Producing Ethanol for Biodiesel in Vermont

VT Agency of Agriculture, Food and Markets
REAP Grant Report (Award #REAP070004)

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March 27, 2010 [Revised August 20, 2010]

EXECUTIVE SUMMARY

This report summarizes the feasibility of sweet sorghum based anhydrous ethanol production on a small Vermont farm. Current biodiesel production models utilize commercially produced methanol and lye, components of the process which have significant embodied energy and financial costs. Although sustainable oil feedstocks for biodiesel have been explored and demonstrated in Vermont, sustainable sources of ethanol and lye have remained elusive.

Based on the research and field trials summarized in this report, the team has made the following conclusions:

1. Sweet sorghum based anhydrous (dry) ethanol appears promising in Vermont as a sustainable source of alcohol and lye to be used in the conversion of vegetable oil to biodiesel. The crop is grown with limited inputs on marginal land and yields both juice and *bagasse* (the byproduct of juice extraction). Together with oilseed crops, sweet sorghum makes an excellent companion in an integrated model of small-scale biodiesel production.
2. The production of sweet sorghum has been demonstrated in southern Vermont with average yields of 1714 gallons of juice / acre (range 1315-2151) with average Brix sugar measurements of 16.0 (range 15.2-16.7). These data correspond to an average alcohol yield of 148 gal/acre (range 107-185) at an estimated production cost of $212.00/acre with manual harvest methods. Mechanization of harvest is projected to reduce this cost to $114.50/acre.
3. Sweet sorghum bagasse (byproduct of pressing juice from the cane) represents a significant fuel crop with an estimated fuel value of 45.6 million BTU/acre which can be harvested at an estimated cost of $1.24 / million BTU (vs. $33.00 / million BTU for biodiesel @ $4.00 / gal.) On a per-acre basis there is a large surplus of energy from bagasse when compared to that required for distillation of the ethanol.
4. Sweet sorghum bagasse also represents a source of potassium hydroxide (KOH) for use in the biodiesel conversion process. The team estimates that 18.8 lbs (43%) of the 44 lbs KOH required for the 532 gal biodiesel production supported by 148 gal sweet sorghum ethanol can be provided from the associated bagasse.
5. Investment of $200,000 in an anhydrous still for production of ethanol from sweet sorghum shows the potential for a 17 year payback when run at a capacity of 10,000 gal/yr assuming a retail value of anhydrous ethanol of $3.00/gal. This is reduced to 9 years if a retail price of $4.00 per gallon is assumed.
6. The estimated breakeven cost per gallon of ethanol produced at a rate of 6,200 gal/yr and with sweet sorghum juice produced at 1714 gal/acre and a cost of $114.50 / acre is $6.07/gal. This cost includes crop production costs, ethanol production costs, labor, fixed asset amortization and cost of capital. The assumptions resulting in this breakeven price match demonstrated crop production from State Line Farm in 2009 and assume a $300,000 capital investment in a distillation facility fueled by biodiesel. The breakeven cost is reduced to $5.50 per gallon if bagasse is used as the fuel. This indicates a need for greater volume of production and lower capital costs in order to compete with retail pricing of $3.00-4.00 per gallon.

The research team is pursuing a Northeast Sun Grant to support the further development of a sustainable anhydrous ethanol production plant at State Line Farm. The following scope of work has been identified.

1. Determine best practices for use of ethanol and potash lye in small scale biodiesel production
2. Determine the most regionally appropriate sugar crops to serve as feedstock for farm-based ethanol production
3. Evaluate harvesting, handling, pressing and storage technologies for sugar crops
4. Demonstrate farm-scale fermentation of sugars to alcohol
5. Demonstrate farm-scale distillation and production of anhydrous ethanol
6. Demonstrate farm-scale production of potash lye from wood ash
7. Integrate on-farm oilseed, ethanol and lye production into on-farm biodiesel production

The research described in this report was funded through the Vermont Agency of Agriculture, Food and Markets as part of the Renewable Energy for Agriculture Grant Program (REAP) with support from the Vermont Sustainable Jobs Fund (VSJF).

INTRODUCTION

Biodiesel represents one component of a diverse renewable energy portfolio, which includes other renewable fuels and power sources. It is a liquid fuel derived from vegetable oil that is converted through transesterification using alcohol and lye (hydroxide) in a minimally heated process. Biodiesel is made from a variety of feedstocks including used vegetable oil (UVO), straight vegetable oil (SVO) and renderings of animal fats. Though sustainable oil feedstocks have been identified and grown successfully, sustainable alcohols and hydroxides remain elusive. In fact, they have largely been ignored. These components of biodiesel, which are largely derived from non-renewable sources and transported long distances, represent a significant portion of the energy embodied in the production of biodiesel (and thus carbon), as well as the cost. Therefore, a locally produced and crop-based substitute for the methanol and lye used in most biodiesel processes should be a high priority for those seeking to generate renewable and sustainable fuels. A schematic of a crop-based biodiesel process is shown in Figure 1.

