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Comparative Life-Cycle Assessments for Biomass-to-Ethanol Production from Different Regional Feedstocks

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This study compares life-cycle (cradle-to-gate) energy consumption and environmental impacts for producing ethanol via fermentation-based processes starting with two lignocellulosic feedstocks: virgin timber resources or recycled newsprint from an urban area. The life-cycle assessment in this study employed a novel combination of computer-aided tools. These tools include fermentation process simulation coupled with an impact assessment software tool for the manufacturing process life-cycle stage impacts. The process simulation file was provided by the National Renewable Energy Laboratory (NREL) and was modified slightly to accommodate these different feedstocks. For the premanufacturing process life-cycle stage impacts, such as the fuels and process chemicals used, transportation, and some preparatory steps (wood chipping, etc.), a life-cycle inventory database (the Boustead Model) coupled with an impact assessment software tool were used (the Environmental Fate and Risk Assessment Tool). The Newsprint process has a slightly lower overall composite environmental index (created from eight impact categories) compared to the Timber process. However, the Timber process consumes less electricity, produces fewer emissions in total, and has less of a human health impact. The amount of life-cycle fossil energy required to produce ethanol is 14% of the energy content of the product, making the overall efficiency 86%. Process improvement strategies were evaluated for both feedstock processes, including recycle of reactor vent air and heat integration. Heat integration has the greatest potential to reduce fossil-derived energy consumption, to an extent that fossil-derived energy over the life cycle is actually saved per unit of ethanol produced. These energy efficiency values are superior to those observed in conventional fossil-based transportation fuels.

Introduction

During the late 1900s, the OPEC oil embargo and increased concern over the perceived dangers of CO_2 released from fossil fuels increased the priority to find renewable sources of energy for transportation fuel. These concerns spurred investigations into renewable fuel sources, such as ethanol produced from biomass. As of the year 2000, there was an estimated 279.9 million (MM) dry metric tons of waste biomass available in the United States per year (*1*). Using typical conversion factors of biomass-to-ethanol conversion, the total amount of ethanol that can be produced from waste biomass is about 100 billion liters of ethanol per year (*2*). This amount is equivalent to approximately 15% of gasoline consumption to power the United States light duty fleet of vehicles (*3*).

Due partially to personal transportation, the United States is responsible for a quarter of the world's anthropogenic fossil-based carbon dioxide emissions (*3*). Using renewable biomass as a fuel source not only decreases the dependence on imported petroleum but also decreases the accumulation of fossil-derived carbon dioxide in the atmosphere. The amount of this reduction can be measured using life-cycle assessments of the renewable biomass processes.

Although ethanol can be produced from anything containing starch or fermentable sugars, the current focus on ethanol production is the conversion of starch in corn and cellulosic materials. Corn-to-ethanol processes have been commercialized, but an economical and energy efficient process for the conversion of cellulosic material to ethanol currently has not been achieved yet (*4*). Since fuel ethanol has the possibility of so many environmental benefits, research to improve the environmental economic efficiency of the cellulose-to-ethanol process is important.

The composition and incomplete conversion of cellulosic material are two of the reasons for a lower conversion efficiency of feedstock to product. Much of the current research deals with the problem of incomplete conversion employing novel approaches such as simultaneous saccharification and fermentation (SSF) to increase the conversion rates of cellulose to ethanol and overall ethanol yield (*5*).

Recombinant DNA technology has also been utilized to create organisms capable of fermenting both the hexose and pentose sugars (*4*). This technology also results in an increase in ethanol production. These methods have addressed the incomplete conversion problem, but a more complete solution to the economic barriers of cellulose-to-ethanol conversion must include an investigation into general process improvements, such as heat and mass integration.

The environmental impacts of ethanol production must also be investigated. Looking at the use stage of ethanol as a fuel produces obvious benefits in the reduction of

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climate-active carbon dioxide. However, the environmental impacts from the premanufacturing process and the manufacturing process of ethanol must also be quantified if the complete benefits are to be determined. A life-cycle assessment (LCA) takes into account all resource and energy inputs required to make a product, the wastes, and the health and ecological burdens associated with the product and then evaluates opportunities to reduce the environmental impacts of the product from cradle to grave (*6*). In effect, performing a life-cycle assessment of the entire ethanol production systsem (preproduction through consumption) would quantify the total benefits as well as any drawbacks that the process might contain and identify opportunities for process improvement.

Previous technoeconomic or life-cycle analyses of ethanol from lignocellulosic biomass have focused on energy, greenhouse gases, criteria pollutants, and economics. Lynd et al. identified costs of production as the key barrier, while acknowledging environmental and energy benefits using a limited life-cycle analysis that excluded premanufacturing stages (*7*). Wang et al. (*8*) showed that corn ethanol used in conventional internal combustion engines reduce fossil energy consumption between 28% and 50%, but only ethanol from lignocellulose can achieve reductions over 90%. Similarly, Sheehan et al. (*9*) conducted a thorough life-cycle assessment of ethanol production from corn stover in Iowa and discovered that E85 (85% ethanol blend with gasoline) reduces petroleum consumption 95% per kilometer traveled compared to conventional gasoline, reduces ozone precursor emissions, reduces total fossil energy consumption and greenhouse gas emissions by 102% and 113%, respectively, but increases emissions of CO, NO_x, and SO_x. However, none of these studies investigated the effects of process improvements on life-cycle impacts.

A life-cycle assessment approach is used in this study to evaluate the environmental impacts of a lignocellulosic biomass-to-ethanol process using two different regional biomass options: timber from Michigan's Upper Peninsula and recycled newsprint from a large urban area, such as Chicago, IL. The scale of production is approximately 60 million gallons of ethanol per year. Our focus is "cradle to gate" and this study identifies and quantifies process improvement options to enhance the economics and reduce environmental impacts. Although previously LCAs have been conducted for ethanol production from cellulosic feedstocks, no studies were found on ethanol produced from a newsprint feedstock.

Simulation of the Biomass-to-Ethanol Process

A life-cycle assessment on a lignocellulosic biomass-to-ethanol process requires the inputs and outputs of mass and energy. We generated process data through process simulation. The National Renewable Energy Laboratory (NREL) of the U.S. Department of Energy (DOE) has produced a simulation model of a lignocellulosic biomass-to-ethanol process using yellow poplar as a feedstock employing the commercial process simulation software ASPEN Plus (*10*). The process includes current core technologies such as dilute acid prehydrolysis, simultaneous saccharification and cofermentation, and cellulase enzyme production. The model employs a lignocellulosic feedstock physical property package developed by NREL. The simulation file provides a solid foundation for conducting our LCA.

