rain	1.1E+08	J	30576	30576	301	0	0	0	0	0	0	301
4	Evapotranspiration	9.0E+07	J	30576	30576	251	0	0	0	0	0	0	251
Free Non-renewable (N)													
5	Net topsoil loss	4.1E+07	J	73800	73800	273	0	0	0	0	0	0	273
Purchased (F)													
Feedback from economy Resources (M)													
6	Herbicide	3.2E+06	J	1.10E+05	0	0	0	0	0	0	1.10E+05	32	32
7	Nitrogen (NH_3)	0.00E+00	g	2.87E+09	0	0	0	0	0	0	0	0	0
8	Phosphate(P_2O_5)	90	g	6.55E+09	0	0	1.68E+09	14	4.56E+09	38	3.11E+08	3	54
9	Potash (K_2O_5)	121	g	1.85E+09	1.06E+08	1	1.68E+09	18	5.97E+07	1	4.59E+06	0.050	20
10	Lime	12054	g	1.73E+09	9.80E+06	11	1.68E+09	1841	2.06E+07	23	1.96E+07	21	1896
11	Machinery	32	g	1.30E+10	0	0	1.68E+09	5	9.55E+09	28	1.77E+09	5	37
12	Fuel	3.5E+06	J	1.1E+05	0	0	0	0	0	0	1.1E+05	35	35
Feedback from economy in Services (S)													
13	Herbicide	0.13	$	1.10E+12	1.32E+11	2	9.90E+10	1.21	4.51E+11	6	4.18E+11	5	13
14	Fertilizers	0.13	$	1.10E+12	1.32E+11	2	9.90E+10	1.21	4.51E+11	6	4.18E+11	5	13
15	Lime	0.24	$	1.10E+12	1.32E+11	3	9.90E+10	2.17	4.51E+11	10	4.18E+11	9	24
16	Labor	0.14	$	1.10E+12	1.32E+11	2	9.90E+10	1.24	4.51E+11	6	4.18E+11	5	14
17	Fuel	0.07	$	1.1E+12	1.3E+11	0.82	9.90E+10	0.61	4.5E+11	3	4.18E+11	3	7
18	Operating costs	1.38	$	1.10E+12	1.32E+11	17	9.90E+10	12.45	4.51E+11	57	4.18E+11	53	138
19	**Total Emergy**												**2802**

*Prorated to 11 year cycle

Lines 1, 2, and 3 Excluded from Total (line 21) to avoid double counting

Footnotes to Table B1. All agricultural inputs were determined on a per hectare basis and divided by the estimated gallons of ethanol that would be produced per hectare of cropland under the conservative assumptions, which equaled 371 gallons per ha. Farmed area was 1 ha. Prices for 2006 were used for goods. Operating and labor cost were higher prices due to inflation between 2000 and 2006 (Dept. of Labor, 2006). Older transformity values were corrected by factor of 1.68 (Odum et al., 2000).

1. Transformity of sunlight = 1 sej/J by definition (Odum, 1996). Baseline sunlight energy was 6.73E10 J per gallon of ethanol (Table 2). Assumed yield of hemicellulose and cellulose conversion to ethanol declined from output production from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Updated energy in sunlight = (baseline 6.7E10 joules)X(1.67) = 1.1E11 J

2. Transformity of wind = 2513 sej/J (Odum, 1996). Baseline wind energy was 3.63E08 J per gallon of ethanol (Table 2). Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Updated energy in wind = (baseline 3.63E08 joules)X(1.67) = 6E08 J

3. Transformity of rain = 30576 sej/J (Odum, 1996). Baseline rain energy was 6.49E07 J per gallon of ethanol (Table 2). Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Updated energy in rain = (baseline 6.493E07 joules)X(1.67) = 1.1E08 J

4. Transformity of evapotranspiration (ET) = 30576 sej/J (Odum, 1996). Baseline ET energy was 5.43E07 J per gallon of ethanol (Table 2). Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Updated energy in ET = (baseline 5.43E07 joules)X(1.67) = 9E07 J

5. Transformity of topsoil = 73,800 sej/J (Odum, 1996). Baseline topsoil energy was 2.44E07 J per gallon of ethanol (Table 2). Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Updated energy in topsoil = (baseline 2.44E07 joules)X(1.67) = 4.1E07 J

6. Transformity for fuels = 1.1E05 sej/g (Odum, 1996). Baseline herbicide energy was 1.91E06 J per gallon of ethanol (Table 2). Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Updated energy in herbicide = (baseline 1.91E06 joules)X(1.67) = 3.2E06J

7. Mass Transformation Ratio for ammonia = 2.87E09 sej/g calculated from Haldor Topsoe Plants (Smil, 1999). The process uses 35.6 MJ/kg of nitrogen as the total energy for ammonia production. There was **no** nitrogen required for switchgrass during establishment and re-seeding (Duffy and Nanhou, 2002).

8. Mass Transformation Ratio for P_2O_5 = 6.55E09 sej/g (Odum, 1996). Baseline grams of phosphate were 28 grams per gallon of ethanol (Table 2). Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Updated grams phosphate = (baseline 28 grams)X(1.67) = 45 grams

9. Mass Transformation Ratio for potash (K_2O_5) = 1.85E09 sej/g calculated here based on energy and environmental profile for potash (DOI, 1997). Baseline grams of potash were 58 grams per gallon of ethanol (Table 2). Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Updated grams of potash = (baseline 58 grams)X(1.67) = 96 grams

10. Mass Transformation Ratio for lime = 1.73E09 sej/g calculated here based on energy content for surface mining and beneficiation (DOI, 1997). Baseline grams of lime were 7239 grams per gallon of ethanol (Table 2). Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Updated mass in lime= (baseline 7239 grams)X(1.67) = 12054 grams

11. Mass Transformation Ratio for machinery = 1.30E10 sej/g (Odum, 1996). Baseline grams in machinery were 19 grams per gallon of ethanol (Table 2). Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Updated mass in machinery = (baseline 19 grams)X(1.67) = 32 grams

12. Tranformity diesel = 1.1E5 sej/J (Odum ,1996). Baseline diesel energy was 2.08E06 J per gallon of ethanol (Table 2). Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Updated energy in diesel = (baseline 2.08E06 joules)X(1.67) = 3.5E06 J

13. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost on herbicides in 2006 were $3.2 per liter for Atrazine and $3.9 per liter of 2,4-D (Ferrell et. al., 2006). However, there is a 25% reapplication rate during establishment and reseeding or factor of 1.25. Total herbicide cost = 1.25 [(3.5 liters Atrazine per ha)X($3.2 per liter of Atrazine) + (1.77 liters of 2,4-D per ha)X($3.9 per liter of 2,4-D)] = $55.87 per ha. Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from619 gallons per ha to 317 gallons per ha. Updated total herbicide cost per gallon of ethanol = (total herbicide cost, $55.87)/(371 gallons per ha) = $0.13 per gallon

14. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: costs of fertilizers in 2006 were $0.815 per kg of phosphate and $0.507 per kg of potash (USDA, 2006). Total fertilizer cost = [(33.63 kg phosphate per ha)X($0.8149 per kg of phosphate) + (44.8 kg of potash per ha)X($0.507 per kg of potash] = $50.10. Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 619 gallons per ha to 317 gallons per ha. Updated total fertilizer cost per gallon of ethanol = (total fertilizer cost, $50.10)/(371) = $0.13

15. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of services on lime $20 per ton (Dobbins and Miller, 2006). Total lime cost = ($ 20 per ton)X(4.48 tons per ha) = $89.6. Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from619 gallons per ha to 317 gallons per ha. Updated total lime cost per gallon of ethanol = (total lime cost, $89.6)/(371) = $0.24

16. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Baseline cost of labor was $0.07 per gallon of ethanol (Table 2). Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Also, assumed cost increased at general rate of inflation from 2000 to 2006 by a factor of 1.17 (Dept. of Labor, 2006). Updated cost of labor = ($0.07)X(1.67)X(1.17) = $0.14

17. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: based in early 2005 estimated fuel cost in Midwest was $ 0.72 per liter (2.74 per gallon) (EIA, 2006). Based on farming operations required fuel was 35 liters (9.26 gallons) per ha (Duffy and Nanhou, 2002). Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 619 gallons to 371 gallons per ha. Updated cost of fuel = (35 liters)($0.72 per liter)/(371) = $0.07

18. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Baseline operational cost was $0.71 per gallon of ethanol (Table 2). Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Also, assumed cost increased at general rate of inflation from 2000 to 2006 by a factor of 1.17 (Dept. of Labor, 2006). Updated operational cost = ($0.71)X(1.67)X(1.17) = $1.38

19. Sum of all components except 1, 2 & 3

*Table B2: Solar emergy required for crop production of switchgrass (***Panicum virgatum** *L.) Conservative Scenario (per gallon of ethanol)*

Index	**Item**	**Input (A)**	**Unit**	**Solar Emergy per Unit (B)**	***Env. Fraction R &N$_o$ (C)**	***Env. Emergy E09 sej/gallon (D)**	**Mineral Fraction N$_m$ (E)**	***Mineral Emergy E09 sej/gallon (F)**	**Coal and Nat.gas Fraction N$_f$ (G)**	***Coal and Nat. gas Emergy E09 sej/gallon (H)**	**Petroleum Fraction N$_p$ (I)**	***Petroleum Emergy E09 sej/gallon (J)**	***Total Emergy E09 sej/gallon K=D+F+H+J**
	Nature Contribution (I)												
	Free Renewable Inputs (R)												
1	Sun	1.12E+11	J	1	1	122	0	0	0	0	0	0	122
2	Wind	6.05E+08	J	2513	2513	1658	0	0	0	0	0	0	1658
3	Water, rain	1.08E+08	J	30576	30576	3608	0	0	0	0	0	0	3608
4	Evapotranspiration	9.05E+07	J	30576	30576	3017	0	0	0	0	0	0	3017
	Free Non-renewable (N)												
5	Net topsoil loss	4.56E+05	J	73800	73800	307	0	0	0	0	0	0	307
	Purchased (F)												
	Feedback from economy Resources (M)												
6	Herbicide	2.55E+06	J	1.10E+05	0	0	0	0	0	0	1.10E+05	313	313
7	Nitrogen (NH$_3$)	302	g	2.87E+09	0	0	0	0	2.87E+09	866	0	0	866
8	Phosphate (P$_2$O$_5$)	23	g	6.55E+09	0	0	1.68E+09	53	4.56E+09	144	3.11E+08	10	207
9	Potash (K$_2$O$_5$)	229	g	1.85E+09	1.06E+08	25	1.68E+09	403	5.97E+07	14	4.59E+06	1	443
10	Lime	0.00	g	1.73E+09	9.80E+06	11	1.68E+09	1844	2.06E+07	23	1.96E+07	22	1899
11	Machinery	15.80	g	1.30E+10	0	0	1.68E+09	31	9.55E+09	179	1.77E+09	33	243
12	Fuel	2.73E+06	J	1.11E+05	0	0	0	0	0	0	1.11E+05	338	338
13	Herbicide	0.11	$	1.10E+12	1.32E+11	16	9.90E+10	12	4.51E+11	54	4.18E+11	50	132
14	Nitrogen	0.27	$	1.10E+12	1.32E+11	36	9.90E+10	27	4.51E+11	123	4.18E+11	114	300
15	Phosphorus	0.02	$	1.10E+12	1.32E+11	4	9.90E+10	3	4.51E+11	14	4.18E+11	13	34
16	Potassium	0.01		1.10E+12	1.32E+11	1	9.90E+10	1	4.51E+11	4	4.18E+11	4	10
17	Lime	0.00		1.10E+12	1.32E+11	3	9.90E+10	2	4.51E+11	10	4.18E+11	9	24
18	Labor	0.90		1.10E+12	1.32E+11	121	9.90E+10	90	4.51E+11	412	4.18E+11	382	1005
19	Fuel	0.054	$	1.10E+12	1.32E+11	8	9.90E+10	6	4.51E+11	27	4.18E+11	25	66
20	Operating Cost	0.60	$	1.10E+12	1.32E+11	96	9.90E+10	72	4.51E+11	326	4.18E+11	302	796
21	**Total Emergy**												**10007**
22	Yield biomass			2.31E04	g								
23	Energy in oil			4.44E08	J								
24	emergy/mass (sej/g)				4.34E08								
25	Transformity (sej/J)				2.11E04								

*Include values from Table 3 Establishment and Reseeding prorated to 11 year cycle. Lines 1, 2, and 3 Excluded from Total (line 21) to avoid double counting

Footnotes to Table B2. All agricultural inputs were determined on a per hectare basis and divided by the estimated gallons of ethanol that would be produced per hectare of cropland under the conservative assumptions, which equaled 371 gallons per ha. Farmed area was 1 ha. Prices for 2006 were used for goods. Operating and labor cost were higher prices due to inflation between 2000 and 2006 (Dept. of Labor, 2006).Older transformity values were corrected by factor of 1.68 (Odum et al., 2000).