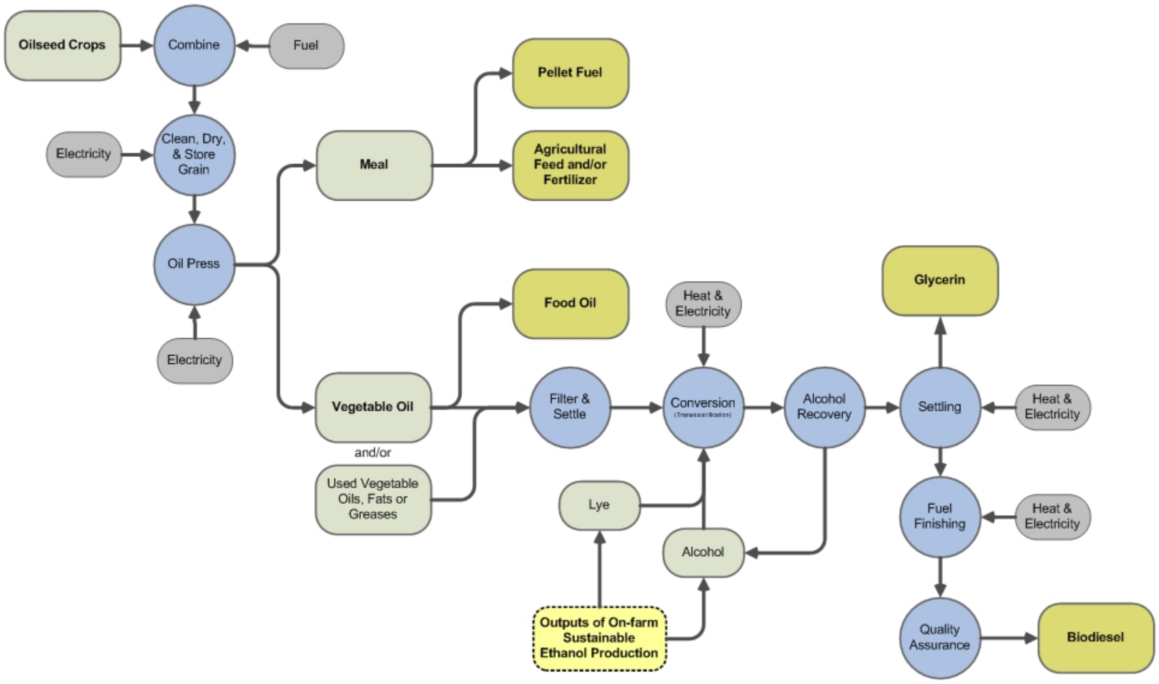

Figure 1 – Conversion of Oilseed Crops to Biodiesel

Ekolott Farm (Newbury, VT) and State Line Farm (Shaftsbury, VT) have identified on-farm production of anhydrous ethanol and potash as a critical requirement for the development of a truly renewable and stable farm fuel supply. An example of how such a system would work is shown in Figure 2. Along with growing oilseed crops as oil feedstocks for biodiesel, Stateline and Ekolott have also experimented with growing sugar crops such as sweet sorghum as a feedstock for ethanol. Stateline has fermented and distilled sorghum juice, resulting in ethanol. This ethanol has been dried using molecular sieves. Additionally, potash lye has been derived from wood ash using traditional techniques. A small batch of biodiesel has been made from these ingredients grown only on the farm; perhaps the first ever batch of a truly renewable liquid fuel.

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BIODIESEL MADE WITH ETHANOL

As noted above, the partner farmers have been producing oil seed crops in Vermont including sunflower, canola, mustard and soy beans. Yields vary considerably from one grower to another and from year to year based on weather, weed and animal pressures as these crops have just recently been tried in Vermont. But oil yields averaging 80 gal/acre are possible and have been demonstrated with sunflower and canola[1]. Vermont oilseed acreage has grown from 1-2 acres in 2004 to 318 in 2009.

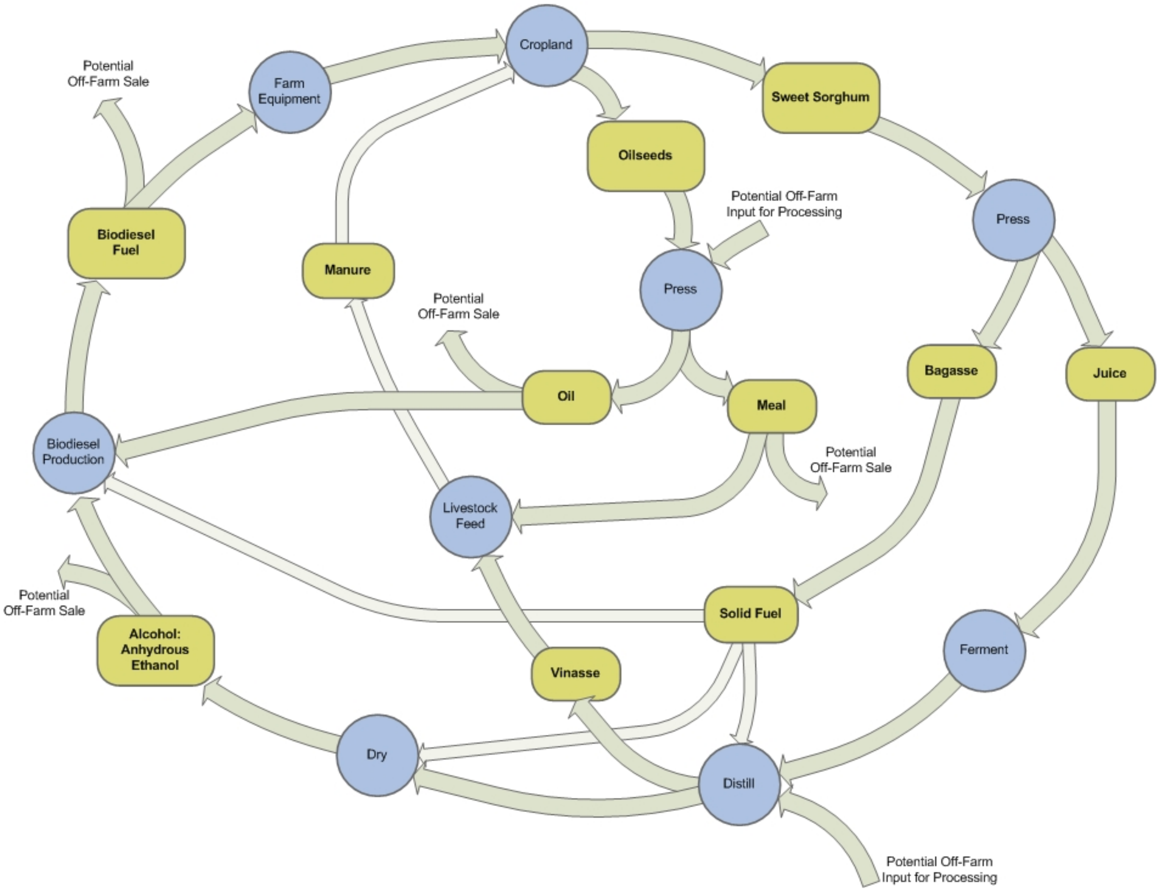

Figure 2 – Overview of Fully Integrated Sweet Sorghum Production at a Small Northeast Farm

Biodiesel production from oilseed crops has relied on imported alcohol (methanol) and lye (potassium hydroxide or sodium hydroxide). These (non-oil) components of the biodiesel process can constitute 47-

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[1] *Darby, H. & Hills, K. 2007 Final Report - Project Title: Oilseed Research and Demonstration Trials (VSJF Grant#04-2007). University of Vermont. 2007.*

67% of the cost per gallon of the fuel and 61% of the embodied energy[2]. Therefore, it becomes clear why farmers in search of fuel self-sufficiency at the farm or cooperative scale are seeking renewable and sustainable substitutes for the alcohol and lye. For some, there is added benefit from the avoidance of costly energy imports and improved price stability when fuel production is local.