In general, the data used for the NREL simulation and study (temperatures, pressures, conversions, yields) were acquired in the laboratory or pilot plant setting (*10*), and the objective was to determine the economic performance of the yellow poplar-to-ethanol process. The research reported here extends that previous work by incorporating environmental impacts of the NREL process depicted in Figure 1 and investigating process improvement options.

Typical input/output values obtained by the NREL simulation model for yellow poplar can be found in Figure 1, for an input rate of 160,000 kg wet wood chips/h. Process material and energy rates based on simulations of Upper Michigan timber and newsprint feedstocks are found to be similar to those displayed in Figure 1. In our work, the NREL model automatically adjusts the associated process input requirements of nutrients, water flow rate, aeration requirements, etc. on the basis of the biomass composition. We adopted the conversions to soluble sugars and to ethanol in the original NREL study (*10*), assuming that these would reflect conditions in the process for the new feedstocks. This is an assumption in our study.

The NREL process begins as yellow poplar chips are delivered to the feed handling area, A100, where they are washed and screened. Next, the hemicellulose sugars are released using dilute sulfuric acid hydrolysis and steam in the pretreatment area (A200). After the pretreatment step, the hydrolyzate stream is split to the fermentation area (A300) and the cellulase enzyme production area (A400) where the cellulase enzymes are formed using the fungus *T. reesei.* The cellulase enzymes are then sent to the fermentation area (A300) where ethanol is formed in simultaneous saccharification and fermentation reactions using the cellulase enzymes and the recombinant *Z. mobilis* bacteria.

Ethanol is then purified by distillation and molecular sieve adsorption in A500 and sent to product storage (A700). The bottoms from the distillation process are sent to wastewater treatment (A600) where they are treated. The recovered water is sent back to the process as recycled water, and the residual solids and methane from this process are combusted using a combined burner/boiler/turbogenerator in A800 to produce steam and electricity.

As shown in Figure 1, each area in the process has material and energy inputs (shown as bold solid arrows) and environmental emissions (shown as hollow unfilled arrows). The environmental emissions can be further classified as land, water, or air emissions.Later, it will be shown that the air emissions are categorized by source: (a) emissions directly discharged into the atmosphere, (b) fugitive emissions resulting from leaking seals and connectors, (c) emissions discharged from reactor, distillation column, and storage tank vents, and (d) emissions generated through utility consumption.

To begin this study, the NREL simulation needed to be modified to reflect the composition and processing conditions for each new feedstock. The first feedstock composition determined was the Upper Michigan Timber feedstock.

The actual tree species and the amounts of these species available in Michigan's Upper Peninsula were identified through the use of the Forest Inventory and Analysis Timber Product Output (TPO) Database developed by the USDA Forest Service (*11*). This database provided a way to determine the kinds of trees available, volume currently harvested, wood residues generated, and the final disposal of tree wastes for each county in the Upper Peninsula by landowner. For this research, the product, source, and species were selected to get a

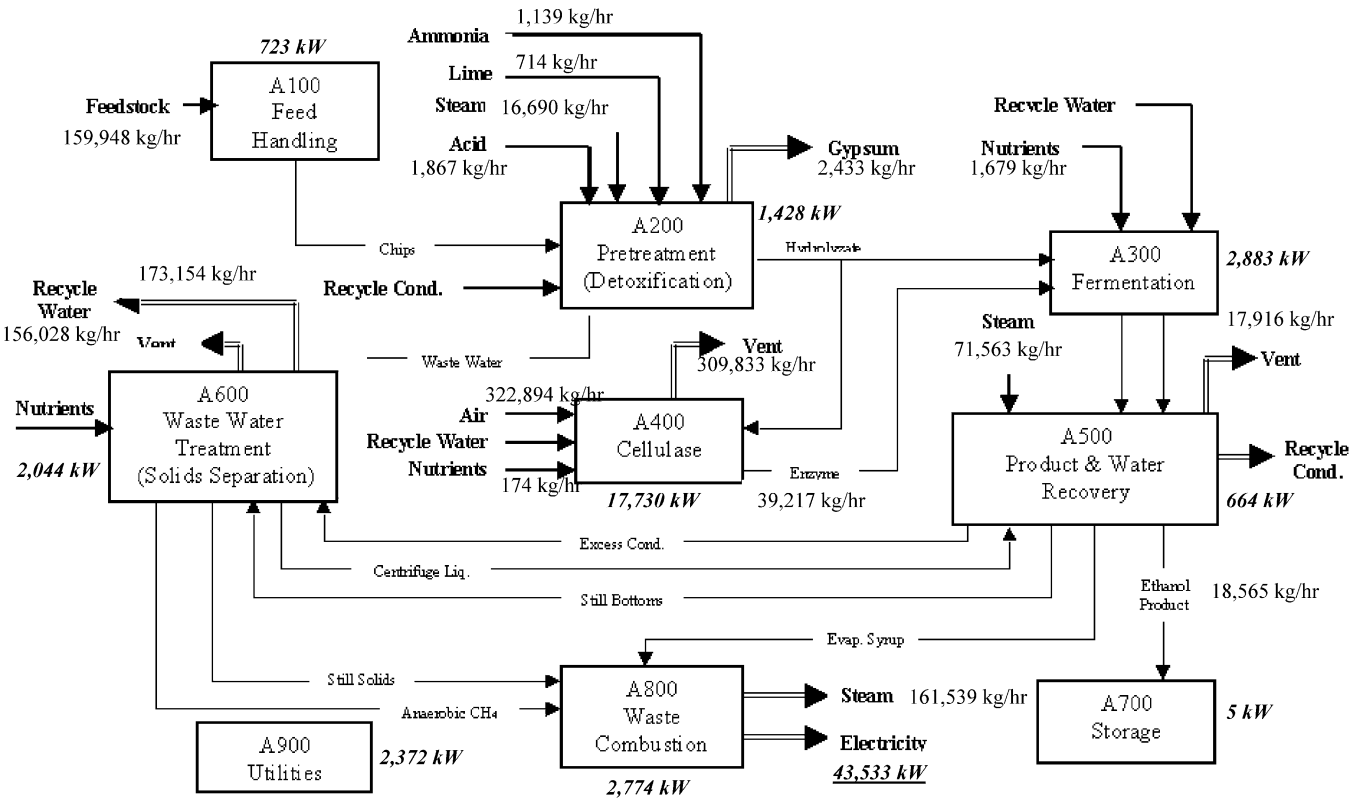

Figure 1. Lignocellulosic biomass-to-ethanol process (Adapted from ref 10). Note the values of energy provided are those consumed by the process units, with the exception of the electricity produced in the waste combustion area (A800).

