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Molasses for ethanol: the economic and environmental impacts of a new pathway for the lifecycle greenhouse gas analysis of sugarcane ethanol

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Abstract
Many biofuel standards, including California's recently adopted low carbon fuel standard, consider just one feedstock from one supplying country for the production of sugarcane ethanol: fresh mill-pressed cane juice from a Brazilian factory. While cane juice is the dominant feedstock for ethanol in most Brazilian factories, a large number of producers in Indonesia, India, and the Caribbean, and a significant number in Brazil, manufacture most of their ethanol from molasses, a low value co-product of raw sugar. Several producers in these countries have the capacity to export ethanol to California, but the GREET (from: greenhouse gas, regulated emissions and energy use in transportation) model, which is the LCA (lifecycle assessment) model of choice for most biofuel regulators including California, does not currently include this production pathway. We develop a modification to GREET to account for this pathway. We use the upstream and process lifecycle results from the existing GREET model for Brazilian ethanol to derive lifecycle greenhouse gas emissions for ethanol manufactured from any combination of molasses and fresh cane juice. We find that ethanol manufactured with only molasses as a feedstock with all other processes and inputs identical to those of the average Brazilian mill has a lifecycle GHG (greenhouse gas) rating of 15.1 gCO_2-eq MJ^{-1}, which is significantly lower than the current California-GREET assigned rating of 26.6 gCO_2-eq MJ^{-1}. Our model can be applied at any level of granulation from the individual factory to an industry-wide average. We examine some ways in which current sugarcane producers could inaccurately claim this molasses credit. We discuss methods for addressing this in regulation.

Keywords: LCA, biofuels, sugarcane ethanol, greenhouse gas emissions, GREET

1. Introduction

The production of raw cane sugar from sugarcane juice results in the formation of molasses, a byproduct that contains minerals regarded as impurities in raw sugar (Hugot and Jenkins 1986). However, this purification process results in the loss of some high value disaccharides and monosaccharides from the final raw sugar product that end up in the molasses. The fermentable sugar content of molasses varies inversely with the purity of the raw sugar produced at the factory.

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Molasses is a low value product that is used as a cattle feed supplement, in specialized yeast propagation or as a flavoring agent in some foods (Troiani 2009a). Although the fermentable sugars in the molasses cannot be further upgraded to raw sugar, they can be converted to ethanol in a distillery. Hence, integrated sugarcane factories that have sugar manufacturing co-located with an ethanol distillery can use molasses as a feedstock for ethanol in addition to raw cane juice directly from the mill. A significant number of sugarcane factories in Brazil and several hundreds of others around the world are of this type (Szwarc 2009). Since molasses has a significantly lower opportunity cost than raw cane juice, factories using it as a feedstock for ethanol deserve to be credited. The current California-GREET model for sugarcane ethanol[5] (hereby referred to as CA-GREET for Brazil) does not include this pathway (CARB 2009). In this paper, we use the outputs of CA-GREET for Brazil to recalculate lifecycle emissions for integrated factories that use any proportion of molasses and cane juice to make ethanol. We present results for such factories using existing Brazilian data but our model will be particularly relevant to other countries, whose producers use substantially higher fractions of molasses to make ethanol, from where data is not yet available. When the data becomes available the model is designed to be an add-on to GREET which will make it a new analytic tool for the biofuel industry and fuel regulators. The output of CA-GREET for Brazil is used by the California Air Resources Board to set the default lifecycle carbon content of sugarcane ethanol under the low carbon fuel standard (LCFS) program and with an estimated 2 billion liters of molasses ethanol manufactured in regions that have the capacity and interest to sell to California (Licht 2006), our add-on is likely have substantial economic implications for the state.

2. Integrated sugar and ethanol factory process

Sugarcane factories can broadly be classified into three categories: (1) ones that produce only raw table sugar (hereby referred to as raw sugar), (2) ones that produce only ethanol and, (3) integrated ones that produce both raw sugar and ethanol. Approximately 80% of the factories in Brazil belong to the third category (BNDES 2008). In other countries, large factories (crushing more than five hundred thousand tons of sugarcane each season), also overwhelmingly belong to the third category (Troiani 2008). The use of both molasses and sugarcane juice to produce ethanol is only economically feasible in factories belonging to the third category. Typically all three types of sugarcane factories meet their process energy demand by combusting bagasse, the ligno-cellulosic fiber that is a byproduct of sugarcane crushing, to power a steam turbine. Figure 1 below is process and mass flow diagram of an integrated sugar and ethanol factory. The figure shows the quantities of intermediate and final products produced from the crushing of 1 wet ton of sugarcane.

