Nicaraguan-Modified GREET Pathway for the Production of Ethanol from Sugarcane Molasses

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Pathway Summary

This lifecycle analysis calculates the carbon intensity (CI) of the production of ethanol from molasses from Nicaragua Sugar Estates Limited (NSEL) sugar mill. The production of raw sugar from sugarcane juice yields molasses as an unavoidable byproduct. Molasses is transported from the sugar refinery to an ethanol distillery where it is converted into anhydrous ethanol using a process that is essentially identical to the process used in Brazilian sugarcane ethanol plants. The finished product is shipped to California by ocean tanker. The carbon intensity (CI) of this pathway is 16.79 grams of CO_2-equivalent greenhouse gas emissions per mega joule (g CO_2e/MJ) of ethanol produced on an anhydrous basis. When emissions associated with denaturant and land use conversion are included the total CI is 21.47 g CO_2e/MJ.

The sugarcane cultivation, sugarcane transport, ethanol production, and finished fuel transport portions of this pathway are essentially identical to the corresponding steps in the Brazilian Sugarcane-to-ethanol Pathway.[1] Emissions associated with the production of the molasses feedstock are disaggregated from the emissions associated with the production of raw sugar. The energy consumption and greenhouse gas (GHG) generation are appropriately allocated between the molasses byproduct and sugar. The bulk of this pathway document, therefore, focuses on molasses production. The analysis in this pathway is modeled after the ARB LCFS pathway for Indonesian sugarcane molasses to ethanol.[2]

The Well-to-Tank (WTT) portion of this Life Cycle Analysis of the NSEL molasses to ethanol pathway includes all steps from sugarcane farming to final finished anhydrous ethanol. The Tank-to-Wheels (TTW) portion includes actual combustion of the resulting fuel in a motor vehicle for motive power. Taken together, the WTT and the TTW analyses comprise a total Well-to-Wheel (WTW) analysis.

A version of the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET)[3] model developed by Argonne National Laboratory was used to calculate the energy use and greenhouse gas (GHG) emissions generated during the entire fuel life cycle, from sugarcane farming to producing ethanol to combusting ethanol in an internal combustion engine.

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1 ARB (2009) Detailed California-Modified GREET Pathways for Brazilian Sugarcane Ethanol: Average Brazilian Ethanol, With Mechanized Harvesting and Electricity Co-product Credit, With Electricity Co-product Credit. http://www.arb.ca.gov/fuels/lcfs/092309lcfs_cane_etoh.pdf

2 ARB (2012) Indonesian-Modified GREET Pathway for the Production of Ethanol from Sugarcane Molasses. California Air Resources Board. January 5, 2012.

3 Argonne National Laboratory (2008). The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model. http://greet.es.anl.gov/main

Life Cycle Associates and ARB staff modified the original GREET model to create a California-specific version known as the CA-GREET model.[4] Changes were restricted mostly to adding California-specific input factors (emission factors, electrical energy generation mix, transportation distances, etc.); no substantial changes were made to the methodology inherent in the original GREET model on which this one is based. The results obtained from the California-modified GREET model (v1.8b, released December 2009) are reported in this document. Those results consist of the energy use and greenhouse gas (GHG) emissions from the production of ethanol using molasses which is an unavoidable by-product of the NSEL sugar refining process. This pathway assumes that the ethanol produced is destined for use in motor vehicle fuels. The calculation methodology and assumptions used to develop the distribution of energy inputs and emissions for the molasses-to-ethanol pathway follow the overall approach in a 2009 article by UC Berkeley researchers Anand Gopal and Daniel Kammen.[5]

Process Configuration

Figure 1 describes NSEL's molasses-to-ethanol process for its plant in Nicaragua. Sugarcane is pressed to extract the sugarcane juice. The juice is refined into raw sugar. The molasses byproduct is shipped to a distillery where it is fermented and distilled to produce ethanol. Some of the molasses is also sold as animal feed. The cogeneration is supplemented with eucalyptus chips to generate additional electric power.