1. Transformity of sunlight = 1 sej/J by definition (Odum, 1996). Baseline sunlight energy was 6.73E10 J per gallon of ethanol (Table 3). Assumed yield of hemicellulose and cellulose conversion to ethanol declined from output production from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Updated energy in sunlight = (baseline 6.7E10 joules)X(1.67) = 1.1E11 J

2. Transformity of wind = 2513 sej/J (Odum, 1996). Baseline wind energy was 3.63E08 J per gallon of ethanol (Table 3). Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Updated energy in wind = (baseline 3.63E08 joules)X(1.67) = 6E08 J

3. Transformity of rain = 30576 sej/J (Odum, 1996). Baseline rain energy was 6.49E07 J per gallon of ethanol (Table 3). Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Updated energy in rain = (baseline 6.493E07 joules)X(1.67) = 1.1E08 J

4. Transformity of evapotranspiration (ET) = 30576 sej/J (Odum, 1996). Baseline ET energy was 5.43E07 J per gallon of ethanol (Table 3). Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Updated energy in ET = (baseline 5.43E07 joules)X(1.67) = 9E07 J

5. Transformity of topsoil = 73,800 sej/J (Odum, 1996). Baseline topsoil energy was 2.73E07 J per gallon of ethanol (Table 3). Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Updated energy in topsoil = (baseline 2.44E07 joules)X(1.67) = 4.5E05 J

6. Transformity for fuels = 1.1E05 sej/g (Odum, 1996). Baseline herbicide energy was 1.53E06 J per gallon of ethanol (Table 3). Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Updated energy in herbicide = (baseline 1.53E06 joules)X(1.67) = 2.55E06J

7. Mass Transformation Ratio for ammonia = 2.87E09 sej/g calculated here based on Haldor Topsoe Plants (Smil, 1999). Baseline nitrogen grams were 181 grams per gallon of ethanol (Table 3). Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Updated grams of nitrogen = (baseline 181 grams)X(1.67) = 302 grams

8. Mass Transformation Ratio for P_2O_5 = 6.55E09 sej/g (Odum, 1996). Baseline grams of phosphate were 7.17 grams per gallon of ethanol (Table 3). Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Updated mass of phosphate = (baseline 7.17 grams)X(1.67) = 12 grams

9. Mass Transformation Ratio for potash (K_2O_5) = 1.85E09 sej/g calculated here based on energy and environmental profile for potash (DOI, 1997). Baseline grams of potash were 131 grams per gallon of ethanol (Table 3). Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Updated mass of K in potash = (baseline 131grams)X(1.67) = 219 grams

10. Mass Transformation Ratio for lime = 1.73E09 sej/g calculated here based on energy content for surface mining and beneficiation (DOI, 1997). Data: lime requirements for switchgrass estimated at 0 (Duffy and Nanhou, 2002). Energy in lime= (10000 m^2)(0 kg/ m^2)(1000 g/kg)/(371 gallon per ha)=0 grams

11. Mass Transformation Ratio for machinery = 1.30E10 sej/g (Odum, 1996). Baseline grams of machinery were 9 gram per gallon of ethanol (Table 3). Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Updated mass of machinery = (baseline 9 grams)X(1.67) = 15.8 grams

12. Tranformity diesel = 1.1E5 sej/J (Odum, 1996). Baseline diesel energy was 1.64E06 J per gallon of ethanol (Table 3). Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Updated energy in diesel = (baseline 1.64E06 joules)X(1.67) = 2.73E06 J

13. Money Transformation Ratio= 1.1E12 sej/$ (Tilley, 2006). Data: cost on herbicides in 2006 were $3.2 per liter for Atrazine and $3.9 per liter of 2,4-D (Ferrell et. al., 2006). Total herbicide cost = [(3.5 liters Atrazine per ha)X($3.2 per liter of Atrazine) + (1.77 liters of 2,4-D per ha)X($3.9 per liter of 2,4-D)] = $22. 94 per ha. Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 619 gallons per ha to 317 gallons per ha. Updated total herbicide cost per gallon of ethanol = (total herbicide cost, $22.94)/(371 gallons per ha) = $0.11

14. Money Transformation Ratio= 1.1E12 sej/$ (Tilley, 2006). Data: cost of services on nitrogen in 2006 was $0.0009 per gram (USDA, 2006). Grams of nitrogen required were 302 g per gallon (this table line 7). Updated total nitrogen cost per gallon of ethanol = (total nitrogen cost, $0.0009 per gram)X(302 grams) = $0.27

15. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of services on P_2O_5 $0.815 per kg (USDA, 2006). Grams of P in phosphate required were 12 grams per gallon (this table line 8). However there are 78 moles of P per 153 moles of phosphate. Updated total phosphate cost per gallon of ethanol = (phosphate cost, $0.000815 per gram)X(12 grams)X(78/153) = $0.2

16. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of services on K_2O_5 $ 0.507 per kg (USDA, 2006). Grams of K in potash required were 219 gram per gallon (this table line 8). However there are 21 moles of K per 78 moles of potash. Updated total potash cost per gallon of ethanol = (potash cost, $0.000507 per gram)X(219 grams)X(62/78) = 0.01

17. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of services on lime $0/acre, (Duffy and Nanhou, 2002). (Farmed area, m^2)($ per area, $/ m^2)/(gallon per ha)= $0.0

18. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Baseline cost of labor was $0.46 per gallon of ethanol (Table 2). Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Also, assumed cost increased at general rate of inflation from 2000 to 2006 by a factor of 1.17 (Dept. of Labor, 2006). Updated cost of labor = ($0.46)X(1.67)X(1.17) = $0.90

19. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of services on fuel was $0.723 per liter ($2.74 per gallon) (EIA, 2006). During production 27.6 liters (7.28 gallons) of fuel required per ha (Duffy and Nanhou, 2002). Updated cost of fuel = ($0.723 per liter)(27.6 liters)/(371 gallon per ha)= $0.054.

20. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Baseline operating cost was $0.31 per gallon of ethanol (Table 2). Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Also, assumed cost increased at general rate of inflation from 2000 to 2006 by a factor of 1.17 (Dept. of Labor, 2006). Updated operating cost = ($0.31)X(1.67)X(1.17) = $0.60

21. Sum of all components except 1, 2 & 3

22. Production of switchgrass crop yielded 9.88E06 grams per ha. Moisture content of switchgrass range from 12% to15% moist; average 13.5%. Estimated dry yield = (9.88E06 grams per ha)X(86.5%) = 8.96E6 g per ha. Gallons of switchgrass ethanol per ha were 371. Mass of switchgrass per gallon of ethanol = (8.96E06 grams)/(371 gallon ethanol per ha)=2.31E04 grams per gallon

23. The energy content of switchgrass was reported as 19055 joules per gram (8200 Btu/lb). Energy content switchgrass = (2.31E04 grams)X(19055 joules per gram) = 4.4E08 joules per gallon

24. Specific emergy per mass sensitivity analysis= (Total Emergy, line 21)/(Yield mass, line 22) = (10007E09 sej per gallon)/(2.31E04 grams per gallon) = 4.34E08 sej per gram

25. Transformity of switchgrass sensitivity analysis= (Total Emergy, line 21)/(Yield energy, line 23) = (10007E09 sej per gallon)/(4.4E08 joules per gallon) = 2.25E04 sej per joule

Table B3: Solar emergy required to transport switchgrass from field to ethanol processing plant Conservative Scenario (per gallon of ethanol)

Index	Item	Input (A)	Unit	Solar Emergy per Unit (B)	Env Fraction R&N_o (C)	Env. Emergy E09 sej/gallon (D)	Mineral Fraction N_o (E)	Mineral Emergy E09 sej/gallon (F)	Coal and Nat. gas Fraction N_f (G)	Coal and Nat. gas Emergy E09 sej/gallon (H)	Petroleum Fraction N_p (I)	Petroleum Emergy E09 sej/gallon (J)	Emergy E09 sej/gallon K=D+F+H+J
Purchased (F)													
Feedback from economy Resources (M)													
1	Machinery	2	g	1.30E+10	0	0	1.68E+09	3	9.55E+09	16	1.77E+09	3	22
3	Diesel	2.29E+06	J	1.1E+05	0	0	0	0	0	0	1.1E+05	254	254
Feedback from economy in Services (S)													
2	Services labor	0.084	$	1.10E+12	1.32E+11	11	9.90E+10	8	4.51E+11	38	4.18E+11	35	92
4	Fuels	0.045	$	1.10E+12	1.32E+11	6	9.9E+10	4	4.51E+11	20	4.18E+11	19	50
5	**Total Emergy**												**418**

Footnotes to Table B3. All transportation inputs were determined on a per hectare basis and divided by the estimated gallons of ethanol that would be produced per hectare of cropland, which equaled 371 gallons per ha. Prices for 2006 were used for goods. Operating and labor cost were higher prices due to inflation between 2000 and 2006 (Dept. of Labor, 2006). Older transformity values were corrected by factor of 1.68 (Odum et al., 2000).

1. Mass Transformation Ratio for machinery = 1.25E10 sej/g (Odum, 1996). Baseline mass of machinery was 1 gram per gallon of ethanol (Table 4). Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Updated mass of machinery = (baseline 1 grams)X(1.67) = 2 grams
2. Tranformity diesel 1.1E05 sej/J (Odum, 1996). Baseline diesel energy was 1.37E06 J per gallon of ethanol (Table 4). Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Updated energy in diesel =(baseline 1.37E06 joules)X(1.67) = 2.29E06 J

3. Money Transformation Ratio = 1.1E12 sej/$ (Odum, 1996). . Baseline cost of operating a truck was $0.043 per gallon of ethanol (Table 4). Assumed yield of hemicellulose and cellulose conversion to ethanol declined output production from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Also, assumed cost increased at general rate of inflation from 2000 to 2006 by a factor of 1.17 (Dept. of Labor, 2006). Updated cost of labor = (baseline $0.043)X(1.67)X(1.17) = $0.084

4. Money Transformation Ratio = 1.1E12 sej/$ (Odum, 1996). Data: Cost of services on fuels in 2003 average $0.723 per liter ($2.74 per gallon) (EIA, 2006). Baseline required 23 liters of diesel per ha and 1 ha produced 619 gallons of ethanol. Updated cost of gasoline= ($0.723/liter)X(23)/(371) = $0.045

Table B4: Solar emergy required to produce ethanol from switchgrass biomass Conservative Scenario (per gallon of ethanol)

#	**Item**	**Input (A)**	**Unit**	**Solar Emergy per Unit (B)**	**Env Fraction R&N$_o$ (C)**	**Env. Emergy E09 sej/gallon (D)**	**Mineral Fraction N$_m$ (E)**	**Mineral Emergy E09 sej/gallon (F)**	**Coal and Nat. gas Fraction N$_f$ (G)**	**Coal & Nat. Gas Emergy E09 sej/gallon (H)**	**Petroleum Fraction N$_p$ (I)**	**Petroleum Emergy E09 sej/gallon (J)**	**Emergy E09 sej/gallon K=D+F+H+J**
1	Biomass Input	23060	g	4.34E+08	1.58E+08	3643	1.10E+08	2542	9.55E+07	2201	7.03E+07	1620	10007
Purchased (F)													
Feedback from economy Resources (M)													
2	lime	484	g	1.73E+09	9.80E+06	5	1.68E+09	814	2.06E+07	10	1.96E+07	9	838
3	Ammonia	264	g	2.87E+09	0	0	0	0	2.87E+09	758	0	0	758
4	Corn Steep Liquor	3781	g	5.54E+05	1.55E+05	1	4.99E+04	0	2.05E+05	1	1.44E+05	1	2
5	Nutrients	589	g	1.94E+04	7.37E+03	0	1.75E+03	0	4.85E+03	0	5.43E+03	0	0
6	Antifoam (corn oil)	1246	g	5.54E+05	1.55E+05	0	4.99E+04	0	2.05E+05	0	1.44E+05	0	0.69
7	Amm. Sulfate	32	g	2.87E+09	0	0	0	0	2.87E+09	92	0	0	92
8	BFW chemicals	18	g	9.86E+09	0	0	1.68E+09	30	4.83E+09	87	3.35E+09	60	178
9	Equipment steel	1.93	g	1.30E+10	0	0	1.68E+09	3	9.55E+09	18	1.77E+09	3	25
10	Buildings steel	4.41	g	6.97E+09	0	0	1.68E+09	7	9.53E+08	4	4.34E+09	19	31
11	Cement	5	g	3.33E+09	0	0	1.68E+09	8	1.56E+09	8	8.23E+07	0	16
12	Water make up	1.61E+05	J	3.14E+05	8.48E+04	14	1.29E+05	21	8.17E+04	13	1.88E+04	3	50
13													
14	Gasoline	1.05E+07	J	3.36E+05	0	0	0	0	3.36E+05	3537	0	0	3537
15	Propane	6.54E+06	J	1.11E+05	0	0	0	0	0		1.11E+05	726	726
16	*Transportation Emergy From TABLE 4*				0	0	0	***3***		***16***		***257***	276
Feedback from economy in Services (S)													
17	Sulfuric Acid	0.02	$	1.10E+12	1.32E+11	3	9.90E+10	2	4.51E+11	10	4.18E+11	9	23
18	Lime	0.05	$	1.10E+12	1.32E+11	6	9.90E+10	5	4.51E+11	22	4.18E+11	20	53
19	Ammonia	0.24	$	1.10E+12	1.32E+11	31	9.90E+10	24	4.51E+11	107	4.18E+11	99	262
20	Corn Steep Liquor	0.05	$	1.10E+12	1.32E+11	7	9.90E+10	5	4.51E+11	25	4.18E+11	23	60
21	Nutrients	0.017	$	1.10E+12	1.32E+11	2	9.90E+10	2	4.51E+11	7	4.18E+11	7	18
22	Antifoam	0.04	$	1.10E+12	1.32E+11	5	9.90E+10	4	4.51E+11	19	4.18E+11	17	45
23	Amm. Sulfate	0.006	$	1.10E+12	1.32E+11	1	9.90E+10	1	4.51E+11	3	4.18E+11	2	6
24	Water	0.011	$	1.10E+12	1.32E+11	1	9.90E+10	1	4.51E+11	5	4.18E+11	5	12
25	Electricity	0.28		1.10E+12	1.32E+11	38	9.90E+10	28	4.51E+11	128	4.18E+11	119	313
26	Gasoline	0.14	$	1.10E+12	1.32E+11	18	9.90E+10	14	4.51E+11	62	4.18E+11	57	151
27	Propane	0.002	$	1.10E+12	1.32E+11	0	9.90E+10	0	4.51E+11	1	4.18E+11	1	2
28	Operating cost	1.62	$	1.10E+12	1.32E+11	214	9.90E+10	161	4.51E+11	732	4.18E+11	678	1785
29	***Transportation Emergy From TABLE 4***				1.32E+11	***8***	9.90E+10	***6***	4.51E+11	***27***	4.18E+11	***25***	***65***

Table B4: Continue-Solar emergy required to produce ethanol from switchgrass biomass based Conservative Scenario (per gallon of ethanol)

30	**Total Emergy**				**19427**
31	Yield Oil, mass	2.71E03	g		
32	Energy in oil	8.02E07	J		
33	emergy/mass (sej/gram)			8.03E09	
34	Transformity (sej/J)			2.71E05	