In integrated factories, sugarcane is crushed at a mill that produces both sugarcane juice, which is rich in sucrose, and bagasse, which is used to meet the energy demand of the entire factory. The factories then split the juice into two streams sending one part for raw sugar production and the other part to the ethanol distillery. Molasses, which is a byproduct of raw sugar production is then sent as additional feedstock to the distillery. The yield of ethanol from fermentable sugars in molasses is almost identical to the yield from fermentable sugars in cane juice (Troiani 2009b).

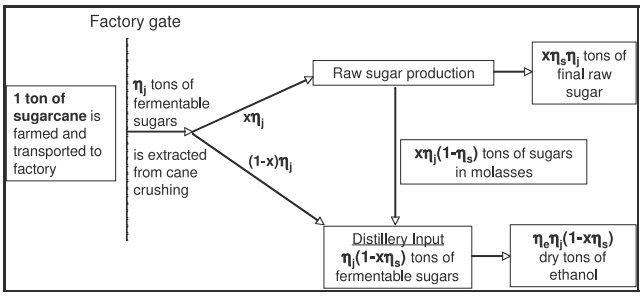

Figure 1. Mass and process flow of an integrated sugar and ethanol factory where x = fraction of cane juice sent to manufacture raw sugar; η_j = cane crushing yield (tons of fermentable sugars in juice/ton of cane); η_s = raw sugar manufacturing efficiency (tons of sucrose in final sugar/ton of sucrose in); η_e = ethanol distillery efficiency (dry tons EtOH/ton of sucrose in).

3. The add-on model for dual feedstock ethanol production

Greenhouse gas (GHG) emissions upstream of the factory are already well described in GREET. The process calculations, however assume that only cane juice is used as a feedstock. We develop an add-on that uses several outputs from CA-GREET for Brazil along with some additional parameters to calculate lifecycle GHG emissions for ethanol production with dual feedstocks.

We include a key additional parameter 'x' that is currently implicitly set to a value of 0 in CA-GREET for Brazil, which is the fraction of sugarcane juice by mass that is sent to manufacture raw sugar. All emissions associated with raw sugar manufacturing need to be allocated between raw sugar, the primary product, and molasses, the co-product. We choose to make this co-product allocation based on the market value method. Since, co-product allocation is a hotly debated issue in lifecycle analysis, especially in the case of biofuels, we discuss the substitution and market value methodologies in detail within the context of this paper and present our reasoning for the one we choose. Note that co-product allocation based on the energy content of sugar and molasses would lead to a solution identical to that of CA-GREET for Brazil where cane juice and molasses are indistinguishable from an LCA standpoint.

3.1. Allocation by the substitution method

Molasses is used in several applications in addition to ethanol production and, in each case is easily substituted by a variety of other products. It is commonly used as a feed supplement for both feedlot and pasture cattle where it normally constitutes

[5] Posted on 27 February, 2009 at http://www.arb.ca.gov/fuels/lcfs/lcfs.htm

4% of the feed mix (Fox *et al* 2001) and is highly substitutable with products made from corn, wheat or barley (Surry and Moschini 1984). Further, it is a difficult product to store and transport and hence only about 15% of the molasses sold worldwide is traded internationally (Westway 2002). Molasses has two further uses where the total demand for it is insignificant when compared to the volume demanded by the cattle feed industry. It functions as a substrate in the propagation of yeast and as a flavoring or coloring agent in some food products. Due to all these factors demand for molasses is highly elastic. Perhaps more importantly, molasses serves as substitute for several products across several industries making the application of the substitution method complicated and highly geographically variant.