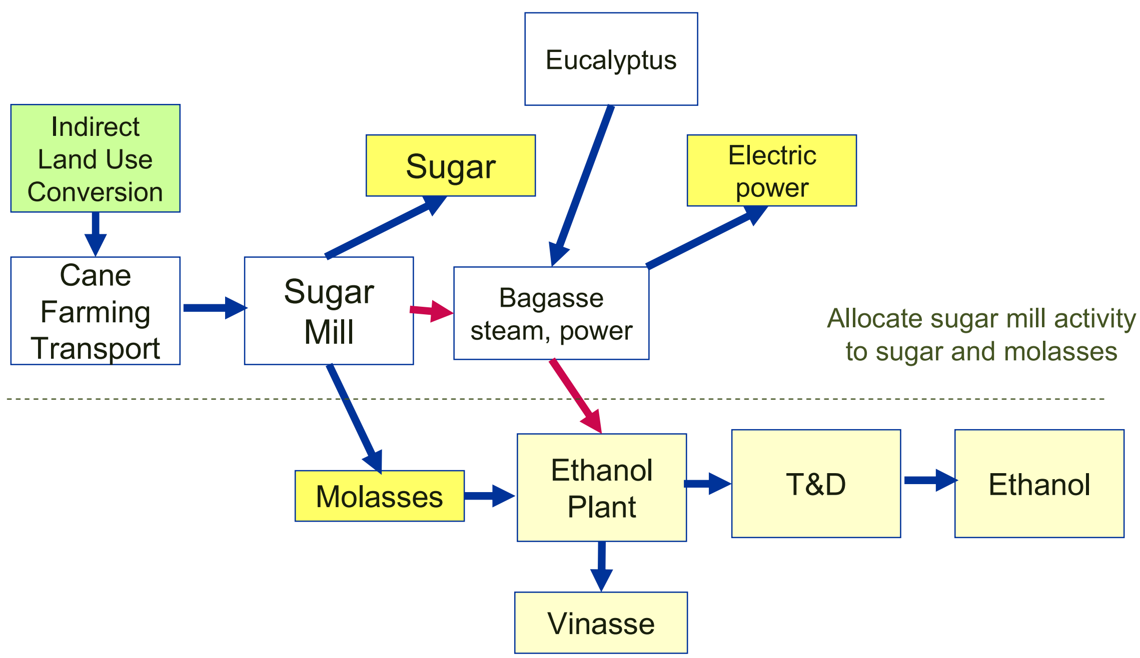

Figure 1. Molasses LCFS Pathway

[4] ARB (2009) Lifecycle Analysis (CA-GREET): http://www.arb.ca.gov/fuels/lcfs/lcfs.htm
[5] Gopal Anand R and Daniel M Kammen. 16 October 2009. Molasses for ethanol: the economic and environmental impacts of a new pathway for the lifecycle greenhouse gas analysis of sugarcane ethanol. Environ. Res. Lett. 4 (2009) 044005 (5pp)

Allocation of GHG Emissions between Sugar and Molasses

The feedstock for the ethanol produced under this pathway is a co-product of the sugar industry. Molasses—is sent to a distillery, where it is fermented and distilled into anhydrous ethanol. Molasses is a low-value byproduct that is used as a livestock feed supplement, primarily to China. This molasses cannot be upgraded to a food-grade product.[6] The life cycle analysis tracks the energy inputs and emissions according to the value of the sugar that is converted to granular sugar and the sugar that is converted to molasses. NSEL tracks the molasses according to its sugar content, so the allocation procedure is straightforward.

Agricultural emissions from the cultivation of the sugarcane from which the raw sugar is produced are distributed between raw sugar and molasses. Similarly, indirect land use emissions are also distributed between raw sugar and molasses. The allocation of inputs is complicated by several factors. Not all molasses is fermented to ethanol. Secondly co-produced power must be allocated to both sugar and molasses production.

The allocation step subtracts the emissions that are associated only with the production of final raw sugar (which is not an ethanol feedstock) from the ethanol production totals. The agricultural and sugar production emissions that are allocated to the ethanol feedstock (molasses) are added to the emissions from the production and transport of ethanol. The result is the total life cycle emissions value for ethanol made from molasses.

The market allocation methodology allocates the total emissions from the sugar production process to the primary product (final raw sugar) and to the byproduct (molasses) based on the relative share of total sales revenues that accrue to each product for each ton of fermentable sugar (in cane juice) that enters the sugar production process. Standards in the ISO 14040 series, which establish guidelines for the conduct of life cycle analysis, state that the system expansion method should be used whenever possible to allocate emissions between main products, co-products, and byproducts. The use of this method would be both extremely difficult. A description of the market-based allocation method appear in a peer-reviewed 2009 article published by UC Berkeley researchers Anand Gopal and Daniel Kammen (referenced in footnote 4). Although the system expansion method—when it can be feasibly implemented—is capable of producing emissions allocations that are more robust than the allocations that other methods produce, the market-based approach has a distinct advantage: it rewards producers for converting a waste or low-value product into a low-CI fuel, only so long as that product retains its low-value status. This is because the pathway CI will act as a check on the price of molasses: if producers seeking to capitalize on the low-CI of molasses-based ethanol create a surge in demand for the feedstock, its price will rise relative to price of sugar. As its price rises, its lifecycle CI will increase. This, of course would dampen the demand for molasses as an ethanol feedstock. System expansion-, mass-, and energy-based allocation methods are all insensitive to this price-CI feedback effect.