As noted in the literature, ethanol for use in biodiesel production also presents an improved personnel and environmental safety situation.

> *"Ethanol will produce a more environmentally benign fuel. The Dangerous Properties of Industrial Materials (Sax, 1975) reports,*
>
> > *The systemic effect of ethyl alcohol differs from that of methyl alcohol. Ethyl alcohol is rapidly oxidized in the body to carbon dioxide and water, and in contrast to methyl alcohol no cumulative effect occurs. Methyl alcohol...once absorbed is only very slowly eliminated. . ..in the body the products formed by its oxidation are formaldehyde and formic acid, both of which are toxic. Because of the slowness with which it is eliminated, methyl alcohol should be regarded as a cumulative poison.*
>
> *Ethanol is also a preferred alcohol in this process compared to methanol because it is derived from agricultural products and is renewable and biologically less objectionable in the environment. Success of rapeseed ethyl ester (REE) production would mean that Biodiesel's two main raw materials would be agriculturally produced, renewable and environmentally friendly.*[3]*"*

The authors also noted that ethyl esters (i.e. biodiesel made using ethanol) demonstrate slightly lower cloud and pour points, slightly higher viscosities, nearly identical heat content, and lower smoke opacity. Ethyl esters are noted, however, to result in higher coking on injectors and have higher glycerol content.

Specific recipes for making biodiesel depend on the free fatty acid content of the feedstock oil. General recipes for the transesterification of vegetable oil to produce biodiesel are based on the volume of oil being processed and use 22.5 vol% methanol with 1.1 wt% potassium hydroxide or 27.8 vol% ethanol with 1.3 wt% potassium hydroxide[4].

State Line Farm has oilseed pressing capacity of approximately 22,300 gallons oil / yr[5] and biodiesel conversion capacity of 27,000 gallon/year[6] which could accommodate approximately 338 acres of oilseed production with average yields. These figures are based on limited assignment of personnel to the processing (5 days x 8 hours) with a limited number of days each year being dedicated to fuel production and are, thus, lower than the maximum 24x7 capacity. Furthermore, the oil press is designed to be expanded in a modular fashion to easily double or triple that capacity.

Applying the generalized biodiesel recipes above to the current production capacity of State Line Farm indicates a need for production of approximately 6,200 gallons/year of anhydrous ethanol to match the capacity of the current biodiesel infrastructure at the farm. This does not include production of surplus anhydrous ethanol for use by others off the farm for their own biodiesel production nor does it account for the potential to distill alcohols for other uses (e.g. consumer beverages). There is no other source of renewable anhydrous ethanol in the region. Therefore, this surplus market could be significant. Assuming methanol pricing at $3.00 / gallon and adjusting the value of ethanol due to the need for more of it, a market price of $2.43 / gallon is indicated.

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[2] *Callahan, C. Feasibility Analysis: Mobile Unit for Processing Oilseed Crops and Producing Biodiesel in Vermont. Vermont Sustainable Jobs Fund. December 2008. Available at http://www.vsjf.org/biofuels/documents/FeasibilityAnalysis_MobileOilseedProcessinginVermont_Dec2008.pdf*

[3] *Peterson C. L., Reece D. L., Hammond B. L., Thompson J., and Beck S.M. Processing, Characterization & Performance of Eight Fuels from Lipids. 1994. Unknown publisher. Material downloaded from ASABE publication database.*

[4] *Peterson C. L., et al. 1994*

[5] *Calculation: Taby 70 Press can press 3 gal/hr of oil from sunflower or canola seed on average. Assuming 24x7 operation with 15% availability of the press (allowing for maintenance, etc.) this equates to 22,300 gal/yr.*

[6] *Calculation: Biodiesel conversion tank is 300 gallons. Three batches are possible in an 8-5 day, and given the other enterprises on the farm active fuel production is limited to 30 days of the year. Thus 27,000 gal/yr is the current capacity. But a maximum capacity of 930,750 gal/yr is possible if run 24x7 with 15% downtime.*

The lye associated with the production capacity above amounts to approximately 1840 lbs (potassium hydroxide, a.k.a. KOH or potash). Renewable sources of lye are discussed below. Commercially available sodium hydroxide and potassium hydroxide generally cost $0.80 / lb and $2.60 / lb in 50 lb bags respectively. Some small scale producers prefer the potassium hydroxide despite the premium cost since it produces a higher quality glycerin that some find easier to handle. Lye made from ashes will be mainly potassium hydroxide since ashes usually have more potassium than sodium.

ETHANOL FEEDSTOCK – WHY SORGHUM?

The development of on-farm alcohol and lye production is a combination of historical research, technology / process development and integration. A century ago both alcohol and lye were produced regularly in most rural communities. With the passing of time, availability of cheap petroleum based fuels and increase in industrialization, these practices have largely ceased.

Recent research has explored various sugar, starch and cellulosic crops as feed stocks for ethanol. Much of this research was tailored specifically for development of ethanol as a gasoline replacement, and was done for large scale operations. As a result there exists some gap between the mainstream research and that needed for sustainable anhydrous (dry) ethanol production as needed to support biodiesel production.