3.2. Allocation by the market value method

The strongest criticism of co-product allocation based on market value is that it does not represent environmental outcomes. While this criticism of the market value method holds true here, it is also true that for reasons described above, the substitution method is difficult to apply and will result in grossly inaccurate results in this case. Further, the main motivation for this letter is to reward producers for the use of a waste or low value input since the technology for molasses ethanol and cane juice ethanol is almost identical. While not perfect, price is the best available indicator of how much of a waste product molasses is. If there is a surge in demand for molasses by ethanol producers looking to take advantage of the better lifecycle rating, the price of molasses will rise relative to sugar to a point where it can no longer be considered a waste or low value product. The substitution method will be blind to such an effect but if the regulation is set based on the market value method, this relative price increase will reduce the lifecycle GHG advantage of molasses ethanol. In fact, if the relative price increase is large enough, we will reach a breakeven point where molasses and cane juice ethanol are indistinguishable from a lifecycle GHG perspective. This is shown in detail in section 4. The potential for better policy design is also the primary reasoning of Nguyen and Gheewala (2008) for adopting the market value allocation method for sugar and molasses.

We estimate the lifecycle emissions of ethanol from any combination of molasses and cane juice using three steps. First we estimate total GHG emissions per ton of raw cane input based on mass flow estimates shown in figure 1 and aggregation of associated individual process emissions. Next we calculate the ethanol yield per ton of cane input, which then is used to estimate GHG emissions per MJ of ethanol produced. Finally, we add the emissions associated with the transportation and distribution of ethanol that is already calculated in GREET. Equations (1)–(3) represent each of the above steps.

Total LCA GHG emissions up to distillery exit

$$(\mathrm{gCO_2\text{-}eq/ton\ of\ cane}) = U(1-x) + x(U+S) \times \left[\frac{\{(1-\eta_s)/m_m\}P_m}{\{(1-\eta_s)/m_m\}P_m + (\eta_s/m_s)P_s}\right] + [(1-x\eta_s)(E \times \mathrm{LHV_{anhyd}} \times \eta_j\eta_e)] \quad (1)$$

where x = fraction of cane juice sent to manufacture raw sugar; η_j = cane crushing yield (tons of sucrose in juice/ton of cane); η_s = raw sugar manufacturing efficiency (tons of sucrose in final sugar/ton of sucrose in); η_e = ethanol distillery efficiency (dry tons EtOH/ton of sucrose in); $\mathrm{LHV_{anhyd}}$ = LHV of anhydrous ethanol (~25.4 mmBtu/dry ton EtOH); U = all emissions upstream of factory (GREET value = 4.02×10^4 $\mathrm{gCO_2}$-eq/ton of cane); S = raw sugar production emissions ($\mathrm{gCO_2}$-eq/ton of cane, currently not calculated in GREET); E = ethanol production emissions (GREET value = 2.0×10^3 $\mathrm{gCO_2}$-eq/mmBtu of anhydrous ethanol); P_s = price of final raw sugar on the market ($330/ton in Sao Paulo Bovespa); m_s = tons of sucrose in final sugar/ton of final sugar product (≈0.95); P_m = price of molasses on the market (~$60/ton); m_m = tons of fermentable sugars in standard molasses/ton of standard molasses (≈0.50).

CA-GREET for Brazil assumes a fixed ethanol yield of 24 gallons of hydrous ethanol per ton of cane which is quite accurate when cane juice is the only feedstock. However, when molasses is also used as a feedstock, the ethanol yield depends on the fraction of cane juice sent to raw sugar production as well as the process efficiencies of each production stage. The efficiency of the distillery in converting fermentable sugars to ethanol is effectively the same for molasses and cane juice. The lower concentration of fermentable sugars in molasses does not affect the performance of the distillery.

$$\text{Ethanol yield} = \mathrm{LHV_{anhyd}} \times \eta_e\eta_j[(1-x\eta_s)] \times \frac{10^6}{947.8}\ \text{MJ of anhydrous ethanol/ton of cane.} \quad (2)$$

To obtain the total well-to-tank lifecycle greenhouse gas emissions for ethanol from any combination of molasses and cane juice in GREET equivalent units of $\mathrm{gCO_2\text{-}eq\ MJ^{-1}}$ of anhydrous ethanol, we divide equation (1) by equation (2) and add the CA-GREET for Brazil calculated emissions due to transportation and distribution of the fuel. This calculation in CA-GREET for Brazil includes transportation of anhydrous, denatured ethanol by rail and pipeline within Brazil and then by ocean tanker to California. Once in California, the ethanol is blended with gasoline and then transported and distributed by truck, which is also included in the term 'T' in equation (3). The dehydration and denaturing are assumed to be done at the distillery.

$$\text{WTT GHG emissions } (\mathrm{gCO_2\text{-}eq\ MJ^{-1}}) = \frac{(\text{equation (1)})}{(\text{equation (2)})} + T \quad (3)$$

where, T = emissions due to transportation and distribution of ethanol (4.1 $\mathrm{gCO_2\text{-}eq\ MJ^{-1}}$ in CA-GREET for Brazil).