[6] The molasses that is sold for baking is actually raw sugar with a higher-than-normal mineral content.

The allocation approach used here tracks the price of the commodity and sugar content for raw sugar, total molasses produced and molasses used for ethanol production. The sugar content of each commodity is tracked by NSEL, so the allocation procedure is simplified.

Emissions from the NSEL process are represented by the following variables.

U = Upstream fuel cycle for sugarcane
S = Sugar processing emission = Total emissions – E
E = Emissions from ethanol production
T = Ethanol Transport
EC = credit for co-produced power

The emissions from upstream of the ethanol plant, U, S, E, and EC, are distributed allocated according to the market value of the products, which are tracked according to their sugar content. The parameters include:

Mc = mass of cane
Ms = mass of raw sugar sold
Mm = sugar content of molasses sold
Mme = sugar content of molasses converted to ethanol
Xme = Mme/Mm
Ps = Price of sugar ($/ton)
Pm = Price of molasses based on sugar content ($/ton)
Ye = ethanol yield, gallons /tonne of cane, no allocation
LHV = Lower heating value of ethanol

These variables are similar to the variables in reference 4. Emissions are simply allocated according to the $ value. For example, upstream emissions are allocated such that

$$CI = \frac{(U + S + EC) \times Mme \times Pm/(Ms \times Ps \times Xme + Mme \times Pm)}{Ye \times LHV}$$

$$+ (E + T)/LHV$$

All of the upstream emissions are distributed among the raw sugar, molasses not converted to ethanol and molasses that is converted to ethanol. Emissions associated with the ethanol plant and transport emissions are all assigned to the ethanol product. Note that less than half of the molasses produced is used for ethanol production. Therefore, the total amount of cane harvested is large compared to the ethanol output. However, the emissions are allocated among all of the products,

Table 1 shows the distribution of sugar cane, processing steam, and electric power credit to the sugar streams. The inputs are broken out according to total cane harvest and cane distributed between molasses for sales and molasses for ethanol. The electricity credit is adjusted to align more closely with the Brazilian sugarcane ethanol pathway.

Table 1. Inputs and Products.

Gopal-Kammen Model Parameters (refer to ERL paper for explanation of parameters)			
U (gCO2-eq/ton of cane) (Emissions Upstream of Sugar Factory, Inc Transportation)	28,126.84	ηj (tons of fermentable sugars in juice/ton of cane)	0.1219
S (g CO2-eq/ton cane) - not from CA-GREET, see paper for source	3,700.00	ηs (tons of sucrose in final sugar/ton of sucrose into sugar factory)	0.9155
E (gCO2-eq/mmBtu of anhyd EtOH)	2,068.98	ηe (dry tons of EtOH/ton of fermentable sugars into distillery)	0.3868
T (gCO2-eq/MJ of anhyd EtOH)	2.34	Lower heating value of anhyd EtOH (mmBtu/dry ton EtOH)	25.4

Table 2. Market Allocation of Inputs to Products

WTT LCA GHG emissions for any mixture of cane juice and molasses for Sugar Group						
Fraction of cane juice sent to make sugar with rest going directly to EtOH distillery (for Sugar Production = 1)	Cane farming, ag use and cane transport GHG Emissions (gCO2/MJ of anhyd EtOH)	Ethanol processing GHG Emissions (gCO2/MJ of anhyd EtOH)	Total WTT GHG Emissions (gCO2/MJ of anhyd EtOH)	Cane farming, ag use and cane transport GHG Emissions (gCO2/MJ of anhyd EtOH)	Cane Farming, Ag Use, Straw Burning, Cane Transport. and Sugar Prod Emissions (gCO2/MJ of anhyd EtOH)	**Market Value-Based Allocation Factor**
1.0	13.66	1.96	17.71	13.66	24.36	0.56

Carbon Intensity

Table 3 summarizes the energy used and GHGs emitted from each stage in the production of ethanol from molasses. In this analysis, the carbon intensity of sugarcane ethanol is calculated by considering all the incremental emissions that occur from farming through the production of ethanol. Land use change emissions are also included, as well as the emissions from adding a denaturant. The resulting carbon intensity of the sugarcane-molasses-to-ethanol pathway is 21.47 g CO_2e/MJ.