Footnotes to Table B4. Inputs that were based on the quantity required to produce gallons of ethanol were corrected for lower enzymatic conversion yield (51%) that resulted in 60% less gallon of ethanol output and higher prices due to inflation between 1997 and 2006 and between 2000 and 2006. A lower enzymatic conversion decreased the ethanol output from 69.27E06 gallons by 60% to 41.6E06 gallons. Inflation increased by a factor of 1.24 and 1.17, respectively (Dept. of Labor 2006). (Numbers may differ slightly due to rounding off)

1. Mass Transformation Ratio of switchgrass biomass =5.57E08 sej/g, calculated in this study. Biomass required increased in per gallon basis because the output of ethanol gallons was decreased from 619 to 371 {(619)X(60%)} as a result of reduction on conversion yield of carbohydrate to ethanol. Updated mass in switchgrass = (dry weigh of swichgrass, grams per ha)/{(baseline scenario gallons per ha)X(60%)} = (8.5 (dry) tons per ha)X(1E06 grams per ton)/(371 gallons per ha) = 23060 grams

2. Mass Transformation Ratio for lime =1.73E09 sej/g calculated here based on energy content for surface mining and beneficiation (DOI, 1997). Baseline grams for lime were 291 grams per gallon of ethanol (Table 5). Assumed yield of hemicellulose and cellulose conversion to ethanol declined from 69.27E06 gallons to 41.6E06 gallons (69.27/41.6=1.665). Updated mass in lime = (baseline, 291 grams)X(1.665) = 484 grams

3. Mass Transformation Ratio ammonia = 2.87E09 sej/g based on process by Haldor Topsoe plants (Smil, 1999). Total energy for ammonia production was 35.6 MJ/kg of nitrogen. Baseline grams for ammonia were 159 grams per gallon of ethanol (Table 5). Assumed yield of hemicellulose and cellulose conversion to ethanol declined from 69.27E06 gallons to 41.6E06 gallons (69.3/41.6=1.67). Updated mass in ammonia = (baseline, 159 grams)X(1.665) = 264 grams

4. Transformity of corn steep liquor from processed foods = 330000 sej/J (Johansson, 2005). Baseline grams for corn steep liquor were 2269 joules per gallon of ethanol (Table 5). Assumed ethanol output declined from 69.27E06 gallons to 41.6E06 gallons (69.27/41.6=1.67). Updated energy in corn steep liquor = (baseline, 2269 joules)X(1.67) = 3781 J

5. Transformity of nutrients from sugarcane = 1.94E04 sej/J (Brandt-Williams, 2001). Baseline grams for nutrients were 354 joules per gallon of ethanol (Table 5). Assumed ethanol output declined from 69.27E06 gallons to 41.6E06 gallons (69.27/41.6=1.67). Updated energy in nutrients = (baseline, 354 joules)X(1.67) = 589 J

6. Transformity of antifoam from processed foods = 330000 sej/J (Johansson, 2005). Baseline grams for antifoam were 748 joules per gallon of ethanol (Table 5). Assumed ethanol output declined from 69.27E06 gallons to 41.6E06 gallons (69.27/41.6=1.67). Updated energy in antifoam = (baseline, 748 joules)X(1.67) = 1246 J

7. Mass Transformation Ratio ammonium sulfate from 2.87E09 sej/g based on process by Haldor Topsoe plants (Smil, 1999). Baseline grams for ammonium sulfate were 19 grams per gallon of ethanol (Table 5). Assumed ethanol output declined from 69.27E06 gallons to 41.6E06 gallons (69.27/41.6=1.67). Updated mass in ammonium sulfate = (baseline, 19 g)X(1.67) = 32 grams

8. Mass Transformation Ratio of BFW chemical used PVC = 9.86E9sej/g (Buranakarn, 2000). Baseline grams for BFW chemicals were 11 grams per gallon of ethanol (Table 5). Assumed ethanol output declined from 69.27E06 gallons to 41.6E06 gallons (69.27/41.6=1.67). Updated mass in BFW chemicals = (baseline, 11 g)X(1.67) = 18 grams

9. Mass Transformation Ratio for machinery = 1.30E10sej/g (Brown and Arding, 1991). Baseline grams for machinery were 1.2 grams per gallon of ethanol (Table 5). Assumed ethanol output declined from 69.27E06 gallons to 41.6E06 gallons (69.27/41.6=1.67). Updated mass in machinery = (baseline, 1.2 g)X(1.67) = 1.93 grams

10. Mass Transformation Ratio for buildings= 6.97E09sej/g (Brown & Buranakarn, 2001). Assume use life of 15 years. Baseline grams for steel in buildings were 2.13 grams per gallon of ethanol (Table 5). Assumed ethanol output declined from 69.27E06 gallons to 41.6E06 gallons (69.27/41.6=1.67). Updated mass in buildings = (baseline, 2.13 g)X(1.67) = 3.56 grams

11. Mass Transformation Ratio of cement = 3.33E09sej/g (Brown & Buranakarn, 2001). Assume use life of 30 years. Baseline grams for cement were 3 grams per gallon of ethanol (Table 5). Assumed ethanol output declined from 69.27E06 gallons to 41.6E06 gallons (69.27/41.6=1.67). Updated mass in cement = (baseline, 3 g)X(1.67) = 5 grams

12. Transformity of potable water = 3.14E05sej/J (Buenfil, 1998). Baseline energy in water was 9.6E04 joules per gallon of ethanol (Table 5). Assumed ethanol output declined from 69.27E06 gallons to 41.6E06 gallons (69.27/41.6=1.67). Updated energy of water = (baseline, 9.6E04 joules)X(1.67) = 1.61E05 J

13. Transformity of electricity = 3.36E05 sej/J (Odum 1996). Production on-site electricity was eliminated and needed to be purchased from grid. Data: 9229 kilowatts (kw) used in plant that runs 7920 hrs and produced 25 million gallons of ethanol (McAloon, et al 2000). Energy in electricity = (9229 kW)X(7920 hrs)X(3.6E06 joules per kWh)/(25E06 gallons ethanol) = 1.05E07 J

14. Transformity gasoline = 1.1E05 sej/J (Odum 1996). Gasoline used to denature was 5% per gallon of ethanol regardless of assumptions. Baseline energy in gasoline was 6.54E06 joules per gallon of ethanol (Table 5). Energy of gasoline = 6.54E06 J

15. Transformity of petroleum products = 1.1E05 sej/J (Odum 1996). Baseline energy in propane was 1.06E05 joules per gallon of ethanol (Table 5). Assumed ethanol output declined from 69.27E06 gallons to 41.6E06 gallons (69.27/41.6=1.67). Updated energy in propane = (baseline, 1.06E05 joules)X(1.67) = 1.76E05 J

16. Transportation Emergy from Table B3

17. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Baseline cost for sulfuric acid was $0.01 joules per gallon of ethanol (Table 5). Assumed ethanol output declined from 69.27E06 gallons to 41.6E06 gallons, then per gallon cost increased by factor of 69.27/41.6=1.67. Also assumed that cost increased at general rate of inflection from 2000 to 2006 by a factor of 1.17 (Dept. of Labor, 2006). Updated cost for sulfuric acid = (baseline, $0.01)X(1.67)X(1.17) = $0.02

18. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: the cost of lime as reagent was estimated to cost $100 per ton in 2006 (Dobbins and Miller, 2006). The amount of lime required in this scenario was 484 grams (line 2) per gallon of ethanol (Table B4). Updated cost of lime = (484 grams of lime)($100 per ton)(1E6 grams per ton) = $0.05

19. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: The cost of ammonia input in 2006 was from nitrogen $.0009 per gram (0.41 per lb) (USDA, 2006). The amount of ammonia required in this scenario was 264 grams (line 3) per gallon of ethanol (Table B4). Updated cost of ammonia= (264 grams)($0.0009 per g)= $0.24

20. Money Transformation Ratio =1.1E12 sej/$ (Tilley, 2006). Baseline cost for corn steep liquor was $0.03 joules per gallon of ethanol (Table 5). Assumed ethanol output declined from 69.27E06 gallons to 41.6E06 gallons, then per gallon cost increased by factor of 69.27/41.6=1.67. Also assumed that cost increased at general rate of inflection from 2000 to 2006 by a factor of 1.17 (Dept. of Labor, 2006). Updated cost for corn steep liquor = (baseline, $0.03)X(1.67)X(1.17) = $0.05

21. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Baseline cost for nutrients was $0.008 joules per gallon of ethanol (Table 5). Assumed ethanol output declined from 69.27E06 gallons to 41.6E06 gallons, then per gallon cost increased by factor of 69.27/41.6=1.67. Also assumed that cost increased at general rate of inflection from 1997 to 2006 by a factor of 1.24 (Dept. of Labor, 2006). Updated cost for nutrients = (baseline, $0.008)X(1.67)X(1.24) = $0.017

22. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Baseline cost for antifoam was $0.02 joules per gallon of ethanol (Table 5). Assumed ethanol output declined from 69.27E06 gallons to 41.6E06 gallons, then per gallon cost increased by factor of 69.27/41.6=1.67. Also assumed that cost increased at general rate of inflection from 1997 to 2006 by a factor of 1.24 (Dept. of Labor, 2006). Updated cost for antifoam = (baseline, $0.02)X(1.67)X(1.24) = $0.04

23. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Baseline cost for ammonium sulfate was $0.003 joules per gallon of ethanol (Table 5). Assumed ethanol output declined from 69.27E06 gallons to 41.6E06 gallons, then per gallon cost increased by factor of 69.27/41.6=1.67. Also assumed that cost increased at general rate of inflection from 2000 to 2006 by a factor of 1.17 (Dept. of Labor, 2006). Updated cost for ammonium sulfate = (baseline, $0.003)X(1.67)X(1.17) = $0.006

24. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: Baseline cost for water was $0.01 joules per gallon of ethanol (Table 5). Assumed ethanol output declined from 69.27E06 gallons to 41.6E06 gallons, then per gallon cost increased by factor of 69.27/41.6=1.67. Also assumed that cost increased at general rate of inflection from 2000 to 2006 by a factor of 1.17 (Dept. of Labor, 2006). Updated cost for water = (baseline, $0.01)X(1.67)X(1.17) = $0.011

25. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: electricity required was 2.9 kWh (line 13) per gallon of ethanol (Table B4). The price of electricity in 2006 was cents 9.8/kWh (EIA, 2006). Services electricity required = (2.9 kWh)($ 9.8/100 per kWh)= $0.28

26. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: price of gasoline in first quarter in 2006 was estimated to be $ 723 per liter (2.74 /gallon) (EIA, 2006). The amount of gasoline required was 0.05 gallons of gasoline per gallon of ethanol for denaturing. Updated cost for gasoline = (0.05 gallon gasoline)($2.74 /gallon gasoline)= $0.14

27. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: price of propane $0.304 per liter ($1.15 per gallon) in 2006 (EIA, 2006). Propane required 0.002 gallons of propane per gallon of ethanol (line 15, Table B4) Updated cost for propane = (.002 gallons of propane)($1.15 per gallon) = 0.0023

28. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Baseline cost operational was $0.74 per gallon of ethanol (Table 5). However, this value included a credit for electricity for $0.09 per gallon (Aden, et. al., 2002); this was added into the operational cost. Assumed ethanol output declined from 69.27E06 gallons to 41.6E06 gallons, then per gallon cost increased by factor of 69.27/41.6=1.67. Also assumed that cost increased at general rate of inflection from 1997 to 2006 by a factor of 1.17 (Dept. of Labor, 2006). Updated operational cost = {(baseline, $0.74)+(Electricity credit, $0.09)}X(1.67) = $1.62

29. Transportation emergy on services from Table B3

30. Total Emergy sum of all.

31. The ethanol mass was calculated from density of ethanol, 789 kg per m^3. Mass gallon of switchgrass ethanol sensitivity analysis= (1 gallon)X(789 kg per m^3)X(1000 grams 1 gram)X(.0038 m^3 per gallon)X(0.903% ethanol in denatured ethanol) = 2.71E03 grams

32. The energy content of ethanol was reported as 8.02E7 joules per gallon (76,000 Btu/lb).

33. Specific emergy per mass of switchgrass ethanol sensitivity analysis = (Total Emergy, line 30)/(Yield mass, line 31) = (19427E09 sej per gallon)/(2.7E03 grams per gallon) = 7.18E09 sej per gram

34. Transformity of switchgrass ethanol sensitivity analysis= (Total Emergy, line 30)/(Yield energy, line 32) = (19427E09 sej per gallon)/(8.07E07 joules per gallon) = 2.42E05 sej per joule

Appendix C: Notes to Emergy Tables for Hybrid Poplar to Ethanol

Footnotes to Table 12. All agricultural inputs were determined on a per hectare basis and divided by the estimated gallons of ethanol that would be produced per hectare of cropland, which equaled 2316 gallons per ha (10,000 m^2). Farm area was 1 ha. Older transformity values were corrected by factor of 1.68 (Odum et al., 2000).