4. Results

Based on our own field research and data from sugarcane factories in Brazil, Indonesia and India, we determined average values for each of the efficiency parameters in the equations above. These are shown in table 1. CA-GREET for Brazil ignores raw sugar production and hence does not report raw sugar process emissions. We estimate raw sugar process

Table 1. Parameter values.

Parameter	Unit	Value
η_s	Tons of final sugar/ton of recoverable sugar in	0.80
η_e	Dry tons of EtOH/ton of fermentable sugar in	0.51
η_j	Tons of recoverable sugars in juice/ton of cane	0.14
U	gCO_2-eq/ton of cane	4.02×10^4
E	gCO_2-eq/mmBtu of anhydrous ethanol	2.02×10^3
S	gCO_2-eq/ton of cane	3.70×10^3
P_s	US$/ton of raw sugar	$330
P_m	US$/ton of standard molasses	$60

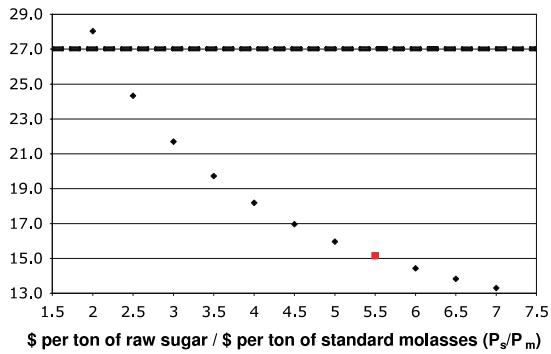

Figure 2. Sensitivity of LCA GHG emissions to the raw sugar to molasses price ratio.

emissions by assuming that all of it is due to the non-CO_2 emissions from bagasse combustion, which, in reality, does make up the majority of sugar production emissions. Additives like lime and flocculant that are consumed in the sugar production process make up the rest of the emissions, which is a very small part of the total emissions for sugar production.

The lifecycle greenhouse gas emissions associated with Brazilian sugarcane ethanol for factories with varying amounts of molasses as feedstock is shown in table 2. Table 2 also shows the quantities of raw sugar, 85 brix molasses and hydrous ethanol that are produced from a ton of cane for each scenario. Our model calculates lifecycle emissions to be 27.0 gCO_2-eq MJ^{-1} when $x = 0$, which is equivalent to the current CA-GREET result for Brazil. Table 2 shows that emissions decrease non-linearly with x to reach 15.1 gCO_2-eq MJ^{-1} for a factory that uses only molasses to make ethanol ($x = 1$).

The key parameter of interest in this model is the ratio of sugar price to ethanol price (P_s/P_m). In figure 2, we show the sensitivity of the results to this parameter for a factory that uses only molasses as feedstock. Based on current sugar and molasses prices, the LCA GHG emissions of 100% molasses ethanol is 15.1 gCO_2-eq MJ^{-1}, shown by the square marker in the figure. The dashed line in figure 2 represents the well-to-tank GHG emissions for 100% cane juice ethanol. Note that once the sugar to molasses price ratio drops below a given breakeven value (which lies between 2 and 2.5), it is worse, from a lifecycle GHG standpoint, to produce molasses ethanol than cane juice ethanol.

5. Issues in applying the model to guide regulation

Our model works with CA-GREET for Brazil's current outputs and hence can initially be applied on the same scale, using a single value for many producers over a large area. If used in this manner, all the parameters in our model and in CA-GREET for Brazil would just be any aggregate central tendency measure for all the factories in the area of regulation. Without any modification of the model, it can also be applied at the factory level to determine an individual greenhouse gas footprint. Hence when used in conjunction with GREET this is a complete well-to-tank lifecycle analysis of sugarcane ethanol when molasses is used as any fraction of the feedstock. The regulatory framework can be identical to those of all other fuels and pathways already in California's LCFS. In the case of Brazil, most integrated factories tend to favor ethanol production over raw sugar and hence are likely to see very little improvement in their rating over the current value. However, for producers in Indonesia, Thailand, India, Guatemala and several other countries, molasses is the majority feedstock for ethanol production. Many producers have both the interest and the capacity to export their ethanol to California and this model will more accurately describe their fuel.