Table 1. Composition of Feedstock for NREL Yellow Poplar Feed (*10*), Mixed Timber from Michigan's Upper Peninsula (*12−16*), and Newsprint (*17*)

	% dry wt basis		
component	NREL	upper Michigan timber	newsprint
cellulose	42.67	49.15	63.77
xylan	19.05	16.89	5.26
arabinan	0.79	1.04	0.61
mannan	3.93	3.76	4.96
galactan	0.24	1.01	0.61
acetate	4.64	3.38	
lignin	27.68	24.45	21.26
ash	1.00	0.31	3.54
moisture	47.90	68.40	5.0

clear representation of the overall harvesting activities in Michigan's Upper Peninsula. The owner option was selected as the forest industry and it was assumed that harvests from the forest industry land would be consistent from year to year, whereas harvests from the National Forest or Public/Private lands would not.

After entering the above selections into the TPO Database, the database provided the overall timber harvested on Forest Industry land in the Upper Peninsula and the tree species involved in this harvesting. This information was multiplied by the overall tree compositions and densities to obtain the overall mixed timber feedstock, as shown in Table 1 (*12−16*). This can be compared in Table 1 to the NREL values for yellow poplar (*10*) and the composition of the newsprint feedstock, obtained from the California Energy Commission (*17*).

The Upper Michigan timber feedstock arrives as logs. This requires that a chipping operation be installed prior to the NREL process. Energy consumption for the chipping process was assumed to be 15 MJ/dry Mg of wood (*18*). The total quantity of electricity was assumed to be supplied from the electricity generated in the waste combustion area of the process and the environmental emissions will be accounted for in that area (A800) of the NREL process. Modifications to the Newsprint process occur prior to and within the feed handling area (A100 in Figure 1). This is accomplished by transforming the paper into pulp prior to the feed handling area. When the paper is in pulp form, the feed handling process such as chip washing and metal removal no longer apply and the feed handling processes are removed for the Newsprint process. This means that the utilities consumed in A100 of the NREL simulation are not used in the Newsprint process. Note that the feed handling area of the NREL simulation was not modified to reflect either the chipping or pulping process. The only physical change to the NREL simulation was the modification of the input values for the feed composition of Upper Michigan timber and newsprint.

LCA Methodologies

The first step in any LCA is to define the scope and goals of the assessment. The goal of the study is to compare the environmental impacts of two processes that utilize different regional cellulosic feedstocks to produce ethanol. The scope of this assessment is "cradle to gate", that, is from acquisition of the raw materials through the production of ethanol (Figure 2). This differs from the "cradle-to-grave" approach in that the assessment will stop at the "gate" or consumption stage of the product and will not investigate the impacts of the use of the ethanol product as it is the same for both processes. To further standardize this assessment, a constant feed rate of 83,333 kg/h of dry biomass will be used for both, sufficient to produce approximately 60 million gallons ethanol per year. In each step of this process, mass/energy inputs and waste outputs must be quantified. In addition, premanufacturing process impacts to produce, deliver, and use (in some cases) the chemicals and fuels are included.

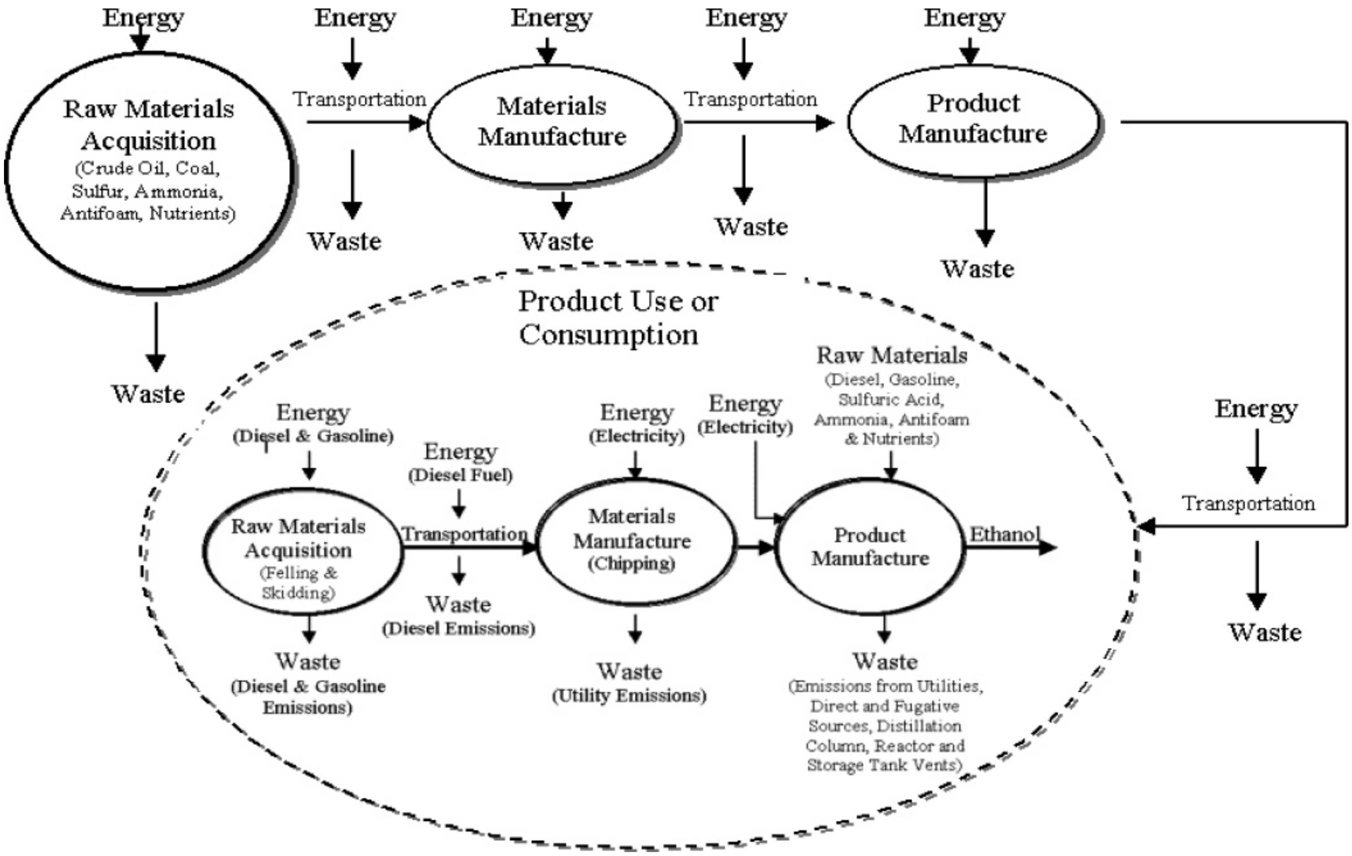

Figure 2. Material and energy flows for an overall life-cycle assessment. (Example for ethanol production from Upper Michigan timber.