The presentation follows the LCFS pathway document developed for Indonesian molasses based ethanol. The calculations first show the carbon intensity per MJ of ethanol without allocation to sugar. The results are then multiplied by the market based allocation factor. This method is consistent with the calculation procedures in the GREET model.

LUC emissions are based on the Indonesian molasses pathway. Since molasses is a globally traded product and most of the molasses in Nicaragua is shipped to Asia, the market effect of molasses would be the same for Nicaraguan and Indonesian molasses.

The calculations are based on actual fertilizer application rates, sugarcane trash burning, ethanol production heat rate, electricity production, and transport distance. The displaced electric power is based on the marginal Central American mix, which is primarily fuel oil as shown in the attachments. The transport distances are also calculated in the attachments.

Table 3. Summary of Well-To-Wheel Emissions for Sugarcane to Ethanol

Disaggregated Item	GHG Emissions: Sugarcane to Sugar ($g\ CO_2e/MJ$)	Allocated GHG Emissions: Molasses to Ethanol ($g\ CO_2e/MJ$)
Well -to-Tank (WTT) GHG Emissions		
Market-Based Allocation Factor[2]		**0.56**
Sugarcane Farming	4.55	2.55
Agricultural Chemicals Production	3.79	2.12
Sugarcane Farming, Agricultural Chemicals, and Straw Burning	18.23	10.22
Sugarcane Transport	3.3	1.85
Sugar Production	2.83	1.59
Market-Based Allocation Factor		**1**
Ethanol Production		1.96
Ethanol Transport and Distribution		2.09
Total Well-to-Tank (WTT) GHG Emissions	28.41	17.71
Electricity Cogeneration and Export Credit	-10.92	-0.92
Carbon in Fuel (1,000,000 Btu / mmBtu)	N/A	N/A
Total Well-to-Wheels (WTW) GHG Emissions	**N/A**	**16.79**
Market-Based Allocation Factor for LUC		**0.085**
Land Use Change	46.00	3.89
Denaturant		0.8
Final Well-to-Wheel (WTW) Carbon Intensity for NSEL Pathway ($g\ CO_2e$ / MJ)	**N/A**	**21.47**

The emissions allocations shown in this column are calculated as described in the Anand and Kamman paper. Note that the values in the Sugarcane Farming, Agricultural Chemicals Production, Straw Burning, Sugarcane Transport, and Sugar Production rows are all allocated from the totals in the pre-allocation "GHG Emissions: Sugarcane to Ethanol" column. The values in the Ethanol Production and Ethanol Transport and Distribution rows, however are equal in the two columns (allocated versus pre-allocated GHG Emissions).

Supporting Data and Calculations

1. Farming Inputs

NSEL provided farm level data for diesel fuel use, fertilizer, and mix of harvesting method.

Sugarcane Farming			
		NSEL	CA GREET
	L/tonne	2	
Farming Energy Diesel	Btu/tonne	67,628	41,592
Electricity	Btue/tonne	0	
Fertilizer Application	g/ AR tonne		
N		1,200	1,092
P2O5		300	121
K2O		0	194
CaCO3		0	5,338

Farming data are comparable to GREET defaults. The diesel fuel use is twice the total energy input for GREET. NSEL's data includes diesel for manual harvesting, mechanical harvesting, farming, and transport. The first three are grouped together in the farming category. Btu/tonne are calculated from L of diesel per year data, and diesel properties. Life Cycle emissions were calculated by setting the fuel shares to 100% diesel and then adding the small amount of electric power with the marginal mix separately.

Fertilizer inputs are somewhat higher than the GREET defaults although no limestone is applied. Life Cycle data for sugarcane farming are calculated by scaling the NSEL data to CA GREET data and multiplying by the data array in CA GREET. The same result is achieved by inputting the data to CA GREET. The scaling calculations are on the worksheet Molasses Disaggregation.

Trash Burning

Emissions from trash burning are based on typical cane burning for Nicaragua.

2. Sugarcane Transport

Energy inputs for sugarcane transport are based on transport distance and truck capacity.

NSEL provided the transportation distances for the cane supply. The average distance is 30 km or 19 miles compared to the GREET default of 12 miles

3. Electricity Mix and Co-product Credit

The marginal electricity mix is calculated using the CA_GREET model. The resource mix was provided by NSEL. The marginal mix is based on the average mix, excluding hydro electric and biomass power. The marginal mix was calculated using the same approach used under the LCFS for electricity mix in California and the Midwest. The key principals are the following:

Geothermal, nuclear, and hydro electric are the lowest cost generation resources. They are used at capacity and are not available on the margin. The dispatchability of other generation resources is impossible to predict, so a best estimate of the marginal mix would be the non renewable resources. This approach was applied in the CA GREET model for the Midwest electricity mix. In any event, bunker fuel is one of the leading sources of power and its use would expand on the margin.