1. Transformity of sunlight = 1 sej/J by definition (Odum, 1996). Solar insolation was annual average for Maryland (USA) at Longitude: 77° 22.3'W Latitude: 39° 29.5'N 6. Data: 4.3 Kwh/m^2/day; albedo = 0.29 (NASA, 2006). Energy in sunlight = (10000 m^2)X(4.3 kWh/ m^2 /day)X(859.9 kcal per kWh)X(365 days per year)X(1-albedo)X(4186 joules per kcal)/(2316 gallons ethanol per ha) = 1.04E11J

2. Transformity of rain = 30576 sej/J (Odum, 1996). Data: annual rainfall of 1.035 m per year (Maryland State Archives, 2006); density of water 1000kg/m^3. Energy in rain was (10000 m^2)X(1.035 m)X(1000 kg/ m^3)X(4940 J/kg)X(6 year rotation)/(2316 gallons ethanol per ha) = 1.32E08J

3. Transformity of evapotranspiration (ET) = 30576 sej/J (Odum, 1996). ET from observed ET of hybrid poplar plots in Oregon (USDOI, 2006). Data: ET was 0.77 m per year; specific gravity of water = 1.0E06 g/m^3. Energy in ET = (10000 m^2)X(0.77 m)X(1E06 g/ m^3)X(4.94, J/g)X(6 year rotation)/(2316 gallons ethanol per ha) =9.8E07J

4. Transformity of topsoil = 73,800 sej/J (Odum, 1996). Estimated annual average soil sediment displacement in hybrid poplar plantations in Tennessee US (Shephard and Tolbert, 1997). The energy in the organic soil content was estimated from average of caloric content on the composition of soil organic matter (SOM) materials from composition of SOM (UM, 2006) and energetic value of particulate organic matter (Malone and Swartout, 1969; Currie et. al., 2003) and energetic value of decomposed organic material (Chubu Shiryo Co. Ltd., 2006). Data: soil erosion was 1.97 megagrams (Mg) per ha per year; average organic percent in soil 1% (NRCS, 2006a); energy organic soil 3.84 kcal/g. Energy in soil = (10000 m^2)X(1.97E06 grams per ha)X(1 ha/10,000 m^2)X(1 %)X(3.84 kcal/g)X(4186 J/kcal)/(2316 gallons ethanol per ha) = 8.21E05J

5. Mass Transformation ratio for biosolid = 3.41E+09 sej/J (Bjorklund et al., 2001). Data: 383,000 kg of dry weight biosolids were applied per ha (Felton, et al, 2006). Mass in biosolid = (383,000 kg)X(1000 grams/ kg)/(2316 gallons ethanol per ha)= 165,366grams

6. Mass Transformation ratio for ammonia = 2.87E09 sej/g calculated here from Haldor Topsoe Plants (Smil, 1999). The process uses 35.6 MJ/kg of nitrogen as the total energy for ammonia production. Data: the nitrogen amount was estimated based on content of nitrogen in biosolid which was reported as 1.15% (Felton et al, 2006). Energy in nitrogen= (10000 m^2)X(383,000 kg/ha)X(1 ha/ 10000 m^2)X(1000 g/kg)X(1.15%, N content)/(2316 gallons ethanol per ha)= 1,902 grams

7. Mass Transformation Ratio for P_2O_4= 6.55E09 sej/g (Odum, 1996). Data: Phosphorus was estimated based in biosolid phosphorus content 0.84% (Felton et al, 2006). Mass in phosphorus = (10000 m^2)X(383,000 kg/ha)X(1 ha/ 10000 m^2)X(1000 g/kg)X(0.84%, P content)/(2316 gallons ethanol per ha) = 1,398 grams

8. Transformity irrigated water = 2.79E05sej/J (Buenfil, 1998). Data: water was based in biosolid water content of 76% (Felton et al, 2006). Energy in water = ((10000 m^2)X(383,000 kg/ha)X(1 ha/ 10000 m^2)X(76 % water content)X(4.94, joules per gram)/(2316 gallons ethanol per ha) = 6.21E05J

9. Mass Transformation Ratio for lime = 1.73E09 sej/g calculated here based on energy content for surface mining and beneficiation from (USDOI, 1997). Data: lime used to stabilize sludge approximately 49.8 tons of lime was used per day in 1224 tons of biosolid. (WASA, 2006). Mass in lime= (10000 m^2)X(383,000 kg/ha)X(1 ha/10000 m^2)X(1000 g/kg)X(49.6/1225, ratio tons of lime per tons of biosolid)/(2316 gallons ethanol per ha) = 6,737 grams

10. Mass Transformation Ratio for machinery = 1.30E10 sej/g (Odum, 1996). Data: total kg in farm machinery was 18,000 kg bulldozer. Equipment had a life cycle of 68000 hrs (7.5yr) and equipment was used 250 hrs per year in 42 ha (Felton et al, 2006). Rate of equipment used = (1 bulldozer)/(42 ha) /(68000 hrs lifetime equipment/ 250 used hrs per year)= 0.00009/ha/y. A truck was used to transport bisolids from wastewater treatment facility to farm. Assumed that a hauling truck weighted about 11,109 kg with a capacity to haul 40 metric tons biosolid, life cycle of 7yr and annual kilometers driven 103,266 (64,000 miles) (Lovins et al., 2004). The biosolids required per ha were estimated at 383 metric tons. The biosolids were transported from wastewater treatment facility to farm assumed 80 km (50 mile) per trip. Number of trips for transporting biosolids per ha = (383 tons/40ton capacity) = 9.575 trips per ha. Rate of truck used = (1 truck)(1/7 year)X(80 km per trip/103,266 km per year)X(9.575 tips per ha) = 0.0011 truck/ha/year. Mass in truck = (11,109 kg truck)X(0.0011 truck/ha/year)X(1000 grams per kg) = 12220 grams. Mass in bulldozer = (0.00009 ha per year)X{(18,000 kg)X(1000 grams per kg) = 1620 grams. Mass in machinery = (12220 + 1620 grams)/(2316 gallons ethanol per ha) = 6 gram

11. Tranformity diesel = 1.1E5 sej/J (Odum, 1996). Data: assumption that machinery was used on average 3 hours per day, 250 days to work on 7 ha (17.3 acres) (Felton et al, 2006), average diesel consumption was estimated at 5.67 liters per hr (1.5 gallons per hour) for a 70 HP bulldozer (Markewitz, 2001). Machinery used per ha = (3 hrs per day)X(250 days)/7 ha = 107 hrs per ha. Energy in diesel= (107 hr per ha) X(1.5 gal per hour) X(132000 Btu/gallon diesel)X(1055 joules per Btu)/(2316 gallons ethanol per ha) = 9.6E06J

12. Tranformity gasoline =1.1E05 sej/J (Odum, 1996). Transportation of biosolid to farm. Data: a class eight used an average of 4.24 km per liter (10 miles per gallon) (Transportation Business Association, 2006). The biosolids were transported an estimated distance of 80 kilometers (50 miles). The truck transports 40 tons per trip. 1 ha used 383 tons of biosolids. Gallons used = (50, miles per trip)X(383/40, tons per ha / tons per trip)X(1 gallon gasoline /10 miles) = 47.9 gal. Energy in gasoline= (47.9 gal)X(125000 Btu/gallon gasoline)X(1055 joules per Btu)/(2316 gallons ethanol per ha) = 2.73E06J

13. Transformity of electricity = 3.36E05 sej/J (Odum, 1996). Data: calculated based on cost of utilities for 308 ha (125 acres) farm were $1200/year (Felton et al, 2006), and cost of electricity was 9 cents per kWh (EIA, 2006b). Energy in electricity=($1200/year)/(0.09, $/kWh)X(3 600 000, joules per kWh)/(308 ha)/(2316 gallons ethanol per ha = 6.71E04 J

14. Money Transformation Ratio = Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 1999). Data: cost of services on utilities $24 /ha, (Felton et al, 2005). (10000 m^2)X(1 ha/10000 m2)X($ 24/ha)/(2316 gallons ethanol per ha) = $.01

15. Money Transformation Ratio = Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 1999). Data: cost of labor $16,254/ha (Felton et al, 2006). (10000 m^2)X(1 ha/10000 m2)X($ 16,254/ha)/(2316 gallons ethanol per ha) = $7

16. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 1999). Cost of services on fuels. Data: Average gasoline cost $0.428 per liter ($1.62 per gallon) for 2003-2004 (EIA, 2006c). The farm required 789 liters (208 gallons). ($1.62 per gallon)X(208 gallons)/(2316 gallons ethanol per ha) = $0.15

17. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: other operational cost $797 /ha, (Felton et al, 2006). (1 ha)X($797per ha)/(2316 gallons ethanol per ha) = $0.34

18. Scenario 1: Sum of all except line items 5, 6, 7 and 8

19. Scenario 2: Sum of all except line items 6, 7 and 8

20. Scenario 3: Sum of all except line items 5

21. Production of hybrid poplar crop produced with biosolids yielded 22.10 dry tons per ha. Gallons switchgrass ethanol per ha were 2316. Mass of hybrid poplar per gallon of ethanol = (22.10E06 grams)/(2316)=9.54E03 grams

22. The energy content of hybrid poplar was estimated at 19287joules per gram (8300 Btu/lb). Energy content hybrid poplar = (9.54E03 grams)X(19287 joules per gram) = 1.84E08 joules

23. Specific emergy per mass Scenario 1= (Total Emergy, line 18)/(Yield mass, line 20) = (12794E09 sej per gallon)/(9,54E03 grams per gallon) = 1.34E09 sej per gram

24. Specific emergy per mass Scenario 2= (Total Emergy, line 19)/(Yield mass, line 20) = (575909E09 sej per gallon)/(9,54E03 grams per gallon) = 6.04E10 sej per gram

25. Specific emergy per mass Scenario 3= (Total Emergy, line 20)/(Yield mass, line 20) = (39179E09 sej per gallon)/(9.54E03 grams per gallon) = 4.1E09 sej per gram

26. Transformity of hybrid poplar Scenario 1= (Total Emergy, line 18)/(Yield energy, line 21) = (12794E09 sej per gallon)/(1.8E08 joules per gallon) = 6.95E04 sej per joule

27. Transformity of hybrid poplar Scenario 2= (Total Emergy, line 19)/(Yield energy, line 21) = (575909E09 sej per gallon)/(1.8E08 joules per gallon) = 3.13E06 sej per joule

23. Transformity of hybrid poplar Scenario 3= (Total Emergy, line 20)/(Yield energy, line 21) = (39179E09 sej per gallon)/(1.8E08 joules per gallon) = 2.13E05 sej per joule

Footnotes to Table 13. Transportation on hectare basis and divided by the estimated gallons of ethanol that would be produced per hectare of cropland, which equaled 2316 gallons per ha (10,000 m^2). Older transformity values were corrected by factor of 1.68 (Odum et al., 2000).

1. Mass Transformation Ratio for machinery = 1.25E10 sej/g (Odum, 1996). Data: class 8 truck weighed about 4540kg, had a capacity to transport 8 tons of wood, had a life cycle of 7yr and was driven 103,266 km (64,000 miles) annually (Lovins, et al, 2004). The transport of 1 ha of hybrid poplar biomass was 49.73 tons; a distance of 80 kilometers (50 mile) per trip was assumed (Urbanchuk and Kapell, 2002). Truck use rate= (1 truck)X(1/7 year)X(50 miles per trip /64,000 miles per year)S(49.73, tons per ha /8 tons per trip) = .0003 /ha/yr. Mass in truck = (.0003/ha/yr)X(4540 kg)X(1000g/kg)/(2316 gallons ethanol per ha) = 0.6 grams

2. Tranformity diesel =1.1E05 sej/J (Odum, 1996). Data: a class eight used an average of 4.24 liter per km (10 miles per gallons) (Transportation Business Association, 2006). The wood was transported a distance of 80 km (50 miles) (Urbanchuk and Kapell, 2002). The truck transported 8 tons per trip. 1 ha produced 49.73 tons hybrid poplar. Gallons used = (80, km per trip)X(1 liter /4.24 km)X(49.73, tons per ha/8 tons per trip) = 117 liters diesel (31.08 gallons diesel). Energy in diesel= (31.08 gal)X(139000, Btu/gallon diesel)X(1055 joules per Btu)/(2316 gallons per ha)= 1.97E06 J

3. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Cost of services on operating a truck. Data: Trips per ha = (49.73 tons per ha/8 tons per trip) = 6.22 trips/ha. Cost of truck operator was estimated at $0.26 per km ($0.43 per mile) (Heartland Express, 2004). ($0.43/mile)X(6.22 trips per ha)X(50 miles per trip)/(2316 gallons per ha) = $0.058

4. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Cost of services on fuels. Data: average for 2003 was estimated at $0.425 per liter ($1.62 per gallon) (EIA, 2006c). ($0.45 /liter)X(117 liters)/(2316 gal per ha) = $0.022

Footnotes to Table 14. Inputs in kg per hour for facility operating 8406 hours per year with and then converted to a per gallon basis by dividing by the volume of ethanol produced annually, which was estimated to be 69.27 million gallons of pure ethanol. Certain numbers may differ slightly due to rounding. Older transformity values were corrected by factor of 1.68 (Odum et al., 2000).