The production of ethanol from newsprint has a similar LCA scope. The "cradle-to-gate" assessment of newsprint considers the collection of newsprint, the transportation of the newsprint to the ethanol production facility, the conversion of newsprint into pulp and the production of the final ethanol product.

In addition to the process data from ASPEN, a complete inventory of emissions is obtained through the use of two life-cycle inventory and assessment tools: the Boustead Model (*19*) for the emissions inventory of the fuels and other raw materials delivered and used in the ethanol production process and the Environmental Fate and Risk Assessment Tool (EFRAT) (*20*) for the NREL process itself.

Boustead Model, Version 5.0. The Boustead Model is a "cradle-to-gate" life-cycle inventory database containing information for fuel and energy use, raw material requirements, and solid, liquid, and gaseous emissions for a specific life-cycle stage, such as transportation, or individual products, such as diesel or electricity production (*19*). For the purposes of this research, the Boustead Model was used to develop the life-cycle inventory for the premanufacturing process steps of the biomass-to-ethanol process.

As shown in Figure 3 for the Upper Michigan Timber process, the Boustead Model was used to develop the inventory data for the felling, skidding, and transportation of Upper Michigan timber to the ethanol production facility. An inventory of emissions was obtained from the Boustead Model using emission factors for the diesel and gasoline usage. These values are input into the environmental impact index calculator of EFRAT, described next.

Environmental Fate and Risk Assessment Tool (EFRAT) Version 1.0.44. As shown in Figure 3, the "cradle-to-gate" inventories and environmental impacts

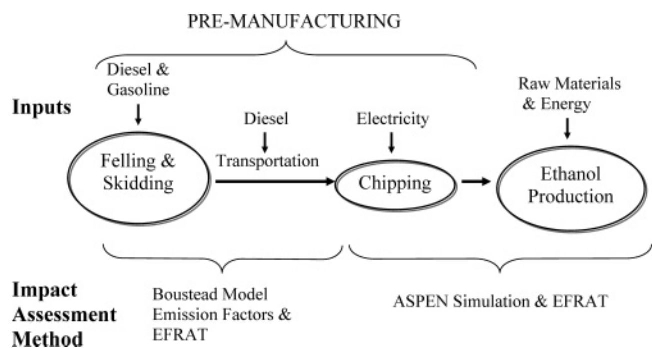

Figure 3. Scope of life-cycle assessment methodologies in Upper Michigan Timber process.

for the Upper Michigan Timber- and Newsprint-to-ethanol processes are developed using process simulation linked to the environmental impact assessment algorithm EFRAT (*20*−*22*). The inputs from the simulation, such as streamflows rates through process units, were manually input into EFRAT to estimate emissions, predict environmental fate via a multimedia model, and calculate nine environmental impact indices. Air emissions are estimated from major process units and from fugitive sources using EPA emission factors and correlations (*22*, Chapter 8). Environmental fate of emitted pollutants is obtained using a "Level I" multimedia partitioning model.

The environmental impact indicators are for global warming (I_{GW}), smog formation (I_{SF}), stratospheric ozone depletion (I_{OD}), acid rain (I_{AR}), human inhalation (I_{INH}) and ingestion toxicity (I_{ING}), human carcinogenic inhalation (I_{CINH}) and ingestion toxicity (I_{CING}), and fish toxicity (I_{FT}). Each indicator represents the emissions from the process in terms of the equivalent emission of a "benchmark" compound, for example, CO_2 for global warming.

Table 2. Energy Consumption from Premanufacturing Chemicals and Operations[a]

	upper MI timber		newsprint	
	kg/h	MJ/h	kg/h	MJ/h
Premanufacturing, Chemicals				
ammonia	1,194	88,620	638	47,370
ammonium sulfate	108	2,216	169	3,376
antifoam	268	21,628	356	28,696
calcium phosphate	108	1,161	169	1,899
diesel	470	557	0	0
gasoline	938	1,088	978	1,134
lime	693	8,124	570	6,647
sulfuric acid	1,839	9,495	1,680	8,651
subtotal		132,887		97,772
Premanufacturing, Operations				
felling (gasoline)	21	1,688	0	0
skidding (diesel)	53	2,216	0	0
transportation (diesel)	157	6,752	232	9,917
chipping (gasoline)	12	633	0	0
pulping (electricity)		0		9,073
subtotal		11,289		18,990

[a] Felling, skidding, and chipping (and the premanufacturing chemicals involved) are only involved in the Upper Michigan Timber process, whereas pulping is only involved in the Newsprint process.

The environmental indicators are “directional” metrics, not indicators of absolute risk, as they report on progress toward reducing impacts. A single composite environmental index (I_{L-CC}) for each process alternative is created from these nine categories of impact through a series of normalization and valuation calculations, using United States normalization data for each category and the Eco-Indicator 95 valuation methodology (*23*). A complete description of the EFRAT methodology is found in Shonnard and Hiew (*20*).

In the simulation, there are six sources of emissions that are included: emissions from utility consumption, emissions from vents on tanks, distillation columns, and reactors, emissions released directly to the environment, and fugitive emissions resulting from leaky pump seals, connectors and pressure relief valves in the process. To quantify these emissions, EFRAT requires information from the ASPEN Plus simulation, as mentioned above. Utility emissions require the type of utility and fuel type used (i.e., electricity, natural gas, etc.) and the total utility consumption.

Results and Discussion

Life-Cycle Energy and Emission Inventories. The energy consumption from the premanufacturing process stage for chemicals used in the process and the premanufacturing process operations are presented in Table 2. For premanufacturing stages of the process chemicals, the major difference in energy consumption is due to the quantity of ammonia used. Ammonia is used primarily in the pretreatment area of the process to regenerate the resin used in the ion exchanger but is also used as a nutrient in the cellulase and fermentation reactors. As there is no acetate present in the newsprint feed, no ammonia is needed in the Newsprint process for ion exchange. This results in the Newsprint process having roughly a third of the ammonia consumption of the Timber process. As ammonia still represents such a large portion of the premanufacturing process energy for both processes, 61% in the Timber process and 41% in the Newsprint process, alternatives could be investigated to reduce the dependency on ammonia.