Sweet sorghum shows promise for small to mid-size farms as a directly fermentable sugar crop. The crop grows well in Vermont on marginal soil with little supplemental nutrients and is drought tolerant. It also can be easily pressed for a sugar-rich juice that is directly fermentable without enzyme-based conversion of cellulose or starch. Recent research into small scale sweet sorghum production for ethanol has identified several areas needing resolution including decentralized juice extraction, yeast development, early fermentation, and small scale distillation[7]. As identified by researchers at Oklahoma State University, the processing of sorghum on a small or mid-sized farm requires a different design than large scale fermentation and distillation centers, but remains an attractive option for a local renewable fuel feedstock[8]. The *vinasse* left over from the fermented beer once the alcohol is distilled has also been identified as a residue with significant feed value[9] and could represent another value stream for the operation. Additionally, the cellulosic matter left after pressing juice from sweet sorghum, known as bagasse, has fuel value. Once burned, the ash from bagasse can also be used to produce potash for use as lye in biodiesel production. This benefit will be discussed in more detail below.

Being a dedicated energy crop that is directly fermentable and has secondary value streams (vinasse and bagasse), is what distinguishes sweet sorghum from other candidate ethanol crops. Its ability to grow on marginal land with minimal inputs is a significant factor that further differentiates it from other energy crops.

AGRONOMY

Sweet sorghum is a specific variety of sorghum which grows relatively tall (approx. 8-12') and with a high sugar content (14-20 Brix). The grain is similar to sugar cane in appearance but requires less nutrient input for the same yield[10,11].

Double cropping trials in Nebraska have resulted in yields of 400-800 gallons of ethanol per acre from sweet sorghum juice[12]. Production costs are estimated at $150/acre by the same researchers[13].

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[7] *Bellmer, D. Small-Scale Conversion of Ethanol from Sweet Sorghum. Oklahoma State University. September 2008.*
[8] *Bellmer, D. In-Field Production of Ethanol from Sweet Sorghum. Oklahoma State University. November 2008.*
[9] *Hidalgo, K. Vinasse in Feed: Good for Animal and Environment. Feed Tech, 13(5):18-20. 2009.*
[10] *ATTRA – Sorghum Syrup. March 2003.*
[11] *Bitzer, M. Sweet Sorghum Varieties and Overview of Sweet Sorghum Ethanol Projects Worldwide. Presentation at the Sweet Sorghum Ethanol Association Conference. Feb 23-24, 2007.*
[12] *Dweikat, I. Sweet Sorghum Research. Topic Page from www.agronomy.unl.edu.*
[13] *Grooms, L. Sweet Energy Crop; Sweet Sorghum Biomass and Stem Juice to Produce Ethanol. BFJ. March/April 2008. p. 38.*

John Williamson and Alan Baker, conducted a sweet sorghum field and fermentation trial as part of this project in order to better understand and document the production of the crop in Vermont. This was done as a single crop and single harvest.

Figure 3 – Sweet Sorghum. Images from http://thefraserdomain.typepad.com/energy/2007/06/biofuels_from_s.html and http://www.agronomy.unl.edu/newfacultystaff/research/sweetsorghum.html

The sorghum was planted in mid May 2009 and was harvested between October 8 and November 11, 2009. The majority of the harvest was on October 14, 2009 with later harvests done only to test the impact of harvest date on sugar content (which proved inconclusive).

Three varieties were grown; Sugar Drip, Umbrella, and Della. They were seeded at variable rates in 36" rows with resulting plant densities of 14714, 24587, and 32138 plants / acre respectively. John notes the seed cost as $5/pound seeded on average with 1 pound/acre ($5/acre).

The field was fertilized only with a small amount of manure (stalks can grow too tall if the field is over fertilized). Sorghum is a unique energy crop that requires very little nutrient input.

Field preparation included plowing and disking in a fashion similar to that used for corn field prep. The production cost of sorghum at State Line Farm is not completely understood. However, one can apply published field preparation rates and costs (including tractor overhead, implement overhead, fuel and lube and labor)[14]. Plowing is typically done with a moldboard plow at a rate of 4.1 acres/hr with a cost of $21.30/acre. Disking is done at a rate of 6 acre/hr with a cost of $11.70/acre. Planting is done at a rate of 7.6 acres/hr and a cost of $11.70/acre. The crop is generally cultivated three times with each cultivation done at a rate of 9.1 acres/hr and a cost of $8.60/acre.

John generally harvests his crop by hand at a rate of 0.125 acres/hr. He notes that mechanized harvesting is possible with a corn chopper at an estimated rate of 2.0 acre/hr.[15]

Juice extraction is done with an antique roller mill at State Line Farm. To date, no better system has been found at a reasonable price and with reasonable energy efficiency. The current mill is driven by a tractor PTO and is manually fed stalks or billets of sweet sorghum. Pressing can be done at a rate of 60 gallons/hr with one attendant.

Production costs based on these assumptions total either $212.00/acre (manual harvest) or $114.50/acre (mechanized harvest) and are summarized in Table 1.

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[14] *University of Illinois. Farm Business Management Handbook. Machinery Cost Estimates: Field Operations. April 2005.*

[15] *Email correspondence and conversation with John Williamson – manual harvest is 8 hours per acre, mechanized is 0.5 hours per acre.*

Estimated Costs and Fuel Use During Production
Sweet Sorghum in Shaftsbury, VT
(end product is juice)

	Manual cost per acre	Man. Fuel Use gal/acre	Mechanized cost per acre	Mech. Fuel Use gal/acre
Seed	$ 5.00	0.00	$ 5.00	0.00
Fertilizer	$ -	0.00	$ -	0.00
Plowing	$ 21.30	2.60	$ 21.30	2.60
Disking	$ 11.70	1.30	$ 11.70	1.30
Planting	$ 11.70	0.80	$ 11.70	0.80
Cultivation	$ 25.80	0.90	$ 25.80	0.90
Harvest				
Manual	$ 104.00	1.00		
Mechanized			$ 6.50	2.00
Pressing	$ 32.50	1.00	$ 32.50	1.00
Total	**$ 212.00**	**7.60**	**$ 114.50**	**8.60**

Table 1 – Estimated costs of production for sweet sorghum juice at State Line Farm in Shaftsbury, VT. The fuel use noted is factored into an estimate of energy return on energy investment in Table 5.