1. Transformity of hybrid poplar biomass Scenario 1 = 1.34E+09 sej/g, calculated in this study. Data: biomass required for corn stover 12 kg per gallon (McAloon, et al, 2000). Theoretical yields for corn stover were on average 83.5 gallons of ethanol per ton. Hybrid poplar yield were around 106 gallons of ethanol. The input biomass was corrected by 0.8, (83.5/106). Mass in hybrid poplar = (12 kg) (1000 g/kg)X(0.8) = 9542 grams

2. Transformity of hybrid poplar biomass Scenario 2 = 6.04E+10 sej/g, calculated in this study. Data: biomass required for corn stover 12 kg per gallon (McAloon, et al, 2000 Theoretical yields for corn stover were on average 83.5 gallons of ethanol per ton. Hybrid poplar yield were around 106 gallons of ethanol. The input biomass was corrected by 0.8, (83.5/106). Mass in hybrid poplar = (12 kg) (1000 g/kg)X(0.8) = 9542 grams

3. Transformity of hybrid poplar biomass Scenario 3= 4.11E+09 sej/g, calculated in this study. Data: biomass required for corn stover 12 kg per gallon (McAloon, et al, 2000 Theoretical yields for corn stover were on average 83.5 gallons of ethanol per ton. Hybrid poplar yield were around 106 gallons of ethanol. The input biomass was corrected by 0.8, (83.5/106). Mass in hybrid poplar = (12 kg) (1000 g/kg)X(0.8) = 9542 grams

Inputs for ethanol conversion for all scenarios:

4. Mass Transformation Ratio for lime =1.73E09 sej/g calculated here based on energy content for surface mining and beneficiation (DOI, 1997). Data: grams calculated from 2395 kilograms per hour (Aden et al., 2002). Mass in lime = (2395 kg per hr)X(1000 g/ kg)X(8406 hr per yr)/(69.27E06 gallons ethanol)= 291 grams

5. Mass Transformation Ratio for ammonia = 2.87E09 sej/g based on process by Haldor Topsoe plants (Smil, 1999). Total energy for ammonia production was 35.6 MJ/kg of nitrogen. Data: ammonia grams calculated from Macon et al., 2000; Aden et al., 2002; and Wooley et al., 1999. Average of ammonia used = (689+1811+1419)/3= 1306 kilograms per hour. Mass in ammonia = (1306 kg per hr)X(1000 g/ kg)X(8406 hr per yr)/(69.27E06 gallons ethanol) = 159 gram

6. Transformity of corn steep liquor from processed foods = 330000 sej/J (Johansson, 2005). Data: grams calculated from 1306 kilograms per hour (Aden et al., 2002); energetic value estimated at 342 calories per 100 grams of cornstarch (USDA, 2006b). Energy in corn steep liquor = (1306 kg per hr)X(1000 g/ kg)X(8406 hr per yr)X(3.42 calories per gram)X(4.186 joules per calorie)/(69.27E06 gallons ethanol) = 2269 J

7. Transformity of nutrients from sugarcane = 1.94E04 sej/J (Brandt-Williams, 2001). Data: assumed that sugar as nutrients energy supplement for anaerobic bacteria; sugar grams estimated at 174 kilograms per hour (Aden et al., 2002); assumed carbohydrates have 4 calories per gram. Energy in sugarcane = (174 kg per hr)X(1000 g/ kg)X(8406 hr per yr)X(4 calories per gram)X(4.186 joules per calorie)/(69.27E06 gallons ethanol) =354 J

8. Transformity of antifoam from processed foods = 330000 sej/J (Johansson, 2005). Data: grams corn oil used as antifoam was estimated at 167 kilograms per hour. (Aden et al., 2002); there were 884 calories per 100 grams of corn oil (USDA, 2006b). Energy in antifoam = (167 kg per hr)X(1000 g/ kg)X(8406 hr per yr)X(8.84 calories per gram)X(4.186 joules per calorie)/(69.27E06 gallons ethanol) = 748 J

9. Mass Transformation ratio for nitrogen 2.87E09 sej/g based on process by Haldor Topsoe plants (Smil, 1999). Total energy for ammonia production was 35.6 MJ/kg of nitrogen. Data: grams of ammonium sulfate calculated from 158 kilograms per hour (Macon et al., 2000); assumed carbohydrates have 4 calories per gram. Mass in nitrogen = (158 kg per hr)X(1000 g/ kg)X(8406 hr per yr)/(69.27E06 gallons ethanol) = 19 grams

10. Mass Transformation Ratio for BFW chemical used PVC = 9.86E9sej/g (Buranakarn, 1998). Data: grams BWF chemicals calculated from 89 kilograms per hour (Aden et al., 2002). Mass in BFW chemicals = (89 kg per hr)X(1000 g/ kg)X(8406 hr per yr)/(69.27E06 gallons ethanol)=11 grams

11. Mass Transformation Ratio for machinery = 1.30E10sej/g (Brown and Arding, 1991). Data: components estimated based in design in Macon et al. (2000); equipment lifetime of 15 years; pumps assume 85% steel data (Gould's Pumps, 2006). Vessels assume 100% steel at gauge 12 thickness and 7.9 grams/cm^3 density (Bushman et al., 2004); mixer assume 95% steel data (HC Davis, 2006); heat exchanger assume 95% steel, (Armstrong International, 2006).

Pumps	3.10E+07	g
Vessels	4.50E+08	g
Mixers	2.30E+08	g
Heat exchanger	3.00E+07	g
Other	4.64E+08	g
Total Mass	1.21E+09	g

Mass in machinery = (1.21E09 grams)/ (15 yrs)/(69.27E06 gallons ethanol)=1.2 grams

12. Mass Transformation Ratio for buildings= 6.97E09sej/g (Brown & Buranakarn, 2001). Assumed use life of 15 years. Data: construction materials for 50 million gallon facility (Midwest Grain Processors LLC, 2006) required 1000 tons of reinforced steel and 600 tons of structural steel. Values were adjusted by factor of 1.24 (69.27 million gallon/50 million gallon) to correct for capacity difference in production at the facility. Mass in buildings = (adjustment factor) (total mass of steel)/(life cycle)/(69.26E06 gallons of ethanol)= (1.4)X(1600 tons of steel)X(1E06 grams per ton)/(15 yrs)/(69.27E06 gallons ethanol) = 2.65grams

13. Mass Transformation Ratio for cement= 3.33E09sej/g (Brown & Buranakarn, 2001). Assume use life of 15 years. Data: 5000 cubic yards of concrete use in 50 million gallon ethanol capacity facility (Midwest Grain Processors, 2006); density of concrete aggregate estimated at 1.13E06 grams per m^3. Mass in concrete = (1.4)X(5000 cubic yards)X(0.7645 cubic meter to cubic yard)X(1.13E06 grams per m^3)/(30 years)/(69.27E06 gallons of ethanol produced) = 3 grams

14. Transformity of potable water = 3.14E05sej/J (Baneful, 1998). Data: grams of water 189649 kilograms per hour (Macon et al., 2000). Energy in water = (1.9E+05 kg/hr)X(8406 hr per yr)X(1000g/kg)X(4.186 joules per gram)/ gallon ethanol produced = 9.6E+04 J

15. Transformity gasoline = 1.1E05 sej/J (Odum, 1996). Data: calculated based on 5% gasoline needed to denature a gallon of ethanol. Energy in gasoline = (1 gal ethanol)X(5%)X(124000 Btu per gallon)X(1055 joules per Btu) = 6.54E+06 J
16. Transformity of petroleum products 1.1E05 sej/J (Odum, 1996). Data: amount required 20 kg of propane per hour (Macon et. al., 2000). Energy in propane = (20, kg/year)X(8406, hr per yr)X(m^3/ 584kg)X(246 gal/ m^3)X(91000 Btu per gal)X(1055 joules per Btu)/(69.27E6 gallons ethanol) = 9.82E04 J
17. Transportation Emergy from Table 13.

18. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: Sulfuric acid is produced by capturing the sulfur from stack emissions and recycled as sulfuric acid. Since this is a byproduct, it only account for the cost involved with processing the sulfur into sulfuric acid. Cost of acid input estimated at $0.01 per gallon. (Aden et al., 2002)

19. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cervices lime $.02/gallon (Adén et al., 2002)

20. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of ammonia input is $0.040/gallon (Wooley et al., 1999).

21. Money Transformation Ratio =1.1E12 sej/$ (Tilley, 2006). Data: cost of corn steep liquor is $0.03 /gallon (Aden et al., 2002)

22. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: nutrients cost $0.008/gallon (Wooley et al., 1999)

23. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: services antifoam $0.02 /gallon (Wooley et al., 1999)

24. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: services ammonium sulfate $0.003/gallon (Wooley et al., 1999)

25. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: services water: $0.01/ year/gallon (Aden et al. 2002)

26. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: Services gasoline required $0.05/gallon (Wooley, et al., 1999)

27. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: services propane required $0.00001/gallon (Aden et al. 2002)

29. Money Transformation Ratio = $1.1E12 (Tilley, 2006). Cost included insurance, taxes, capital charge, labor, maintenance, overheads and credits for electricity sales. Data: operating cost: $0.074/gallon (Wooley et al., 1999 and Aden et al., 2002)

29. Transportation Emergy from Table 13

30. Total Emergy Scenario 1 sum of all (excluding lines 2 and 3)

31. Total Emergy Scenario 2 sum of all (excluding lines 1 and 3)

32. Total Emergy Scenario 3 sum of all (excluding lines 1 and 2)

33. The ethanol mass was calculated from density of ethanol, 789 kg per m^3. Mass gallon of ethanol = (1 gallon)X(789 kg per m^3)X(1000 grams 1 gram)X(.0038 m^3 per gallon)X(0.903% ethanol in denatured ethanol) = 2.71E03 grams

34. The energy content of ethanol was reported as 8.02E7 joules per gallon (76,000 Btu/lb).

35. Specific emergy per mass Scenario 1= (Total Emergy, line 30)/(Yield mass, line 33) = (17187E09 sej per gallon)/(2.7E03 grams per gallon) = 6.4E09 sej per gram

36. Transformity of hybrid poplar ethanol Scenario 1= (Total Emergy, line 30)/(Yield energy, line 34) = (17187E09 sej per gallon)/(8.07E07 joules per gallon) = 2.14E05 sej per joule

37. Specific emergy per mass Scenario 2= (Total Emergy, line 31)/(Yield mass, line 33) = (580301E09 sej per gallon)/(2.7E03 grams per gallon) = 2.14E11 sej per gram

38. Transformity of hybrid poplars ethanol Scenario 2 = (Total Emergy, line 31)/(Yield energy, line 34) = (580301E09 sej per gallon)/(8.07E07 joules per gallon) = 7.2E06 sej per joule

39. Specific emergy per mass Scenario 3= (Total Emergy, line 32)/(Yield mass, line 33) = (43572E09 sej per gallon)/(2.7E03 grams per gallon) = 1.61E10

40. Transformity of hybrid poplar ethanol Scenario3= (Total Emergy, line 32)/(Yield energy, line 34) = (43572E09 sej per gallon)/(8.07E07 joules per gallon) = 5.4E05 sej per joule

Appendix D: **Notes to Emergy Tables for Biodiesel**

Footnotes to Table 22. All agricultural inputs were determined on a per hectare basis and divided by the volume of biodiesel that would be produced per hectare of soybean cropland, which equaled 122 gallons per ha (10,000 m^2). Farmed area was 1 ha. Older transformity values were corrected by factor of 1.68 (Odum et al., 2000).

1. Transformity of sunlight = 1 sej/J by definition (Odum, 1996). Solar insulation was annual average for Virginia (USA) latitude 37.55 & longitude -78.56. Data: 4.3 kWh/m^2/day and Aledo = 0.13 (NASA, 2006). Energy in sunlight = (10000 m^2)X(4.3 kWh/ m^2 /day)X((859.9 kcal per kWh)X(365 days per year)X(1-albedo)X(4186 joules per kcal)/(122 gallons biodiesel per ha) = 4.04E11 J

2. Transformity of rain = 30576 sej/J (Odum, 1996). Annual rainfall was 30 year average. Data: annual rainfall 1114 mm per year (NOAA, 2006); density of water 1000 kg/m^3. Energy in rain = (10000 m^2)X(1114 mm)X(0.001 m/mm)X(1000 kg/ m^3)X(4940J/kg)/(122 gallons biodiesel per ha) = 4.53E08 J

3. Transformity of evapotranspiration (ET) = 30576 sej/J (Odum, 1996). Averaged of soybean estimates from Climate and Crop Yield Ohio Soil Drainage Research Unit located at Ohio State University (USDA, 2006a). Data: ET= 432 mm/year; specific gravity of water = 1.0E06 g/ m^3. Energy in ET = (10000 m^2)X(432 mm/yr)X(0.001 m/mm)X(1E06 g/ m^3)X(4.94J/g)/(122 gallons biodiesel per ha) = 1.75E8 J

4. Transformity of topsoil = 73,800 sej/J (Odum, 1996). Erosion rate estimated from cultivated areas in Virginia (NRCS, 2006b). Organic content in soil was estimated from eight Virginia soil series (NRCS, 2006a). The energy in the organic soil content was estimated from average of caloric content on the composition of soil organic matter (SOM) materials from composition of SOM (UM, 2006) and energetic value of particulate organic matter (Malone and Sardou, 1969; Currie et al., 2003); and energetic value of decomposed organic material (Chubu Shiryo Co. Ltd., 2006). Data: soil erosion was 13 tons per ha (5.35 tons per acre) per year; average organic percent in soil 3.33%. (NRCS, 2006a); energy in organic soil (O.M.) 3.84 kcal/g. Energy in soil = (10000 m^2)X(13 tons per ha)X(1 ha/10,000 m^2)X(1E6 grams per ton)X(3.33 %, O.M.)X(3.84 kcal/g)X(4186 J/kcal)/(122 gallons biodiesel per ha) = 5.89E07 J

5. Transformity petroleum fuels = 1.1E05 sej/g (Odum, 1996). Virginia herbicide in soybean crops calculated based on total amount of herbicide used divided by area of application (USDA, 2004b). Data: herbicide application was 268,314 kg (591,000 lbs) and pesticide 11,350 kg (25,000 lbs) in 194,400 ha (480,000 acres). Embodied fossil fuel energy of Atrazine 0.005 liter petroleum per gram (0.584 lb per gal) (Hales, 1992). Amount of herbicide and pesticide used per ha = (268,314 + 11350 kg)/194,400 ha)X(454 grams per kg) = 1439 grams per ha. Energy in herbicide used = (1 ha)X(1439 grams per ha)X(0.005 liters fuel/ gram of herbicide)X(0.264 gallons per liter)X(140,000, Btu/ 1 per gal of petroleum fuel)(1055 joules/Btu)/(122 gallons biodiesel per ha)= 2.25E06J

6. Mass Transformation Ratio for ammonia = 2.87E09 sej/g calculated from Haldor Topsoe Plants (Smil, 1999). The process used 35.6 MJ/kg of nitrogen as the total energy for ammonia production. Virginia nitrogen fertilizer was calculated base on total amount of nitrogen used in soybean crop divided by area of application (USDA, 2004b). Data: Approximately 194,400 ha (480,000 acres) of Virginia were planted with soybean and a total of 1.63E09 grams (3.6 million lbs) of nitrogen were applied. Estimated application per ha = (1.63E09 grams)/(94,400 ha) = 8407 grams of nitrogen per ha. Mass in Nitrogen= (1ha)X(8407 g/ha)/(122 gallons biodiesel per ha)= 69 grams

7. Mass Transformation Ratio for P_2O_5 = 6.55E09 sej/g (Odum, 1996). P_2O_5 fertilizer usage in soybean crop in Virginia was calculated base on total amount of phosphate used divided by area of application (USDA, 2004b). Approximately 1.61E09 grams (7.3 million lbs) of P_2O_5 were applied 194,400 ha (480,000 acres). Estimated application per ha = (1.61E09 grams)/(194,400 ha) = 8282 grams per ha. Mass of P_2O_5 = (1 ha)X(8282 g per ha)/(122 gallons biodiesel per ha)=68 grams