The manufacturing process energy consumption is best portrayed in an energy input/output table, using data provided by the NREL simulation of the processing of these feedstocks. Energy inputs include process input streams, and energy consuming units such as heaters pumps, agitators, etc. Energy outputs include process output streams, energy accepting units such as coolers, evaporators plus energy/electricity generated utilities. These energy inputs and outputs have been divided into chemical and process energy for an investigation of the overall energy distribution. The complete energy input/output analyses for the Upper Michigan Timber and Newsprint processes are shown in Tables 3 and 4, respectively.

The first category of input chemical energy in Tables 3 and 4 is the energy content of the biomass feed. This energy was calculated by multiplying an average heating value of biomass, 20 MJ/kg (*24*), to the mass flowrate of dry biomass into the process (83,333 kg/h). The chemical energy available in the outlet ethanol product stream was calculated using a heating value of 27 MJ/kg ethanol (*25*) multiplied by the amount of ethanol produced (Timber, 20,006 kg/h; Newsprint, 20,858 kg/h).

The amount of chemical energy available in the ethanol product is approximately one-third of the chemical energy available in the incoming biomass feed. When the lignin fraction is subtracted from the input feed (energy consumed in the process), the ethanol energy content is roughly half of the incoming chemical energy of the biomass. From these energy balance results and the energy lost as a result of process inefficiencies, it is apparent that there are significant opportunities for process improvement in the saccharification and fermentation areas to increase the energy and mass yields of ethanol from biomass.

The process energy is divided into steam- and electricity-consuming units. These utilities are generated from the combustion of the lignin fraction (shown as generated utilities on the outlet side). The amount of generated electricity for use in the process and for export to the grid was provided in the NREL simulation files for both processes. The Timber process generated roughly 126,000 MJ/h of electricity for plant use and 19,200 MJ/h of excess electricity that is exported and sold to the grid. The Newsprint process, however, produced only 113,000 MJ/h of electricity compared to 143,000 MJ/h required for process use. This electricity generation shortfall in the Newsprint process is due primarily to the lower amounts of lignin available in the newsprint feed for combustion.

When the premanufacturing fossil energy requirements for the Timber process of about 144,000 MJ/h are considered, 19,000/0.33 MJ/h for the primary energy equivalent of electricity exported (assumed coal), then the net primary energy consumed is 86,000 MJ/h. This process for making transportation fuel is therefore $535/(535 + 86) \times 100 = 86\%$ efficient when based on product energy flow and fossil energy consumption over the life cycle of all materials used. This is roughly the same energy efficiency as a petroleum refinery product (*19*). When based on inlet woody biomass, energy efficiency of the process is $535/(1{,}666 + 86) \times 100 = 30.5\%$. This is roughly the same efficiency as burning the biomass for electricity generation.

Table 5 shows the life-cycle emissions to air of the alternatives for ethanol production given a feed of 83,333 kg/h of dry biomass. Carbon dioxide represents approximately 72% (w/w) of the environmental releases from the Timber process and almost 95% of the air emissions from the Newsprint process. The climate-active carbon dioxide that is represented here is primarily due

Table 3. Energy Input/Output Analysis for Upper Michigan Timber Process

source identification	energy flow (MJ/h)	% of inlet energy	source identification	energy flow (MJ/h)	% of outlet energy
Chemical Energy In			Chemical Energy Out, Consumed or Lost		
biomass feed	1,666,660	100.0	ethanol product	535,158	31.4
			coolers		
			cooling water system	510,647	30.0
			chilled water system	90,582	5.3
			subtotal	601,229	35.3
			process efficiency loss	164,917	9.7
			energy consumed in process	401,081	23.6
overall inlet energy	**1,666,660**	**100**	**overall outlet energy**	**1,702,385**	**100**
Energy Consumers And Sources			Outlet Energy, Energy Generation and Supply		
steam-consuming units			generated utilities		
prehydrolysis reactor, M202	24,103	6.1	electricity to grid, WKNET	19,211	4.8
overliming tank heater, Q209	3,951	1.0	LP steam, 815	186,026	46.4
dehydration column reboiler, H501	90,713	23.0	LP steam, 815A	41,400	10.3
rectification column reboiler, H502	11,602	2.9	VLP steam, 860	28,304	7.1
rectification column ovhd heater, H506	806	0.2	electricity to plant, WPLANT	126,139	31.4
baghouse dryer, M801	69,077	17.5	subtotal	401,081	100.0
deaeration column, T826	39,900	10.1			
CIP system water heater, H910	163	0.0			
evaporators	28,304	7.2			
subtotal	268,619	68.0			
electricity-consuming units					
air compressors	57,400	14.5			
agitators	26,189	6.6			
pumps	11,056	2.8			
conveyors and dryers	8,903	2.3			
separators	6,631	1.7			
chemical addition systems	9,149	2.3			
miscellaneous	559	0.1			
additional electricity consumers	6,252	1.6			
subtotal	126,139	32.0			
overall inlet energy	**394,758**	**100**	**overall outlet energy**	**401,081**	**100**

Table 4. Energy Input/Output Analysis for Newsprint Process

source identification	energy flow (MJ/h)	% of inlet energy	source identification	energy flow (MJ/h)	% of outlet energy
Chemical Energy In			Chemical Energy Out, Consumed or Lost		
biomass feed	1,666,660	100.0	ethanol product	557,950	33.6
			coolers		
			cooling water system	477,282	28.7
			chilled water system	109,858	6.6
			subtotal	587,140	35.3
			process efficiency loss	139,280	8.4
			energy consumed in process	376,885	22.7
overall inlet energy	**1,666,660**	**100**	**overall outlet energy**	**1,661,254**	**100**
Energy Consumers And Sources			Outlet Energy, Energy Generation and Supply		
steam-consuming units			generated utilities		
prehydrolysis reactor, M202	23,903	5.9	electricity to grid, WKNET	-	0.0
overliming tank heater, Q209	3,320	0.8	LP steam, 815	190,000	46.7
dehydration column reboiler, H501	94,013	23.4	LP steam, 815A	41,400	10.2
rectification column reboiler, H502	12,002	3.0	VLP steam, 860	32,600	8.0
rectification column ovhd heater, H506	858	0.2	electricity to plant, WPLANT	112,885	27.8
baghouse dryer, M801	61,960	15.4	subtotal	376,885	92.7
deaeration column, T826	30,704	7.6			
CIP system water heater, H910	169	0.0	provided utilities		
evaporators	32,600	8.1	electricity from grid	29,736	7.3
subtotal	259,530	64.5			
electricity-consuming units					
air compressors	73,021	18.2			
agitators	29,025	7.2			
pumps	10,581	2.6			
conveyors & dryers	8,111	2.0			
separators	5,013	1.2			
chemical addition systems	10,000	2.5			
additional electricity consumers	6,870	1.7			
subtotal	142,621	35.5			
overall inlet energy	**402,152**	**100**	**overall outlet energy**	**406,621**	**100**