On October 14, 2009 25 foot sections of each variety were harvested while noting the number of plants, number of tillers (secondary shoots), and number of lodged (fallen) plants. The green weight of the harvest was also measured. Each variety was pressed separately using a roller mill and the resulting volume of juice extracted was measured along with the sugar content (Brix). A sample of 700 mL from each variety's juice was put into a one quart canning jar and one teaspoon of Fleischman's bread yeast was added. A hole was drilled through the lid of each caning jar with an airlock was inserted, sealed with silicone, and filled with water.

The samples were allowed to ferment for 35 days which the team believes is not complete fermentation. The team plans to remeasure the alcohol content of the samples which have been allowed to continue fermentation.

This year's trial demonstrated yields of 1,714 gallons juice / acre on average. Sugar content measured in Brix using a refractometer ranged from 15.2-16.7 with an average of 16.0, indicating potential alcohol content in fermented juice of 8.1-9.0 %vol with an average of 8.6 %vol and average alcohol yields of 148 gal/acre (and a range of 107-185 gal/acre). More detailed data is provided in Table 3.

These results translate to a sugar cost of $0.03 per lb[16], which is 50% of the target cost of $0.06 per lb established by the Northeast region of the Sun Grant Initiative[17]. The potential alcohol cost based on these production data (and not including distillation costs) is $0.78 per gallon (including distillation labor @ $15/hr).

Others have demonstrated the ability to densify sweet sorghum's energy content by extracting juice as a continuous, in-field, process which minimizes transport costs.[18] [see variation in Figure 4].

Although the energy requirements for distillation at State Line have not been determined, examples from literature note an energy input of 18,000 BTU/gallon for distillation of anhydrous ethanol from an 8% alcohol beer[19]. Assuming fuel is purchased at $33 per million BTU (e.g. biodiesel at $4.00 per gallon and 120,000 BTU/gal), the variable cost of alcohol coming off the still is $1.57 per gallon. Capital amortization

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[16] *Calculation of sugar cost: Assuming 1714 gal juice / acre with production cost of $114.50/acre, SG of juice = 1.055 (8.8 lb/gal) and Brix of 16.0 (21 %wt sugar). $114.50 / 1714 gal juice / acre = $0.067 / gal juice = $0.0068 / lb juice. $0.0068 / lb juice / 0.21 (sugar wt %) = $0.03 / lb sugar.*

[17] *Sun Grant Northeast Region. A Strategic Road Map for the Northeast Region of the Sun Grant Research Initiative: Research, Education and Outreach Priorities. Biobased Energy and Product Technologies Fueling America's Future. July 2004.*

[18] *Bellmer, D. In-Field Production of Ethanol from Sweet Sorghum. Oklahoma State University. November 2008.*

[19] *Stampe, S. et al. Energy Consumption of a Farm-Scale Ethanol Distillation System. Energy in Agriculture. V2 1983 pp 355-368.*

of an estimated facility & equipment cost of $300,000 over 30 years would add another $1.61 per gallon at an estimated production of 6,200 gallons/yr. Cost of capital when fully financed over 7 years at 5% adds $2.88 per gallon.

Thus, an estimated of cost of production for ethanol from sweet sorghum at a volume of 6,200 gallons per year is $6.07 per gallon. Although this cost is above the likely retail cost of ethanol, it is important to note that this volume is relatively low (2 full weeks of operation at 75 gal / hr). It is likely that such a facility would distill more alcohol than this which would reduce the fixed costs per gallon. Scenarios exploring this and other alternative modes of operation are provided in Table 6.

Bagasse can likely be used to fuel the distillation, and it is expected that this residue can be collected similarly to baled hay. Assuming a cost of $8.00 per large, round, 900 lb bale and a dry fuel value of 7,162 BTU/lb of bagasse, the energy cost of using bagasse is approximately $1.24 per million BTU. Which, when combined with other changes in agronomic production, facility cost and operation can result in significant cost reductions. For example, assuming cost of production of $110/acre with yield of 2000 gal juice/acre, fueling the still with bagasse, production volume of 20,000 gal/yr and capital investment of $200,000 to cost drops to $1.82 per gallon, below the retail level.

Consider one acre of sweet sorghum. Assume the total alcohol yield from this acre is 148 gal/acre and requires 18,000 BTU/gal to distill it. Thus for the one acre's equivalent of ethanol (148 gal) 2.7 million BTU of energy are required for distillation. The estimated dry bagasse bi-product from the same acre is 3.2 tons / acre with a fuel value of 7,162 BTU/lb (dry) with a resulting overall energy content of 45.6 million BTU/acre. This indicates an energy surplus in the form of dry bagasse of 42.9 million BTU/acre.

Variable Costs		**Example**	
Crop production cost	$	114.50	/acre
Juice yield		1714	gal/acre
Juice cost	$	0.07	/gal
Alcohol conversion		8.6	% in beer
Alc yield		148	gal/acre
Alc sub cost	$	0.78	/gal
Fermentation & distillation energy		18,000	BTU/gal
Energy cost	$	33.00	/million BTU
Alc conversion cost	$	0.59	/gal
Production rate		75	gal/hr
Labor rate	$	15.00	/hr
Labor cost	$	0.20	/gal
Total Variable Cost (production, conversion, labor)	**$**	**1.57**	**/gal**
Fixed Costs			
Annual Production		6,200	gallons /yr
Capital investment	$	300,000	
Life of investment		30	years
Annual capital ammortization	$	10,000	/year
Loan interest rate		5.0%	
Loan term		7	years
Cost of capital	$	17,916	/year
Total Fixed Costs	**$**	**4.50**	**/gal**
Breakeven cost	**$**	**6.07**	**/gal**

Table 2 – Cost per Gallon for Ethanol Derived from Sweet Sorghum at a crop production cost of 114.50/acre, yield of 1714 gal juice/acre production of 6,200 gal/yr (to match State Line's biodiesel production capacity). This cost includes capital amortization and cost of capital ($4.50/gal combined). Variable costs are estimated at $1.57/gal. Additional production scenarios are explored in Table 6