8. Mass Transformation Ratio for potash (K_2O_5) = 1.85E09 sej/g calculated here based on energy and environmental profile for potash (DOI, 1997). K_2O_5 fertilizer used in soybean crop in Virginia was calculated base on total amount of potash used divided by area of application (USDA, 2004b). Approximately 8.35E09 grams (18.4 million lbs) of K_2O_5 were applied to 194,400 ha (480,000 acres). Estimated application per ha = (8.35E09 grams)/(194,400 ha) = 42,953 gram per ha. Mass of potash (K_2O_5) = (1 ha)X(42,953 g/ ha) /(122 gallons biodiesel per ha) = 353 grams

9. Mass Transformation Ratio of machinery = 1.30E10 sej/g (Odum, 1996). Data: a 50HP tractor weighed about 2000kg, has a life cycle of 7.5yr and is used in a 121 ha farm (USDA, 2006f). Rate of tractor used per ha was calculated = (1 tractor)/(7.5 yrs lifetime)/(121 ha farm) = 0.0011/ha/yr. Mass in tractor = (0.0011/ha/yr)X(2000 kg) X(1000 grams per kg)/(122 gallons biodiesel per ha)= 18 grams

10. Tranformity diesel = 1.1E5 sej/J (Odum, 1996). Average diesel used in Virginia for soybean production in 2003-2004 was estimated at 17.6 liters per ha (1.9 gallons per acre) (USDA, 2006h). Energy in diesel= (10000 m^2)X(1 ha per 10000 m^2)(17.6 liters per ha)X(0.264 gal per liter)X(132000, Btu/gallon diesel)X(1055, joules per Btu)/(122 gallons biodiesel per ha) = 5.37E06 J

11. Tranformity gasoline= 1.1E5 sej/J (Odum 1996). Based on average gasoline used in Virginia for soybean production in 2003-2004 estimated at 11.22 liters per ha (1.2 gallons per acre) (USDA, 2006h). Energy in gasoline= (10000 m^2)X(1 ha per 10000m^2)X (11.22 liters per ha)X(0.264 gal per liter)X(124000 Btu/gallon gasoline)X(1055 joules per Btu)/(c) = 3.18E06 grams

12. Transformity standardized electricity 3.36E05 sej/J (Odum, 1996). Based on average of electricity used for soybean production average of 1.73 kWh per ha (0.7 kWh per acre) for neighboring states Maryland and North Carolina in 2003-2004 (USDA, 2006h). Energy in electricity= (10000 m^2)X(1 ha per 10000 m^2)X(1.73 kWh per ha)(3.6E06, joules per kWh) = 5.11E04J

13. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of services on chemicals $41.31/ha (USDA, 2004a). (10000 m^2)X(1 ha per 10000 m^2)X ($41.31 per ha)/(122 gallons biodiesel per ha) = $0.339

14. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of services on fertilizers $30/ha (USDA, 2004a). (10000 m^2)X(1 ha per 10000 m^2)X ($30 per ha)/(122 gallons biodiesel per ha) = $0.25

15. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of labor $187.48/ha (USDA, 2004a). (10000 m^2)X(1 ha per 10000 m^2)X ($187.48 per ha)/(122 gallons biodiesel per ha) = $1.54

16. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of services on fuel $26.5/ha, (USDA, 2004a). (10000 m^2)X(1 ha per 10000 m^2)X ($26.5 per ha)/(122 gallons biodiesel per ha) = $0.22

17. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: other production cost $145 /ha, (USDA, 2004a). ((10000 m^2)X(1 ha per 10000 m^2)X ($145 per ha)/(122 gallons biodiesel per ha) = $2.94

18. Sum of all components except 1 & 2

19. Production of soybean crop yielded about 2.9 tons per ha. Moisture content of soybean average 15%. Estimated dry yield = (2.9E06 grams per ha)X(85%, dry content) = 8.96E6 g per ha. Gallons soybean biodiesel per ha were 122. Mass of soybean per gallon of ethanol = (8.96E06 grams)/(122)=2.15E04 grams

20. The energy content of soybean was reported as 4.5 kcal per gram. Energy content soybean = (2.15E04 grams)X(4.5 kcal per gram)(4186 joules per kcal) = 3.45E08 joules

21. Specific emergy per mass soybean = (Total Emergy, line 18)/(Yield mass, line 19) = (18269E09 sej per gallon)/(2.15E04 grams per gallon) = 8.49E08 sej per gram

22. Transformity of soybean = (Total Emergy, line 18)/(Yield energy, line 20) = (18269E09 sej per gallon)/(4.05E08 joules per gallon) = 5.3E04 sej per joule.

Footnotes to Table 23. All agricultural inputs were determined on a per hectare basis and divided by the estimated gallons of biodiesel that would be produced per hectare of castorbean cropland, which equaled 336 gallons per ha. Farmed area was 1 ha. Older transformity values were corrected by factor of 1.68 (Odum et al., 2000)

1. Transformity of Sunlight = 1 sej/J by definition (Odum, 1996). Solar insolation was annual average for Texas latitude 31.2 and longitude 99.4. Data: 3.64 kWh/m^2/day and albedo = 0.22 (NASA, 2006). Energy in sunlight = (10000 m^2)X(3.64 kWh/ m^2 /day)X((859.9 kcal per kWh)X(365 days per year)X(1-albedo)X(4186 joules per kcal)/ (336 gallons biodiesel per ha) = 1.27E11 J

2. Transformity of wind = 2513 sej/J (Odum, 1996). Wind was annual average for High Planes in Texas (USA) (University of Utah, 2006); calculation of geostrophic winds based on fact that observed winds about 0.6 of geostrophic wind. Data: Drag coefficient = 1.0E-3, dimensionless (Miller, 1964 in Kraus, 1972); wind velocity annual average estimated to be 5.35 meter per second (m/s); air density = 1.3 kg/m^3; conversion: 1 joule= kgm^2/s^2. Geostrophic wind = (5.35 m/s)/(0.6)=8.9 m/s. Energy in wind = (10000 m^2)X(1.3 kg/m^3)X(1.0E-03,drag coefficient)X(8.9 m/s)^{3}X(3.14E07 seconds/year)X(1 joule / kg m^2/s^2)/(336 gallons biodiesel per ha) = 8.63E08 J

3. Transformity of rain = 30576 sej/J (Odum, 1996). Based on data from Amarillo Texas. Data: annual rainfall 582 mm per year (NOAA, 2006); density of water 1000kg/m^3. Energy in rain = (10000 m^2)X(582 mm)X(0.001 m/mm)X(1000 kg/ m^3)X(4940J/kg)/(336 gallons biodiesel per ha) = 8.55E07 J

4. Transformity of topsoil = 73,800 sej/J (Odum, 1996). Erosion rate of wind was used because this was a major erosion problem in the High Plains area. Erosion rate estimated in cultivated areas in Texas (NRCS, 2006b). The energy in the organic soil content was estimated from average of caloric content on the composition of soil organic matter (SOM) materials from composition of SOM (UM, 2006) and energetic value of particulate organic matter (Malone and Sardou, 1969; Currie et al., 2003); and energetic value of decomposed organic material (Chubu Shiryo Co., Ltd., 2006). Data: soil erosion 21 tons per ha (9.4short tons/acre/yr); average organic percent in soil 3%. (Hum Alfa Inc., 2006); energy organic soil 3.84 kcal/g. Energy in soil = (10000 m^2)X(21 tons per ha)X(1E06 grams per ton)X(1 ha/10,000 m^2)X(3.84 %)X(3.84 kcal/g)X(4186 J/kcal)/(336 gallons biodiesel per ha) = 3.02E07 J

5. Transformity of groundwater = 278880 sej/J (Odum, 1996). Most irrigation in Texas utilized groundwater. Irrigation requirements for castorbean crop in the US averaged 1750 m3/ha (Duke, 1983). Energy in groundwater= (10000 m^2)X(1 ha per 10000 m^2)X (1750 m3 per ha)X(1000, kg/m^3)X(4940, J/kg)/(336 gallons biodiesel per ha) = 2.57E07 J

6. Mass Transformation Ratio for ammonia = 2.87E09 sej/g calculated from Haldor Topsoe Plants (Smil, 1999). The process used 35.6 MJ/kg of nitrogen as the total energy for ammonia production. Data: nitrogen requirements for castorbean estimated at 90kg/ha (Duke, 1983; Brigham and Spears, 1961). Mass in ammonia = (10000 m^2)X(1 ha per 10000 m^2)X(90 kg per ha)X(1000 g/kg)/(336 gallons biodiesel per ha) = 268 grams

7. Mass Transformation Ratio for P_2O_5 = 6.55E09 sej/g (Odum, 1996). Data: P_2O_5 requirements for castorbean crop estimated at 45 kg/ha (Duke, 1983). Mass of P_2O_5 = (10000 m^2)X(1 ha per 10000 m^2)X(45 kg per ha)X(1000, g/kg)/(336 gallons biodiesel per ha) = 138 grams

8. Mass Transformation Ratio for K_2O_5 = 1.85E09 sej/g calculated based on energy and environmental profile for Potash (DOI, 1997). Data: K_2O_5 estimated at 17 grams per ha (Brigham, 1993). Mass K in potash (K_2O_5) = (10000 m^2)X(17 kg/ha)X(1 ha /10,000 m^2)X(62 grams per mole K/78 grams per moles K_2O_5)X(1000 g/kg)/(336 gallons biodiesel per ha) = 51 grams

9. Mass Transformation Ratio of machinery = 1.30E10 sej/g (Odum, 1996). Data: a 50HP tractor weighed about 2000kg, had a life cycle of 7.5yr and was used in a 121 ha farm (USDA, 2006f). Rate of tractor used per ha was calculated = (1 tractor)/(7.5 yrs lifetime)/(121 ha farm) = 0.0011/ha/yr. Mass in tractor = (0.0011/ha/yr)X(2000 kg) X(1000 grams per kg)/(336 gallons biodiesel per ha)= 8 grams

10. Tranformity of diesel = 1.1E5 sej/J (Odum 1996). Gallons of fuel required per ha per year were estimated from fuel required for field operations for 30 inch rows was 28.52 liter per ha (3.05gal/acre) (Cook et al., 1996). Data: gallons diesel estimated at 3.2 gallons per acre. Energy in diesel = (10000 m^2)X(1 ha /10,000 m^2)X (28.52 liters per ha)X(0.264 gal per liter)X(132000 Btu/gallon diesel)X(1055, joules per Btu)/(336 gallons biodiesel per ha) = 3.28E06 J

11. Transformity of standardized electricity = 3.36E05 sej/J (Odum, 1996). Electricity for irrigation calculated from Water-Related technologies for sustainable Agriculture in U.S. Arid and Semiarid lands (OTA, 1983). Averaged cost for lifting 1-acre feet of water at 200 ft with pump capacities 30, 50 and 70 was $18 (OTA, 1983). Data: cost of elec. In the 1970's the cost of electricity was $0.033/kWh in 1970's. Energy in electricity = (10000 m^2)X(1 ha /10,000 m^2)X(1750 m3 per ha irrigation required)(.000811 acre-ft per cubic meter)X($18/acre feet)(1/.033 kWh per $)(3.6E06, Joules per kWh)/(336 gallons biodiesel per ha) = 8.29E06 J

12. Money Transformation Ratio = 1.27E13 sej/$ (Odum, 2006). Data: seeds required were 14572 grams per ha (13 lb/acre) and cost of seeds $0.00011 per g ($.05 per lb) (Brigham and Spears, 1961). (10000 m^2)X(1 ha /10,000 m^2)X($14572 g per ha)X(0.00011 per g)/(336 gallons biodiesel per ha) = $0.005

13. Money Transformation Ratio = 1.27E13 sej/$ (Odum, 2006). These included cost of land preparation, planting, irrigation, fertilizer, cultivation, insect control, mechanical harvesting and hauling and was estimated at $130 per ha ($52.5 per acre) (Brigham and Spears, 1961). (10000 m^2)X(1 ha /10,000 m^2)X($130 per ha)/(336 gallons biodiesel per ha) = $0.39

14. Sum of all components except 1 & 2

15. Production of castorbean crop yielded about 2.28E06 grams per ha. Moisture content of castorbean was estimated at 5.6%. Estimated dry yield = (2.3E06 grams per ha)X(94.4%, dry content) = 2.17E06 g per ha. Gallons castorbean biodiesel per ha were 336. Mass of castorbean per gallon of biodiesel = (2.17E06 grams)/(336)=6.4E03 grams

16. The energy content of castorbean was reported as 9 kcal per gram. Energy content castorbean = (6.4E03 grams)X(9 kcal per gram)(4186 joules per kcal) = 2.4E08 joules

17. Specific emergy per mass castorbean = (Total Emergy, line 14)/(Yield mass, line 19) = (21999E09 sej per gallon)/(6.4E03 grams per gallon) = 3.44E09 sej per gram

18. Transformity of castorbean = (Total Emergy, line 14)/(Yield energy, line 16) = (21999E09 sej per gallon)/(2.4E08 joules per gallon) = 9.14E04 sej per joule.

Footnotes to Table 24. Transportation based on agricultural output. All agricultural inputs were determined on a per hectare basis and divided by volume of biodiesel that would be produced per hectare of soybean cropland, which equaled 122 gallons per ha. Transformity values are corrected by factor of 1.68 (Odum et al., 2000).