to the premanufacturing life-cycle stages of chemicals used in the process and the use of utilities in the ethanol production process for newsprint. Comparing the two processes, the major difference between them is the amount of utilities used in each process. The Timber process is energy self-sufficient, whereas the Newsprint process requires additional electricity from the grid. It is interesting to note that the total air emissions from the premanufacturing process life-cycle stage is comparable to the ethanol manufacturing process stage emis-

Table 5. Life-Cycle Emissions to Air for the Biomass-to-Ethanol Alternatives[a]

chemical	upper Michigan timber (Mg/year)	newsprint (Mg/year)
acetaldehyde	2.73×10^{-6}	3.78×10^{-6}
acetic acid	8.24×10^{2}	3.76×10^{2}
ammonia	2.90×10^{3}	2.49×10^{3}
butane	9.87×10^{1}	7.26×10^{1}
carbon dioxide [b]	2.09×10^{4}	1.40×10^{5}
carbon disulfide	3.41×10^{-7}	4.54×10^{-7}
carbon monoxide	9.27×10^{2}	5.48×10^{2}
ethanol	1.50×10^{2}	7.35×10^{2}
hydrochloric acid	2.03×10^{0}	1.92×10^{0}
nitrogen dioxide	4.77×10^{2}	6.78×10^{2}
nitrous oxide	1.67×10^{-4}	2.24×10^{-4}
sulfur dioxide	2.71×10^{3}	2.74×10^{3}
TOC	−1.50	1.98
toluene	3.36×10^{-2}	3.79×10^{-2}
total	2.90×10^{4}	1.48×10^{5}

[a] Data obtained through use of NREL simulation results for the ethanol process and the Boustead Model for the emissions from the life-cycle stages prior to the ethanol process. Some emissions were obtained by inputting NREL results into EFRAT. [b] Climate-active C

sions in the Newsprint alternative and is much greater in the Upper Michigan Timber alternative (*26*).

Life-Cycle Impact Assessment. In this section, the overall emissions of specific chemicals are translated into eight environmental indices, discussed previously (minus ozone depletion), and shown in Table 6. To compare results between the processes, the indices were divided by the annual ethanol production for each process. In the case of the Timber process, this amounts to 222.2 MM L/year of ethanol, whereas the Newsprint process yields 231.7 MM L/year. When the impacts are displayed in this fashion, the premanufacturing process impacts are very small compared to the manufacturing process impacts with the exception for I_{GW}. The Upper Michigan Timber process has slightly lower impacts compared to Newsprint in 4 out of the 8 categories but is significantly lower for I_{GW}. The opposite is true for I_{FT}.

Table 7 shows the normalized and weighted environmental impact indices plus the sum of these categories, yielding a single life-cycle composite index, I_{L-CC}, for each process. The Upper Michigan Timber process has a slightly larger environmental impact (I_{L-CC}) compared to the Newsprint process. The human ingestion toxicity index (I_{ING}) contributes approximately 83% to I_{L-CC} for the Upper Michigan Timber process and 91% of the Newsprint process composite index.

After I_{ING}, I_{FT} and I_{INH} contribute the most to I_{L-CC}. Since acetic acid contributes the majority of the I_{FT}, it is expected that the Upper Michigan Timber process, which has more hemicellulose sugars to convert to acetic acid, would have a higher index value for I_{FT}. Finally, more carbon monoxide is produced during utility use in the Newsprint process producing the higher value for I_{INH} for this process.

Life-Cycle Improvement Analysis. Ethanol, carbon monoxide, and acetic acid appear to be the major released pollutants contributoring to I_{L-CC}, and their reduction should be at the center of any possible process improvement options. Ethanol and acetic acid are primarily released directly from process equipment. Carbon monoxide, although being released directly also, is primarily released during the use of utilities. Since these emissions occur in the biomass-to-ethanol facility itself, they present an opportunity for impact minimization.

In this stage, the results from the life-cycle inventory and impact assessment are used to identify targets for reductions in energy consumption and/or environmental impacts. Several improvement alternatives, involving stream recycle and heat integration, are evaluated.

The energy inventory (Tables 3 and 4) identified heaters as the largest energy-consuming units in both biomass-to-ethanol processes. Utilities also contribute to a significant portion of process energy consumption and to environmental emissions. Chemical engineering techniques are available to improve upon these items. A possible option is process stream recycle.

Cellulase Seed Reactor Vent Stream. Using the Newsprint-to-ethanol process as an example, from the process energy inventory in Table 4, air compressors contribute to 51.2% of the total electricity demand. While utilities contribute 35.5% of the total process life-cycle energy requirement and 28.0% of the total environmental emission generation (*26*), decreasing the amount of air that requires compression would reduce both energy consumption and environmental impacts as a result of reduction in electricity required for air compression. By recycling a portion (75%) of the cellulase seed reactor vent back into the cellulase seed reactor (already at the required pressure and at 90% of the required O_2 concentration), an opportunity exists to decrease utility consumption, utility emissions, and direct emissions. The Upper Michigan Timber and the Newsprint ASPEN simulation flowsheets were modified to reflect the recycle loop, and resulting impacts were generated and compared to the original processes.