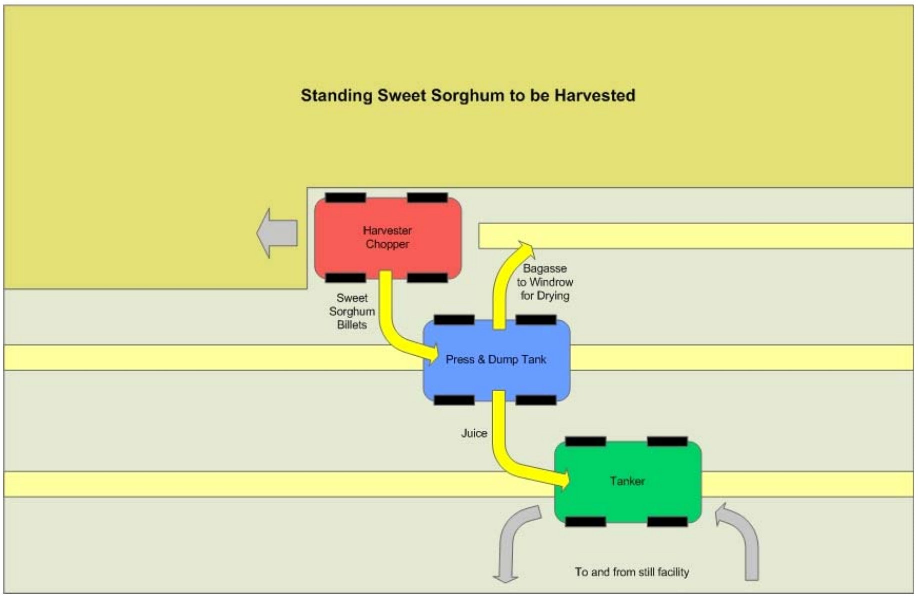

Figure 4 – Sweet Sorghum Harvesting Concept – In-field Pressing and Bagasse Windrowing for Later Bailing and Wagon Transport

The amount of lye needed to match the production capacity above amounts to approximately 1,840 lbs (potassium hydroxide, a.k.a. KOH or potash). Wood generally contains about 0.5% ash (once burned), and within this ash is 0.05% potash (lye)[20]. Therefore, for hardwoods weighing an average of 3,800 lbs/cord ashes from about 970 cord of wood would be required to produce 1,840 lbs of potash. This equates to about 970 acres of woodland being required at a relatively low wood harvest rate of 1 cord/acre/yr (with a resulting KOH yield of 1.9 lbs/acre or 1.9 lbs/cord).

Alternatively, as noted above, the bagasse left over from sweet sorghum harvesting also has fuel value and could serve as an integrated ash source for lye production. Green weight measured during the 2009 harvest of sweet sorghum at State Line indicates an average of 14.4 tons/acre with average pressed juice weight of 7.5 tons/acre. Thus, residual wet bagasse yields of 6.9 tons/acre are expected at 54% moisture indicating a dry bagasse yield of 3.2 tons/acre. The estimated fuel value is 7,162 BTU/lb of dry bagasse or 45.6 million BTU/acre.

A chemical analysis of sweet sorghum bagasse indicates that the ash content is 5.9% dry weight with 5% of that ash being water soluble potassium[21]. Thus, an estimated 18.8 lbs/acre of potassium hydroxide could be expected if sweet sorghum bagasse ash is used.

Consider one acre of sweet sorghum being converted to 148 gal of anhydrous ethanol. This can support the production of 532 gal of biodiesel which will also require 44 lbs of potassium hydroxide. Unfortunately, there is not a potassium balance from sweet sorghum bagasse ash alone to support biodiesel conversion on an acre by acre basis. The balance of potassium hydroxide (44 – 18.8 = 25.2 lbs / acre) will have to come from another source. For example, from the ashes from burning 13.3 cord of firewood (per acre of sweet sorghum).

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[20] *Nikitin, N. I. The Chemistry of Cellulose and Wood. Translated from Russianby J. Schmorak. Israel Program for Scientific Translation. Jerusalem. 1966.*
[21] *ECN. Phyllis Database of Biomass. "Organic Residue / Product: Bagasse, Sweet Sorghum". Downloaded January, 2010.*

Figure 5 – John Williamson and Alan Baker test fermented sweet sorghum beer for alcohol content at State Line Farm in Shaftsbury, VT.

Sorghum Field Trial - State Line Farm - Shaftsbury, VT - Fall 2009

	Crop Data (10/14/2009)				Juice Data (10/14/2009)						
Variety and replication	**Plants per 25'**	**Lodged per 25'**	**Tillers per 25'**	**Green weight lbs.**	**Juice**		**Specific Gravity**	**Brix** (by Refractometer)	**Sugar (%wt)**	**Potential Alcohol** (% vol)	**Potential Alcohol** (gal/acre)
					Liters	**Gallons**					
Sugar Drip 1	24	1	100	N/A	16.0	4.2	1.065	16.0	21%	8.6%	211
Sugar Drip 2	27	1	100	68	15.8	4.2	1.060	16.0	21%	8.6%	209
Sugar Drip 3	25	4	64	40	10.2	2.7	1.050	16.0	21%	8.6%	135
Sugar Drip average	*25*	*2*	*88*	*54*	*14.0*	3.7	*1.058*	*16.0*	*21%*	*8.6%*	*185*
Sugar Drip average/acre*	***14,714***	***1,162***	***51,110***	***31,363***	***8,141***	***2,151***	***1.058***	***16.0***	***21%***	***8.6%***	***185***
Umbrella 1	37	0	54	34	6.9	1.8	1.054	16.5	22%	8.9%	94
Umbrella 2	46	4	83	63	14.1	3.7	1.066	17.0	23%	9.2%	199
Umbrella 3	44	7	83	55	11.8	3.1	1.054	16.5	22%	8.9%	161
Umbrella average	*42*	*4*	*73*	*51*	*10.9*	2.9	*1.058*	*16.7*	*22%*	*9.0%*	*151*
Umbrella ave/acre*	***24,587***	***2,130***	***42,592***	***29,427***	***6,348***	***1,677***	***1.058***	***16.7***	***22%***	***9.0%***	***151***
Della 1	53	0	98	41	7.5	2.0	1.044	15.0	20%	8.0%	92
Della 2	45	0	83	38	7.3	1.9	1.046	15.2	20%	8.1%	91
Della 3	68	1	104	54	10.8	2.9	1.054	15.5	21%	8.3%	138
Della average	*55*	*0*	*95*	*44*	*8.6*	2.3	*1.048*	*15.2*	*20%*	*8.1%*	*107*
Della ave/acre*	***32,138***	***194***	***55,176***	***25,749***	***4,976***	***1,315***	***1.048***	***15.2***	***20%***	***8.1%***	***107***
Overall Average	***23,813***	***1,162***	***49,626***	***28,846***	***6,488***	***1,714***	***1.055***	***16.0***	***21%***	***8.6%***	***148***