1. Mass Transformation Ratio for machinery = 1.25E10 sej/g (Odum, 1996). Data: class 8 truck weighed about 4540kg, had a capacity to transport 8 tons of beans, had a life cycle of 7 yr and was driven 103, 266 kilometers (64,000 miles) annually (Lovins, et al, 2004). The yield of 1 ha of bean was about 3 tons (wet) and the trip distance was assumed at 80 kilometers (50 miles) (Urbanchuk and Kapell, 2002). Total truck use = (1 truck)X(1/7 year)X(80, kilometers per trip /103,266 kilometers per year)X(3 tons per ha /8 tons per trip) = 0.00004 truck/y. Mass in truck = (0.00004 truck per year)X(4540 kilograms)X(1000 grams/1 kilogram)/(122 gallons biodiesel per ha) = 2 grams

2. Transformity of diesel = 1.1E05 sej/J (Odum, 1996). Data: a class eight truck used an average of 4.24 km per liter (10 mile per gallon)(Transportation Business Association, 2006). The beans were transported a distance of 80 kilometers (50 miles) (Urbanchuk and Kapell, 2002). The truck transported 8 tons per trip. 1 ha produced an estimated 3 tons wet tons of soybean. Gallons of diesel = (80, kilometers per trip) (3 tons per ha / 8 tons per trip) (1/4.25, km per liter) = 7.57 liters of diesel. Energy in diesel= (7 liters)X(0.264 gallons/ 1 liter)X(132000 Btu/gallon diesel)X(1055 joules per Btu)/(122 gallons biodiesel per ha) = 2.14E06 J

3. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Cost of services on operating a truck. Data: 0.375 trips/ha, cost for trucker was $0.266 per km ($0.43 per mile) (Heartland Express, 2004). ($0.267/km)X(80 km)X(0.375 trips per ha)/(122 gallons biodiesel per ha) = $0.18

4. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Cost of services on fuels average was estimated at $0.425 per liter ($1.62 per gallon) for 2003 (EIA, 2006c). ($0.425/liter)X(7.57 liters of diesel)/(122 gallons biodiesel per ha) = $0.025

Footnotes to Table 25. Transportation based on agricultural output. All agricultural inputs were determined on a per hectare basis and divided by the volume of biodiesel that would be produced per hectare of castorbean cropland, which equaled 336 gallons per ha. Transformity values are corrected by factor of 1.68 (Odum et al., 2000).

1. Mass Transformation ratio machinery = 1.25E10 sej/g (Odum, 1996). Data: class 8 truck weighed about 4540kg, had a capacity to transport 8 tons of beans, had a life cycle of 7 yr and was driven 103, 266 kilometers (64,000 miles) annually (Lovins, et al, 2004). The yield of 1 ha of bean was 2.5 tons (wet) and the trip distance was assumed at 80 kilometers (50 miles) (Urbanchuk and Kapell, 2002). Total truck use = (1 truck)X(1/7 year)X(80, kilometers per trip /103,266 kilometers per year)X(2.5 tons per ha /8 tons per trip) = 0.00003 truck/y. Mass in truck = (0.00003 truck per year)X(4540 kilograms)X(1000 grams/1 kilogram)/(336 gallons biodiesel per ha) = 5 grams

2. Transformity of diesel = 1.1E05 sej/J (Odum, 1996). A class eight truck used an average of 4.24 km per liter (10 mile per gallon)(Transportation Business Association, 2006). The beans were transported a distance of 80 kilometers (50 miles) (Urbanchuk and Kapell, 2002). The truck transported 8 tons per trip. 1 ha produced an estimated 2.5 tons wet tons of castorbean. Gallons of diesel = (80, kilometers per trip) (2.5 tons per ha / 8 tons per trip) (1/4.25, km per liter) = 5.88 liters of diesel. Energy in diesel= (5.88 liters)X(0.264 gallons/ 1 liter)X(132000 Btu/gallon diesel)X(1055 joules per Btu)/(336 gallons biodiesel per ha) = 6.5E05 J

3. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Cost of services on operating a truck. Data: 0.375 trips/ha, cost for trucker was $0.266 per km ($0.43 per mile) (Heartland Express, 2004). ($0.267/km)X(80 km)X(0.3125 trips per ha)/(336 gallons biodiesel per ha) = $0.02

4. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Cost of services on fuels average was estimated at $0.425 per liter ($1.62 per gallon) for 2003 (EIA, 2006c). ($0.425/liter)X(5.88 liters of diesel)/(336 gallons biodiesel per ha) = $0.008

Footnotes to Table 26. All inputs were determined on a per annual basis and divided by volume of soybean oil that produced per year in an oil crushing facility. The oil crushing facility processed approximately 1.1E06 metric tons per year of soybean annually (3.93E07 bushels). The volume of virgin soy oil per year produced after losses was estimated at 4.93E07 gallons, after losses in the process. Older transformity values were corrected by factor of 1.68 (Odum et al., 2000).

1. Transformity of soybean = 8.32E+08 sej/g, calculated in this study. Data: Data: literature review of Purdue oil crushing facility located in Virginia indicated 39.3 million bushels of soybean were crushed per year (Dishneau, 2006). Conversion 36.74 bushels in a metric ton. Mass soybean per gallon= (3.93E+07 bushels soybean per year)X(1 ton per 36.74 bushels)X(1.0E+06 grams per ton)/(4.93E07 gal vegetable oil) = 21521 grams

2. Transformity of petroleum products = 1.1E05 sej/J (Odum 1996). Hexane also referred as petroleum naphtha had an energy value of 118,700 Btu/gal and density of 665 kg/m^3. Data: hexane was estimated at 2.02 kg per metric ton of soybean (Sheehan et al., 1998). Energy in hexane = (2.02 kg per metric ton)X(1.1E+06 tons soybean processed per year)X(1 m^3/ 665 kg)X(264.2 gal/m^3)X(118700 Btu/gal)X(1055 Joules/Btu)/(4.93E07 gal crude vegetable oil) = 2.16E06 J

3. Mass Transformation Ratio for machinery = 1.30E10sej/g (Brown and Arding, 1991). Equipment required for oil processing was gathered from EPA air permit submitted by the Purdue facility (VADEQ, 2006) and from literature review (Parker Boiler, 2006; HC Davis, 2006). It was assumed that equipment was 95% steel and had 15 year lifetime. The equipment mass total was 5.68E08 grams. Mass in machinery = (5.68 E08 grams)X(95% lifetime)/(15 years)/(4.93E07 gal crude vegetable oil) = 0.73 grams

4. Mass Transformation Ratio for buildings = 6.97E09sej/g (Brown & Buranakarn, 2001). Assumed lifetime of 20 years. Mass of buildings was estimated based on 1560 tons used in construction of oil crushing facilitates in Midwest (Fargo Tank & Steel Company, 2006). Mass in buildings = (1560 metric ton)X(1.0E+06 grams per ton)/(20 years)/(4.93E07 gal crude vegetable oil) = 1.05 grams

5. Transformity of cement = 3.33E09sej/g (Brown & Buranakarn, 2001). Assume use life of 15 years. Data: 5000 cubic yards of concrete use in 50 million gallon ethanol capacity facility (Midwest Grain Processors, 2006); density of concrete aggregate estimated at 1.13E06 grams per m^3. Mass in concrete = (5000 cubic yards)X(0.7645 cubic meter to cubic yard)X(1.13E06 grams per m^3)/(30 years)/(4.93E07 gal crude vegetable oil) = 2.92 gram

6. Transformity of potable water = 1.53E05sej/J (Buenfil, 1998). Data water use was estimated at 3.28 kg per metric ton of soybean processed (Sheehan et al., 1998). Energy in water = (3.28 kg per metric ton)X(1.1E+06 tons bean per year)X(1000 grams per kilogram)X(4.186 joules per gram of water)/(4.93E07 gal crude vegetable oil) = 306 J

7. Transformity of coal = 6.69E04sej/J (Odum, 1996). Drying of beans to reduce moisture required 266,275 kcal per metric ton of bean (Sheehan et al., 1998). Coal was used as energy for drying beans.

- Coal equivalent = (266,275 kcal)X(4184 joules per kcal)X(1 Btu /1055 joules)/(1 lb coal/12,250 Btu) = 86 lbs-coal per metric ton of bean.

Steam generation for other energy requirements was also an input of 220,020 kcal per metric ton. The Oil-Crushing facility in Virginia reported using a coal-fired industrial boiler with an 85% efficiency to produce the steam and to co-generate 1700 kW of electricity (ORNL, 2006c). However, there was only 85% efficiency, so adjust coal requirements by factor of 1.176 (100%/85%).

- Coal used in steam production = 1.176 (220,020 kcal per ton bean)X(4184J/kcal)X(1 Btu/1055 J)X(1 lb coal/12,250 Btu) = 83 lb of coal.

Energy in coal = (86 + 83, lbs-coal per metric ton)X(1.10E+06 MT /year)X(12,250 Btu /lb-coal)X(1055 J /Btu)/(4.93E07 gal crude vegetable oil) = 4.72E07 J

8. Transformity of standardized electricity = 3.36E05 (Odum, 1996). Data: estimated electricity use was 69.66 kWh per metric ton of bean (Sheehan et al., 1998). Electricity require = (69.66 kWh per metric ton)X(1.1E06 metric ton of beans)= 7.66E07kWh. However, there was 1700kW per 8000 hours of self-generated electricity, (ORNL, 2006c). Self-generated electricity = (1700 kW)X(8000 hrs)=1.36E07 kWh. Total Energy in electricity= [7.66E07kWh per year-1.36E07 kWh per year self-generated](3.6E+06 joules per kWh)/(4.93E07 gal crude vegetable oil) = 4.6E06 J

9. Transportation from Table 24.

10. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of hexane of soybean was $0.004 per bushel (English et al., 2002). ($0.004 /bushel of soybean)X(3.9E07 bushels of soybean processed /year)/(4.93E07 gal crude vegetable oil)= $0.003

11. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of water was $0.003 per bushel (English et al., 2002). ($0.003/bushel of soybean processed)X(3.9E07 bushels of soybean processed per year)/(4.93E07 gal crude vegetable oil) = $0.002

12. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of coal was $0.080 per bushel (English et al., 2002). ($.080 /bushel of soybean) X(3.9E07 bushels of soybean processed per year)/(4.93E07 gal crude vegetable oil) = $0.063

13. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of electricity was $0.044 per bushel (Burton et al., 2002). ($0.044/bushel of soybean) X(3.9E07 bushels of soybean processed per year)/(4.93E07 gal crude vegetable oil) = $0.003

14. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Cost included insurance, taxes, capital charge, labor, maintenance, overheads and credits for byproducts and investment capital. Operational cost was $0.412 per bushel of soybean (English et al., 2002). ($0.412/bushel of soybean) X(3.9E07 bushels of soybean processed per year)/(4.93E07 gal oil) = $0.412

15. Transportation Services from Table 24

16. Total Emergy sum of all.

17. Density of biodiesel oil was 3385 grams per gallon.

18. The energy content of biodiesel was estimated at 37 kJ per gram. Energy content soybean crude oil= (3385 grams)X(37 kJ per gram)X(1000) = 1.25E08 joules

19. Specific emergy per mass of soybean crude oil= (Total Emergy, line 16)/(Yield mass, line 17) = (24254E09 sej per gallon)/(3385 grams per gallon) = 7.17E08 sej per gram

20. Transformity of soybean crude oil = (Total Emergy, line 16)/(Yield energy, line 18) = (24254E09 sej per gallon)/(1.25E08 joules per gallon) = 1.94E05 sej per joule

Footnotes to Table 27. All inputs were determined on a per annual basis and divided by the estimated gallons of castorbean oil that would be produced per year in an oil crushing facility. Based on data available for oil crushing facility processing approximately 3.9E07 bushels of castorbean annually (1.06 metric tons per year) this equaled 1.2E+08 gallons per year, after losses in the process. Older transformity values were corrected by factor of 1.68 (Odum et al., 2000).

1. Transformity of Castorbean = 3.37E+09 sej/g, calculated in this study. There were 3385 grams per gallon of biodiesel. 6391 grams per gallon are needed. Mass castorbean per gallon = 6391 grams per gallon

2. Transformity of petroleum products = 1.1E05 sej/J (Odum 1996). Hexane also referred as petroleum naphtha had an energy value of 118,700 Btu/gal and density of 665 kg/m^3. Data: hexane use was estimated at 2.02 kg per metric ton of bean processed (Sheehan et al., 1998). Energy in hexane = (2.02 kg per metric ton)X(1.1E+06 tons bean processed per year)X(1 m^3/665 kg)X(264.2 gal/m^3)X(118700 Btu/gal)X(1055 Joules/Btu)/(1.20E08 gal crude vegetable oil) = 8.8E05J

3. Mass Transformation Ratio for machinery = 1.30E10sej/g (Brown and Arding, 1991). Equipment required for oil processing was gathered from EPA air permit submitted by the Purdue facility (VADEQ, 2006) and from literature review (Parker Boiler, 2006; HC Davis, 2006). It was assumed that equipment was 95% steel and 15 year lifetime. The equipment mass total around 5.68E08 grams. Mass in machinery = (5.68 E08 grams)X(95% lifetime)/(15 years)/(1.20E08 gal crude vegetable oil) = 0.30 gram

4. Mass Transformation Ratio for buildings = 6.97E09sej/g (Brown & Buranakarn, 2001). Assumed lifetime of 20 years. Mass of buildings was estimated based on 1560 tons used in construction of oil crushing facilitates in Midwest (Fargo Tank & Steel Company, 2006). Mass in buildings = (1560 metric ton)X(1.0E+06 grams per ton)/(20 years)/(1.20E08 gal crude vegetable oil) = 0.65 gram

5. Transformity of cement = 3.33E09sej/g (Brown & Buranakarn, 2001). Assume use life of 30 years. Data: 5000 cubic yards of concrete use in 50 million gallon ethanol capacity facility (Midwest Grain Processors, 2006); density of concrete aggregate estimated at 1.13E06 grams per m^3. Values were adjusted by factor of 2.4 (120 million gallon/50 million gallon) to correct for capacity difference in production at the facility. Mass in concrete = (adjustment factor)(mass of concrete)/(lifetime)/(69.27E06 gallons ethanol) = (2.4)X(5000 cubic yards)X(0.7645 cubic meter to cubic yard)X(1.13E06 grams per m^3)/(30 years)/(1.20E08 gal crude vegetable oil) = 2.88 gram

6. Transformity of potable water = 1.53E05sej/J (Buenfil, 1998). Data water used was estimated at 3.28 kg per metric ton of bean processed (Sheehan et al., 1998). Energy in water = (3.28 kg per metric ton)X(1.1E+06 tons bean per year)X(1000 grams per kilogram)X(4.186 joules per gram of water)/(1.20E08 gal crude vegetable oil) = 121 J

7. Transformity of coal = 6.69E04sej/J (Odum, 1996). Drying of beans to reduce moisture required 266,275 kcal per metric ton of bean (Sheehan et al., 1998). Coal was used as energy for drying beans.