A number of concerns exist if firms are given credit for the use of molasses. First, firms may begin to start using more and more molasses to make ethanol, diminishing its status as a low value product. This is the strongest argument for doing the co-product allocation based on revenue ratio like we have in the paper, since higher molasses demand will simply raise its price relative to sugar, which will result in increased fuel lifecycle GHG emissions.

Second, firms may re-engineer their process whereby they direct more cane juice to the raw sugar factory but deliberately produce raw sugar less efficiently leaving more fermentable sugars in the molasses (also known as intermediate molasses) which they will then use to make ethanol. Such re-engineering will need substantial capital investment in factories that are operating at full capacity to allow the sugar factory to handle a greater throughput of cane juice than its original design capacity. A vast majority of sugarcane factories worldwide operate at full capacity since their sugar and ethanol markets are predictable and, they do not want to under-utilize capital. The additional revenue gained from their improved GHG rating is unlikely to justify such investment. Hence, a bi-annual inspection audit of these factories should be sufficient to prevent any fraud. Several Brazilian factories do have additional sugar and ethanol capacity but production of intermediate molasses is still non-trivial. A moderately more frequent audit of these factories is probably sufficient to prevent such actions.

If this model is to be used in regulation, it will be important to examine the volatility of sugar and molasses prices in order to determine how often the fuel lifecycle rating should be adjusted. If the prices are too volatile relative to

Table 2. Well-to-tank GHG emissions for sugarcane ethanol manufactured with cane juice and molasses at current prices of sugar and molasses.

Fraction of cane juice sent to manufacture sugar	LCA GHG emissions for sugarcane ethanol (gCO_2-eq MJ^{-1} of anhydrous ethanol)	Tons of raw sugar produced per ton of cane	Tons of 85 brix molasses produced per ton of cane	Liters of hydrous ethanol produced per ton of cane
0.0	27.0	0.000	0.000	93.0
0.1	26.8	0.012	0.006	85.5
0.2	26.5	0.024	0.011	78.1
0.3	26.1	0.035	0.017	70.7
0.4	25.6	0.047	0.022	63.2
0.5	25.0	0.059	0.028	55.8
0.6	24.3	0.071	0.034	48.3
0.7	23.2	0.083	0.039	40.9
0.8	21.7	0.094	0.045	33.5
0.9	19.4	0.106	0.050	26.0
1.0	15.1	0.118	0.056	18.6

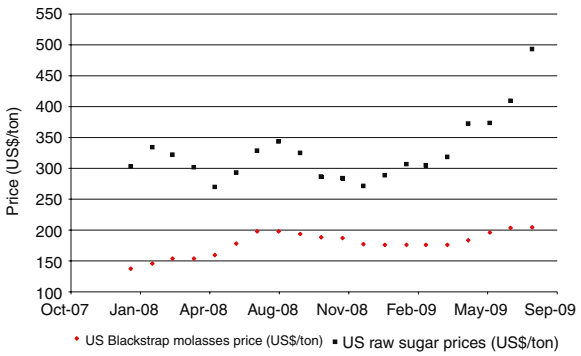

Figure 3. US raw sugar and molasses prices by month (US$/ton).

each other, the prices may have to be averaged over longer timescales in order to make the regulation feasible in practice. While it is impossible to predict future trends in molasses and raw sugar prices, we analyzed the price trends of the two commodities over the last 20 months. Figure 3 shows US prices for blackstrap molasses (which mirrors the price variations of standard molasses) and raw sugar from January 2008 to August 2009. The data is from the USDA's Economic Research Service. From the figure we can see that there is enough relative volatility in the spot price that it will be better to employ moving averages for regulation, but not so much volatility to make it infeasible to use this model in regulation. A thorough analysis of price data to determine how to design regulation is beyond the scope of this paper so our intention here is to highlight the importance of this issue.

Our analysis results in a general-purpose add-on for GREET and other LCA tools that more completely describes lifecycle greenhouse gas emissions from sugarcane ethanol. This pathway much more accurately describes sugarcane mills in major cane producing countries who are well-placed to take advantage of export opportunities. Most importantly, if the model is used to set fuel lifecycle ratings for the LCFS, it is likely to results in substantial monetary savings for California.

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