NOTES:

* Calculation for average/acre: Test plots were 25' x 3' = 75 ft^2. One acre = 43,560 ft^2. Each plot is approximatley 1 / 580.8 acre. Plot result x 580.8 = avg / acre
On 10/14/09 700ml of each sample was put into a one quart canning jar and one teaspoon of Fleischmans bread yeast was added. A hole was drilled through the lid of each caning jar, an airlock was inserted and sealed with silicone. All readings taken at a temperture 60 degF.

(1) Sugar Drip 2 and 3 had off colors and smelled similar to silage when fermented.
(2) Della 1 smell similar to buytric acid when fermented. This was excluded from fermentation data averages.
(3) All samples tested with maple sap hydrometer registered less than one except Della 1 which was at 5 %
(4) 11/19 readings taken at 70° F

Table 3 – Summary of 2009 Sweet Sorghum field trial at State Line Farm in Shaftsbury, VT. Both specific gravity and Brix were directly measured on the juice as precursors to determining sugar content and potential alcohol in the juice. Specific gravity was measured with a beer and wine making hydrometer. Brix was measured with a refractometer. The sugar content and potential alcohol noted above are based on conversion from the measured Brix since the team noted particulate in the unstrained juice and consider the refractometer measurement of Brix to be more accurate than the specific gravity measurement. Sugar content can be derived from measurement of either specific gravity or Brix as noted in Figure 6. Potential alcohol can be determined by a number of generally accepted formulae relating it to Brix and/or specific gravity. The data presented above uses the formula generally accepted for use by home brewers; Potential Alcohol = 0.6xBrix-1.0.

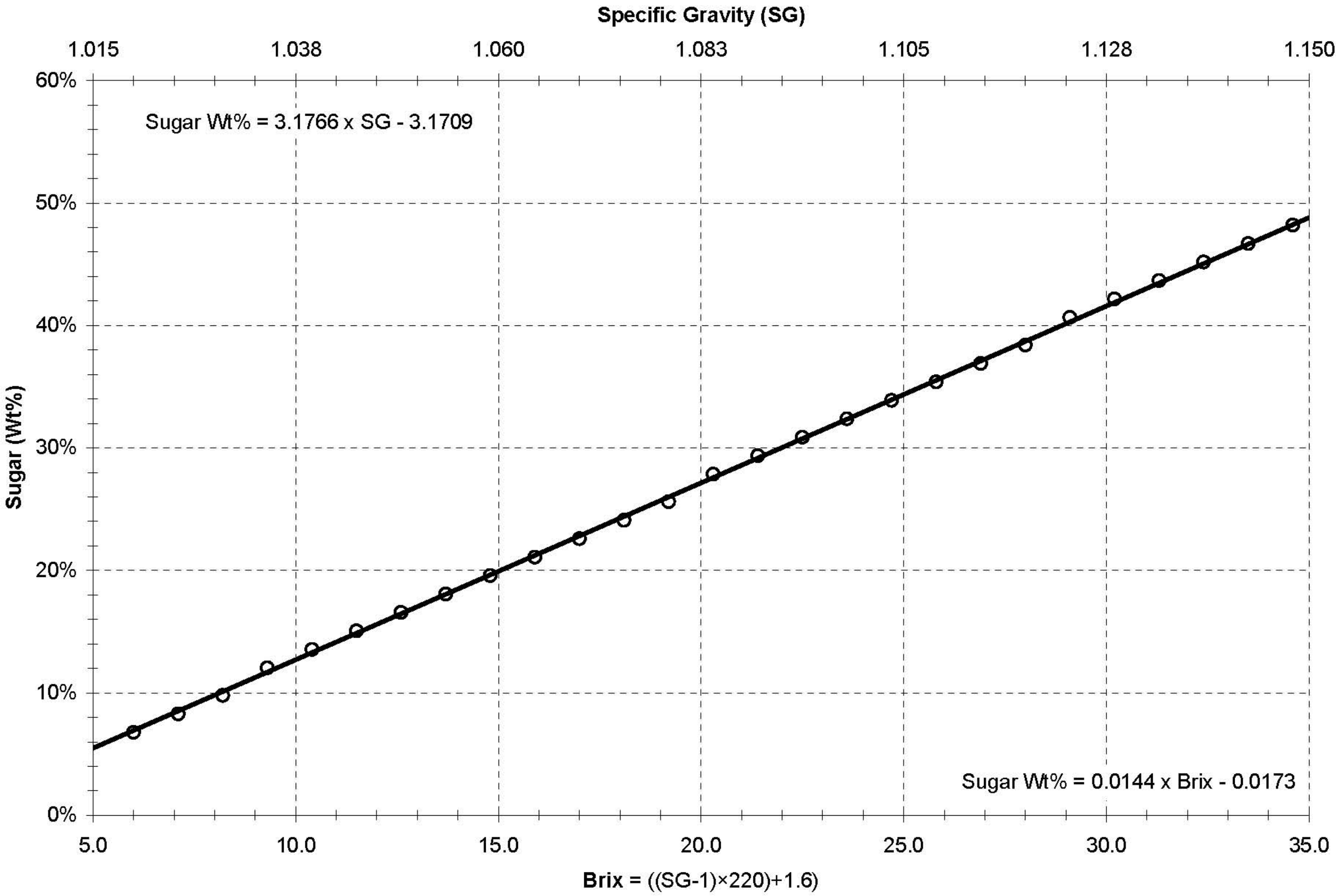

Figure 6 – Sugar content can be derived from measurement of either specific gravity or Brix as noted in the chart. Potential alcohol can be determined by a number of generally accepted formulae relating it to Brix and/or specific gravity. The data presented in Table 3 uses the formula generally accepted for use by home brewers; Potential Alcohol = 0.6xBrix-1.0.