- Coal equivalent = (266,275 kcal)X(4184 joules per kcal)X(1 Btu /1055 joules)/(1 lb coal/12,250 Btu) = 86 lbs-coal per metric ton of bean.

Steam generation for other energy requirements was also an input of 220,020 kcal per metric ton. The Oil-Crushing facility in Virginia reported using a coal-fired industrial boiler with an 85% efficiency to produce the steam and to co-generate 1700 kW of electricity (ORNL, 2006c). However, there was only 85% efficiency, so adjust coal requirements by factor of 1.176 (100%/85%).

- Coal used in steam production = 1.176 (220,020 kcal per ton bean)X(4184J/kcal)X(1 Btu/1055 J)X(1 lb coal/12,250 Btu) = 83 lb of coal.

Energy in coal = (86 + 83, lbs-coal per metric ton)X(1.10E06 metric tons /year)X(12,250 Btu /lb-coal)X(1055 J /Btu)/(1.20E08 gal crude vegetable oil) = 1.74E07J

8. Transformity of standardized electricity = 3.36E05 (Odum, 1996). Data: estimated electricity use was 69.66 kWh per metric ton of processed bean (Sheehan et al., 1998). Electricity require = (69.66 kWh per metric ton)X(1.1E06 metric ton of beans)= 7.66E07kWh. However, there was 1700kW per 8000 hours of self-generated electricity, (ORNL, 2006c). Self-generated electricity = (1700 kW)X(8000 hrs)=1.36E07 kWh. Total Energy in electricity= [7.66E07kWh per year-1.36E07 kWh per year self-generated](3.6E+06joules per kWh)/(1.20E08 gal crude vegetable oil) = 1.89E06J

9. Transportation from Table 25.

10. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of hexane was $0.004 per bushel (English et al., 2002). ($0.004 /bushel of bean)X(3.9E07 bushels of bean processed /year)/(1.20E08 gal crude vegetable oil) = $0.001

11. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of water was $0.003 per bushel (Burton et al., 2002). ($0.003 /bushel of bean)X(3.9E07 bushels of bean processed /year)/(1.20E08 gal crude vegetable oil) = $0.001

12. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of coal was $0.080 per bushel of bean (English et al., 2002). ($0.080 /bushel of bean)X(3.9E07 bushels of bean processed /year)/(1.20E08 gal crude vegetable oil) = $0.026

13. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of electricity was $0.044 per bushel of bean (Burton et al., 2002). ($0.044/bushel of bean) X(3.9E07 bushels of soybean processed per year)/(1.20E08 gal crude vegetable oil) = $0.001

14. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Cost included insurance, taxes, capital charge, labor, maintenance, overheads and credits for byproducts and investment capital. Operational cost $0.412 per bushel of bean (English et al., 2002). ($0.412/bushel of soybean) X(3.9E07 bushels of soybean processed per year)/(1.20E08 1.20E08 gal crude vegetable oil) = $0.412

15. Transportation Services from Table 25.

16. Total Emergy sum of all.

17. Density of biodiesel oil was 3385 grams per gallon.

18. The energy content of biodiesel was estimated at 37 kJ per gram. Energy content castorbean crude oil= (3385 grams)X(37 kJ per gram)X(1000) = 1.25E08 joules

19. Specific emergy per mass of soybean crude oil= (Total Emergy, line 16)/(Yield mass, line 17) = (24566E09 sej per gallon)/(3385 grams per gallon) = 7.26E08 sej per gram

20. Transformity of switchgrass = (Total Emergy, line 16)/(Yield energy, line 18) = (24566E09 sej per gallon)/(1.25E08 joules per gallon) = 1.96E05 sej per joule

Footnotes to Table 28. Transportation of "crude" oil, either soyoil or castoroil, from crushing facility to refining facility, based on gallons of crude oil needed per gallon of biodiesel produced. Transformity values are corrected by factor of 1.68 (Odum et al., 2000).

1. Mass Transformation ratio machinery = 1.25E10 sej/g (Odum 1996). Data: class 8 truck weighed about 4540kg, had a capacity to transport 2364 gallons, had a life cycle of 7 yr and was driven 103, 266 kilometers (64,000 miles) annually (Lovins et al., 2004). The trip distance was assumed at 80 kilometers (50 miles) (Urbanchuk and Kapell, 2002). Total truck use estimated = (4540 kg)X(1000 grams per kg)(1/7 year)X(80, kilometers per trip /103,266 kilometers per year)X(1 gallon crude vegetable oil /2364 gallons capacity per trip) = 2 grams

2. Transformity of diesel = 1.1E05 sej/J (Odum, 1996). A class eight truck used an average of 4.24 km per liter (10 mile per gallon)(Transportation Business Association, 2006). The beans were transported a distance of 80 kilometers (50 miles) (Urbanchuk and Kapell, 2002). The truck transported 8 tons per trip. Gallons of diesel = (80, kilometers per trip)X(1 gallon crude vegetable oil /2364 gallons capacity per trip)X(1/4.25, km per liter) = 0.008 liters of diesel. Energy in diesel= (0.008 liters)X(0.264 gallons/ 1 liter)X(132000 Btu/gallon diesel)X(1055 joules per Btu) = 2.95E05 J.

3. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Cost of services on operating a truck. Data: 0.0004 trips/gallon of biodiesel, cost for trucker was $0.266 per km ($0.43 per mile) (Heartland Express, 2004). ($0.267/km)X(80 km)X(0.0004 trips per gallons) = $0.021

4. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Cost of services on fuels average was estimated at $0.425 per liter ($1.62 per gallon) for 2003 (EIA, 2006c). ($0.425/liter)X(0.008 liters of diesel) = $0.003

Footnotes to Table 29. . All inputs were determined on a per annual basis and divided by the gallons of biodiesel produced per year in a refining oil facility. The proposed refining oil facility produces approximately 1.0E06 gallons per year of 100% biodiesel annually (3.35E03 metric tons of soybean biodiesel). Older transformity values were corrected by factor of 1.68 (Odum et al., 2000).

1. Mass Transformation ratio of soybean oil = 7.06E+09 sej/g, calculated in this study. Data: 3.38E03 grams of oil per gallon of biodiesel oil (Sheehan et al., 1998).

2. Mass Transformation ratio of castorbean oil = 7.12E+09 sej/g, calculated in this study. Data: 3.38E03 grams of oil per gallon of biodiesel oil (Sheehan, et al., 1998).

3. Transformity of liquid fuels = 1.11E05sej/J (Odum, 1996). Natural gas common building block for industrial production of methanol. Data: Estimated amount of methanol was 89.51 kg per metric ton of biodiesel produced (Sheehan, et al., 1998). Energy content of methyl alcohol (methanol) high heating value of 9,750 Btu per lb and low heating value of 8,570 Btu per lb (USDOE, 2006f), average was 9160 Btu/lb. Energy in methanol= (89.51, kg / metric ton of biodiesel) (3.35E03 tons biodiesel per year)(2.2 lbs per kg)(9160 Btu/ lb)(1055 joules/Btu)/(1.0E+06 gallons) = 6.44E6 J

4. Transformity for liquid fuels = 1.11E05sej/J (Odum, 1996). Data: estimated amount of sodium methoxide was 46.06 kg per metric ton of biodiesel produced (Sheehan et al., 1998). Sodium Methoxide was prepared by mixing methanol and sodium hydroxide, at a rate of 21.77 kg of methanol per 2.28 kg of sodium hydroxide to prepare the desired concentration. Energy in sodium methoxide = (21.77 kg of methanol/ metric ton of biodiesel)X(3.35E0 tons biodiesel per year)X(2.2 lbs per kg)X(9160 Btu/ lb)X(1055 joules/Btu)/(1.0E+06 gallons) = 1.57E06 J

5. Mass Transformation ratio of potash = 1.85E9sej/g calculated based on energy and environmental profile for Potash (DOI, 1997). Data: estimated amount of sodium hydroxide for alkaline refining was 24 kg per metric ton of biodiesel t (Sheehan et al., 1998). Mass of potash = (24.06 kg / metric ton of biodiesel)X(3.35E03 tons biodiesel per year)X(1000 grams per kg))/(1.0E+06 gallons) = 81 gram

6. Mass Transformation ratio of plastic = 9.24E9sej/g (Brown, 2001) base on fact that the largest production of hydrochloric acid was integrated with the formation of chlorinated and fluorinated organic compounds, e.g., Teflon, Freon and other CFCs, chloro-acetic acid, and PVC. Data: estimated amount was 75.43 kg per metric ton of biodiesel (Sheehan et al., 1998). Hydrochloric acid was diluted in water to 10% concentration, only 7.53 kg of active ingredient were needed. Mass of hydrochloric acid = (75.43 kg HCl Solution / metric ton of biodiesel)X(10%)X(3.35E03 tons biodiesel per year)X(1000 grams per kg)/(1.0E+06 gallons) = 26 gram

7. Mass Transformation ratio for machinery = 1.30E10sej/g (Brown and Arding, 1991). Data: equipment required for soybean oil refining 71.9 grams per gallon (API Steel Tanks, 2006). Assumed 10 year steel lifetime.
Mass of machinery = (7.19E07grams)/(10 years) = 5 grams

8. Mass Transformation ratio for buildings = 6.97E09sej/g (Brown & Buranakarn, 2001). Data: About 256 tons of steel were used to construct 8 million gallon capacity biodiesel refinery (Fargo Tank & Steel Company, 2006). Assumed facility had production capacity of 1 million gallons, adjust by factor of 0.125 (1 million gallons /8 million gallons). Mass of buildings = (256 tons)X(0.125)X(1E6 grams per ton)X(1.28E+08, grams)/(15 years)/(1E06 gallons)= 2.13 grams

9. Mass Transformation ratio of cement = 3.33E09sej/g (Brown & Buranakarn, 2001) Assume use life of 15 years. Data: 356 cubic yards of concrete slab used in 18.3 million gallon ethanol capacity facility (Equity Partners Inc., 2006); density of concrete aggregate estimated at 1.13E06 grams per m^3. Adjustment factor 0.055 (1.0E6/18.3E6). Mass in concrete = (adjustment factor)(mass of concrete)/(lifetime)/(69.27E06 gallons ethanol) = (356 cubic yards)X(0.7645 cubic meter to cubic yard)X(1.13E06 grams per m^3)/(30 years)/(1E06 gallons) = 1 gram

10. Transformity of potable water = 3.14E05sej/J (Buenfil, 1998). Estimated amount needed was 356 kg per metric ton of biodiesel (Sheehan et al., 1998). Energy in water = (356 kg/metric ton biodiesel)X(3.35E03 tons biodiesel per year)X(1000 grams per kg)X(4.186 joules per gram of water)/(1.0E+06 gallons) =5030 J

11. Transformity of petroleum products = 1.1E05 sej/J (Odum, 1996). Data: steam energy input was 327,979 kcal per metric ton of biodiesel (Sheehan et al., 1998). Assumed that industrial boiler to produce steam was fired with recycled motor oil. The energy content in 1 gallon of motor oil was estimated at 139,000 Btu. The boiler efficiency was assumed at 75%, therefore to calculate the required oil for heating was increased by a factor of 1.43 (100% efficiency/ 75% efficiency). Energy required for steam production = (1.43)X(327,979, kcal steam/metric ton)X(3.96 Btu/kcal) /(139,00, Btu/gallon of oil) = 13.36 gallon to generate heat to produce a ton of biodiesel. Energy in petroleum products= (13.36 gallons of oil per ton of biodiesel)(3.35E03, metric tons biodiesel)(1055, joules per Btu)/(1.0E+06 gal/year) = 6.18E06 J

12. Transformity of standardized electricity = 3.36E05 (Odum 1996). Data: electricity requirements estimated at 28.90 kWh/metric ton of biodiesel (Sheehan et al., 1998). Energy in electricity = (28.9 kWh/metric ton of biodiesel)(3.6E+06 joules per kWh)(3.35E3 metric ton biodiesel per year)/(1.0E+06, gal/year) = 3.52E05 J

13. Transportation from Table 28

14. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of chemicals $0.094 per gallon of biodiesel (Burton et al., 2002). ($0.094/gallon biodiesel)(1.0E06 gallons per year) = $0.094

15. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost of utilities for producing $0.018 per gallon of biodiesel (Burton et al., 2002).

16. Money Transformation Ratio = 1.1E12 sej/$ (Tilley, 2006). Data: cost included insurance, taxes, capital charge, labor, maintenance, overheads and credits for byproducts and investment capital. The cost was estimated to be $0.325 per gallon of biodiesel (Burton et al., 2002).

17. Transportation Services from Table 28

18. Total Emergy Soybean-Biodiesel (exclude line 2)

19. Total Emergy Castrobean-Biodiesel (exclude line 1)

20. Mass content in 1 gallon of biodiesel 3.26E03 grams

21. The energy content of biodiesel 1.24E08 joules per gallon.

22. Specific emergy per mass of biodiesel soybean= (Total Emergy, line 18)/(Yield mass, line 20) = (26997E09 sej per gallon)/(3.26E3 grams per gallon) = 8.27E09

23. Transformity of soybean biodiesel = (Total Emergy, line 18)/(Yield energy, line 21) = (26997E09 sej per gallon)/(2.66E08 joules per gallon) = 2.19E05 sej per joule

24. Specific emergy per mass of biodiesel castorbean= (Total Emergy, line 19)/(Yield mass, line 20) = (27309E09 sej per gallon)/(3.26E3 grams per gallon) = 8.37E09

25. Transformity of castorbean biodiesel = (Total Emergy, line 19)/(Yield energy, line 21) = (27309E09 sej per gallon)/(2.66E08 joules per gallon) = 2.21E05 sej per joule

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