Table 8 shows the environmental impact reduction results from the cellulase reactor vent stream recycle. Significant improvement in I_{GW} is shown for both processes, but especially for the Newsprint process, since the Newsprint process was shown in the simulation to require more air. In both biomass-to-ethanol processes, the reduction in compressed air also translates to a reduction in utility usage, utility emissions, and direct emissions. In the Upper Michigan Timber process, this recycle option yields a 4.8% reduction in compressed air utilities for a savings of 9,500 MJ/h of electricity or 7.5% of the total process utility consumption. The reductions

Table 6. Environmental Indices for the Upper Michigan Timber- and Newsprint-to-Ethanol Processes on a per Liter of Ethanol Production Basis

	I_{FT}	I_{ING}	I_{INH}	I_{CING}	I_{CINH}	I_{GW}	I_{SF}	I_{AR}
			Upper Michigan Timber					
premfg process[a]	3.83×10^{-6}	1.52×10^{-7}	0.129	1.83×10^{-11}	6.10×10^{-13}	0.526	1.85×10^{-5}	3.59×10^{-3}
mfg process	2.32	26.1	0.415	0.00	0.00	−0.330	6.66×10^{-4}	3.46×10^{-2}
total (kg/L EtOH)	2.32	26.1	0.542	1.83×10^{-11}	6.10×10^{-13}	0.196	6.68×10^{-4}	3.83×10^{-2}
			Newsprint					
premfg process[b]	3.20×10^{-6}	1.65×10^{-7}	0.119	2.42×10^{-11}	8.08×10^{-13}	0.478	1.78×10^{-5}	3.36×10^{-3}
mfg process	1.02	26.9	0.433	0.00	0.00	0.291	5.44×10^{-4}	3.09×10^{-2}
total (kg/L EtOH)	1.02	26.9	0.552	2.42×10^{-11}	8.08×10^{-13}	0.769	5.60×10^{-4}	3.43×10^{-2}

[a] Impacts from producing chemicals used in the ethanol process, for felling, skidding, and transportation of timber and of chipping. [b] Impacts from producing chemicals used in the ethanol process, of transportation of newsprint, and of pulping.

Table 7. Environmental Indices on a per Liter of Ethanol Production Basis

normalized environmental index (multiplied by weighting factor)	upper MI timber	newsprint
fish toxicity, I_{FT}	1.78×10^{-8}	7.85×10^{-9}
human ingestion toxicity, I_{ING}	1.01×10^{-7}	1.04×10^{-7}
human inhalation toxicity, I_{INH}	2.09×10^{-9}	2.13×10^{-9}
human carcinogenic ingestion toxicity, I_{CING}	4.33×10^{-17}	5.76×10^{-17}
human carcinogenic inhalation toxicity, I_{CINH}	1.45×10^{-18}	1.93×10^{-18}
smog formation, I_{SF}	8.80×10^{-14}	7.40×10^{-14}
acid rain, I_{AR}	2.12×10^{-11}	1.91×10^{-11}
global warming, I_{GW}	8.93×10^{-14}	3.49×10^{-13}
life-cycle composite index, I_{L-CC}	**1.20×10^{-7}**	**1.14×10^{-7}**

in environmental indices for the Timber process translate to a 2.2% decrease in I_{L-CC} due primarily to a reduction in ethanol emissions from the cellulase seed vent.

In the Newsprint process, a 5.0% reduction in compressed air is achieved leading to an 8.6% reduction in the utility consumption or 12,300 MJ/h. I_{SF} and I_{ING} increase as a result of increases in tank emissions of ethanol, even though there is no increase in the amount of ethanol produced in this process. The reason for this result is complicated and could only be uncovered using process simulation. Excess ethanol, from the cellulase seed vent, diffuses into the cellulase reactor media and is carried through the fermentation and purification stages. A fraction of this excess remains with the distillation bottoms, which is sent to the evaporators. The evaporator condensate, containing this excess ethanol, is recycled back to the pretreatment area tanks, where the increased emissions occur. It is due primarily to this increase in ethanol emissions that the overall process composite index increases by 6.4% for the Newsprint process.

Cellulase Seed Reactor Vent Stream as Combustion Air. Another stream recycle option is also available: recycling the cellulase and cellulase seed vents as combustion air for the boiler. In this scenario, the VOCs present in the cellulase vents will be converted to energy and CO_2 in the boiler, reducing emissions of VOCs and the need for a portion of the natural gas. For the Upper Michigan Timber process, this recycle stream option resulted in an energy savings of 528 MJ/h or 0.4% of the total process utility consumption. The Newsprint process energy consumption is reduced by 3,060 MJ/h (2.1% of the total utilities). The difference between these processes is due primarily to the amount of byproducts present in the Timber process. A larger amount of byproducts available for combustion requires a larger amount of air.

Table 9 shows the change in environmental impacts for this improvement option. The reductions in impacts for the Timber and Newsprint processes are relatively modest, but significant reductions are seen for I_{SF} in the Timber process and for I_{SF} and I_{ING} in the Newsprint process of about 20%. These reductions are a result of lower direct emissions from the release of this vent stream. For the Timber process, the reductions in emissions result in a 2.7% reduction in I_{L-CC}. and for the Newsprint process, an 18.0% reduction in I_{L-CC}. The large reduction in the Newsprint process I_{L-CC} is due primarily to the large reduction in direct emissions of ethanol, affecting I_{ING}.

Heat Integration Analysis. Tables 3 and 4 identify process heaters and coolers as the largest energy-consuming units in both biomass-to-ethanol processes; therefore an additional process improvement option is a heat exchanger network (HEN). The objective of heat integration is to transfer the optimum amount of energy between hot streams needing cooling and cold streams needing heating (*27*). Using the stream source and target temperatures, flow rates, and heat capacities, a heat load diagram was created (see Figure 4) (*26*) where a hot composite curve displaying the combined heat loads of all hot streams needing cooling is plotted with a cold composite curve to identify the maximum possible reduction in energy consumption. After selecting a suitable minimum temperature driving force for the exchangers (10 °C), the maximum energy exchange load accomplished through an internal network was identified. This heat load represents the maximum energy savings possible using a heat exchanger network. This heat integration analysis showed that a maximum possible reduction in utility consumption of 183,000 MJ/h in the Timber process and 205,000 MJ/h in the Newsprint process is possible (*26*).