NSEL provided actual data for power production. The power production is sufficiently high to justify the use of the GREET default. The GREET default (7 g/MJ) corresponds to 0.96 kWh/gal of ethanol or 23.04 kWh/tonne of cane. The power is allocated according to the sugar content of the molasses and cane.

ARB notes that the co-product credit should be distributed to the sugar, weighted by market value in their comments on the pathway. The power is allocated in the same manner as the farming inputs. The effect is that co-product credits and farming inputs are both reduced compared to the pure sugarcane option because the sugar in molasses has a lower value than the sucrose in refined sugar.

4. Ethanol Transport

Transportation differs from the default Brazilian sugarcane pathway, which assumes that 50 percent of the ethanol transported to the port is by pipeline, and another 50 percent by rail. For the NSEL LCFS pathway, all ethanol is transported by heavy-duty truck (HHDDT) from the NSEL facility over a distance of 30 km (19 mi) to Port.

The mode of transport from Nicaragua to Long Beach is assumed to be by Ocean tanker over a distance of 2,356 miles. The calculation is performed with the US regional mix for the sugarcane ethanol pathway in CA GREET. The local distribution distance is set to zero so only the overseas portion is calculated in the first step.

From distribution in California, the LCFS default pathway assumes 100 miles of truck transport followed by 80% of the ethanol travelling an additional 50 miles the local fuel station. For the purposes of simplification, this truck transport mode was modeled with Regional LT set to CA Marginal, and by assuming that 100 percent of the ethanol is transported by truck. The California transport segments are calculated separately. The effect is a slight increase in CO_2 emissions due to the energy intensity for California petroleum assumed in CA GREET. The CI impact follows the approach in the Brazil pathway.

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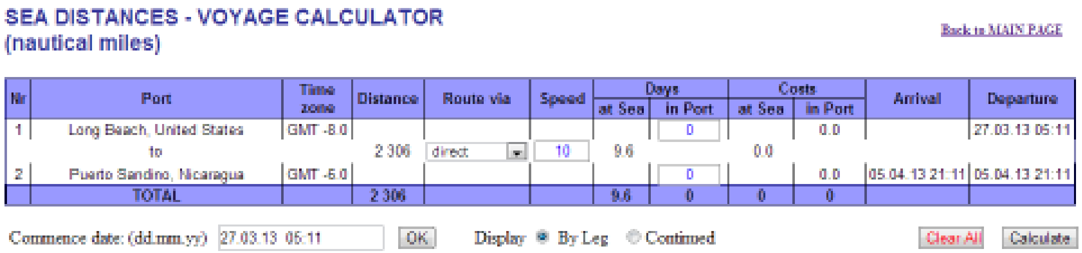
Table 4. Transport Logistics

Parameters for Transportation	
Source	Nicaragua
Feedstock Location	Chichigalpa
Local Transport	
Truck distance (km)	30 km (19 mi)
Marine Transport	
Shipping Port	Puerto Sandino, Nicaragua
Destination Port	Long Beach, CA
Route	Direct
Max. Tanker Capacity (DWT)	550000
Distance (kn)	2306
Distance (mi)	2654
U.S. Transport	
Destination Port	Long Beach, CA
Storage Terminal	Port Storage Terminal
Distance (ft)	300
Storage Terminal	Port Storage Terminal
Blending Terminal	Blending Terminal
Truck distance (mi)	100 + 80% x 50


SEA DISTANCES - VOYAGE CALCULATOR
(nautical miles)

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Nr	Port	Time zone	Distance	Route via	Speed	Days at Sea	Days in Port	Costs at Sea	Costs in Port	Arrival	Departure
1	Long Beach, United States	GMT -8.0					0		0.0		27.03.13 05:11
	to		2 306	direct	10	9.6		0.0			
2	Puerto Sandino, Nicaragua	GMT -6.0					0		0.0	05.04.13 21:11	05.04.13 21:11
	TOTAL		2 306			9.6	0	0	0		

Commence date: (dd.mm.yy) 27.03.13 05:11 OK Display By Leg Continued Clear All Calculate

Figure 2. Marine Distance from Nicaragua to Long Beach, CA

5. Pathway Calculation

The NSEL pathway was developed with the CA-GREET model using an external calculation. LCI data and transport emissions are calculated in the spreadsheet ca_gree1.8b_dec09_NSEL.

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