This study shows that the amount of fossil-fuel-derived energy required over the life cycle to produce 1.0 MJ of ethanol energy is 0.14 MJ in the Timber process. After heat integration to the maximum extent the amount of fossil fuel *saved* is 0.22 MJ per 1.0 MJ of ethanol

Table 8. Incremental Changes in Environmental Indices for the Cellulase Seed Recycle Option Compared to Process Impacts

	Δ environmental index (kg /L EtOH)					
	I_{FT}	I_{ING}	I_{INH}	I_{GW}	I_{SF}	I_{AR}
			Upper MI Timber			
total	−0.040	−0.602	-4.04×10^{-3}	−0.031	-1.41×10^{-4}	-4.54×10^{-5}
% change	−1.7	−2.3	−1.0	−9.3	−21.7	−0.1
			Newsprint			
total	.115	1.69	−0.0380	−0.240	2.42×10^{-5}	-9.62×10^{-4}
% change	11.3	6.3	−8.7	−82.8	4.5	−3.1

Table 9. Incremental Changes in Environmental Indices for Cellulase Seed Recycle for Combustion Option Compared to Process Impacts

	Δ environmental index (kg /L EtOH)					
	I_{FT}	I_{ING}	I_{INH}	I_{GW}	I_{SF}	I_{AR}
			Upper MI Timber			
total	.034	−0.914	-2.91×10^{-3}	-4.94×10^{-3}	-1.46×10^{-4}	-4.33×10^{-4}
% change	1.5	−3.5	−0.7	−1.5	−22.5	−1.3
			Newsprint			
total	.025	−5.36	-1.37×10^{-3}	-5.63×10^{-3}	-9.70×10^{-5}	-7.24×10^{-4}
% change	2.4	−19.8	−0.3	−1.9%	−17.8	−2.3

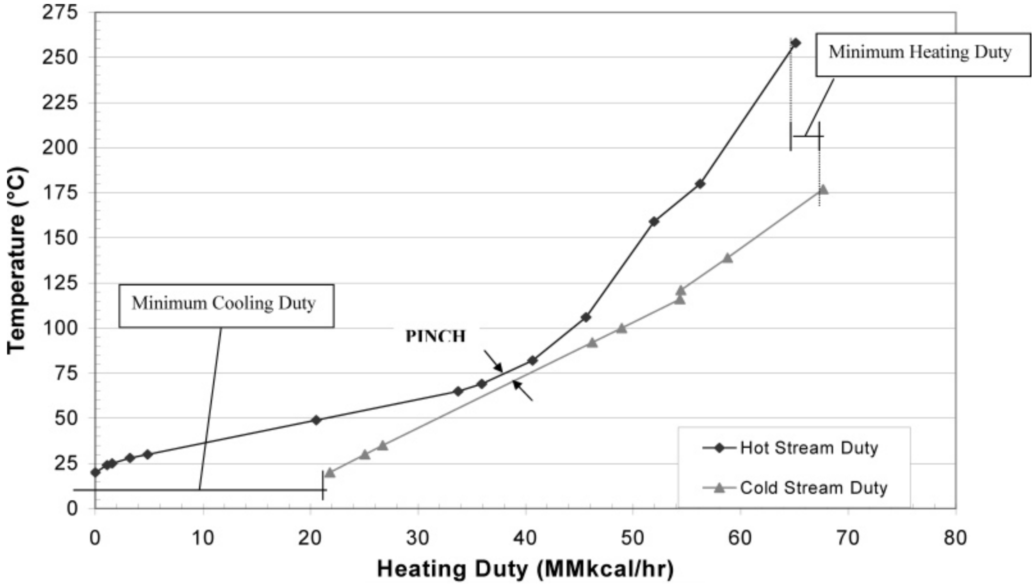

Figure 4. Graphical pinch for Timber process.

produced. In the Newsprint process, heat integration can theoretically reduce the fossil fuel energy requirements over the life cycle from 0.21 to 0.003 MJ per 1.0 MJ ethanol produced. These results clearly show that a heat exchanger network would be an effective strategy for increasing the energy efficiency in ethanol production.

Summary and Conclusions

The conversion of waste or virgin lignocellulosic biomass to ethanol is a potential alternative to fossil-derived fuels for transportation. The closed carbon cycle that results when bio-based feedstocks are used lowers the release of climate-active fossil fuel-based carbon dioxide to the atmosphere. This study shows that an aggregate life-cycle environmental impact indicator is nearly the same for producing ethanol via the NREL fermentation process for virgin timber versus recycled newsprint feedstocks. However, large differences were observed in fossil energy consumption, release of climate-active CO_2, and emissions to the air of organic compounds during the premanufacturing process and the manufacturing process life-cycle stages. The Newsprint process uses less fossil energy resources for the premanufacturing process stage, but the Upper Michigan Timber process is energy self-sufficient and actually exports electricity to the grid, whereas the Newsprint process is not energy self-sufficient. The Timber process has lower global warming impact potential and lower impacts to human health, but has a higher ecotoxicity impact score.

The amount of fossil energy over the life cycle required to produce ethanol using the Timber or the Newsprint processes is about 14 and 27% respectively of the energy content in the product. This percentage is approximately the same as the 20% additional energy that is needed to produce transportation fuels from fossil resources (*19*). However, this percentage decreases to about 0.003% (newsprint) and a savings of fossil-derived energy of 22% (timber) after implementing heat integration to the maximum extent.

The life-cycle environmental impact assessment in this study used a combination of process simulation coupled with an impact assessment software tool for the manufacturing process life-cycle stage plus a life-cycle inventory database coupled with an impact assessment software tool for the premanufacturing process impacts of fuels, process chemicals, transportation, and some preparatory steps (wood chipping, etc.). The major advantage of this approach is that process alternatives are relatively easily to simulate and evaluate for environmental impacts, facilitating the comparison of process improvement and pollution prevention modifications.

Of the eight impact categories, the Newsprint process had larger impacts in five categories (I_{ING}, I_{INH}, I_{CING}, I_{CINH}, and I_{GW}). This was due primarily to an increased level of cellulose in the newsprint feedstock, more diesel consumed in the transportation of newsprint, and a dependence on bituminous coal-produced electricity (not energy self-sufficient). For both processes, three environmental indices had the largest effect on the overall process composite index: I_{FT}, I_{INH}, and I_{ING}. The main chemical contributors to these indices were acetic acid, carbon monoxide, and ethanol, respectively. The sources of these chemical releases were primarily direct emissions from process units, utilities, and reactor vents.

Looking at these LCA results, it appears there are tradeoffs between feedstock choices for ethanol production from these lignocellulosic feedstocks. The Newsprint process has a slightly lower overall composite environmental index. The Timber process consumes less electricity, produces fewer emissions in total, and has less of a human health impact. These tradeoffs, in and of themselves, pose a challenge for decision-making with regard to selecting a biomass feedstock. Another challenge is determining the ecological impacts of large-scale timber harvesting, a topic not included in this study, but one which must be known before implementing these technologies on a large scale. Additional studies comparing biomass-to-ethanol facilities to petroleum refineries needed to evaluate local health impacts of their operations.

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