Estimate of Sweet Sorghum Bagasse Energy & KOH Content

	Green Weight		Juice				Sugar	Wet Bagasse		Dry Bagasse		Bagasse Heating Value (Dry)	Ash	KOH	
	lbs/acre	tons/acre	gal/acre	specific gravity (SG)	lbs/acre	tons/acre	lbs/acre	lbs/acre	tons/acre	lbs/acre	tons/acre	mill BTU / acre	lbs/acre	lbs/acre	lbs/ton dry bagasse
Averages per acre				*water ref* *8.3* *lbs/gal*				*54%* *moisture*				*BTU/lb* *7162* *mill BTU/ton* *14.3*	*% dry of dry matter* *5.9%*	*% dry mass of ash* *5%*	
Sugar Drip	31,363	15.7	2,151	1.058	18,893	9.4	4,026	12,470	6.2	5,736	2.9	41.1	338	16.9	5.9
Umbrella	29,427	14.7	1,677	1.058	14,728	7.4	3,280	14,699	7.3	6,762	3.4	48.4	399	19.9	5.9
Della	25,749	12.9	1,315	1.048	11,434	5.7	2,310	14,314	7.2	6,585	3.3	47.2	388	19.4	5.9
Overall Average	**28,846**	**14.4**	**1,714**	**1.055**	**15,007**	**7.5**	**3,205**	**13,828**	**6.9**	**6,361**	**3.2**	**45.6**	**375**	**18.8**	**5.9**

Table 4 – Summary calculation to estimate the amount of bagasse, its energy content and the amount of KOH which can be derived from it. Bagasse is a byproduct of pressing juice from sweet sorghum. Elemental, biochemical and ash composition assumptions are based on analysis from reference 8.

PLANT COST ESTIMATES

A budgetary estimate was developed to understand the cost of a reasonably sized anhydrous still if constructed from all new materials. The capital cost of a new anhydrous ethanol plant with 75 gal/hr capacity is approximately $1.0 million based on a recent USDA feasibility study of sugar based ethanol production[22]. The project team has identified a mothballed still with this capacity which has been valued at $80,000.

COST/BENEFIT ANALYSIS and PROFORMA

Table 6 summarizes a number of cost / benefit & payback scenarios. This spreadsheet is setup to accommodate changes to any figure in blue. The scenarios demonstrate the importance of production costs, yield, energy cost and capital expenditures on the per gallon cost of ethanol and the resulting payback period. It is important to note that if the cost of production is too high and yield is too low, the venture does not make financial sense (Scenario C). However, with reasonable costs of production, reasonable yields, reducing energy costs by using bagasse, and minimizing capital expenditures the payback can be reduced to 16 years (Scenario F). The other scenarios result in payback periods somewhere in between these extremes and represent intermediate variance of the assumptions.

In addition to financial payback, the team also reviewed energy return on energy invested for production of ethanol from sweet sorghum (all field operations, harvest, pressing and distillation). Two scenarios were considered; (1) mechanized harvest with biodiesel fueled distillation and (2) mechanized harvest with bagasse fueled distillation. The latter includes the energy cost associated with bagasse harvest.

Energy Return on Energy Investment (EROEI)

	gal BD / gal EtOH		**EROEI**	
	Component	Cumulative	Component	Cumulative
Sweet Sorghum Juice Production	0.0580	0.0580	17.2	17.2
Distillation				
Using Biodiesel as Fuel	0.1500	0.2080	6.7	4.8
Using Bagasse as Fuel	0.0020	0.0600	500.0	16.7

Table 5 – Summary of Energy Return on Energy Investment associated with two scenarios of sweet sorghum based anhydrous (dry) ethanol production. Both show positive returns, but the advantage of using bagasse for distillation energy is clear.

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[22] *The Economic Feasibility of Ethanol Production From Sugar In The United States. July 2006.http://www.usda.gov/oce/reports/energy/EthanolSugarFeasibilityReport3.pdf.*

Sweet Sorghum Ethanol Per Gallon Cost, Breakeven and Simple Payback Proforma

Variable Costs	**Example**		**Scenarios**										
			A	B	C	D	E	F	G	H	I	J	
Crop production cost	$ 114.50	/acre	$ **150**	$ **120**	$ **100**	$ **100**	$ **150**	$ **100**	$ **110**	$ **110**	$ **110**	$ **110**	/acre
Juice yield	1714	gal/acre	**2000**	1700	1700	**2000**	**1500**	**2000**	**1500**	**1700**	**1700**	**2000**	gal/acre
Juice cost	$ 0.07	/gal	$ 0.08	$ 0.07	$ 0.06	$ 0.05	$ 0.10	$ 0.05	$ 0.07	$ 0.06	$ 0.06	$ 0.06	/gal
Alcohol conversion	8.6	% in beer	8.6	8.6	8.6	8.6	8.6	8.6	8.6	8.6	8.6	8.6	% in beer
Alc yield	148	gal/acre	172.2	146.37	146.37	172.2	129.15	172.2	129.15	146.37	146.37	172.2	gal/acre
Alc sub cost	$ 0.78	/gal	$ 0.87	$ 0.82	$ 0.68	$ 0.58	$ 1.16	$ 0.58	$ 0.85	$ 0.75	$ 0.75	$ 0.64	/gal
Fermentation & distillation energy	18,000	BTU/gal	18,000	18,000	18,000	18,000	18,000	18,000	18,000	18,000	18,000	18,000	BTU/gal
Energy cost	$ 33.00	/million BTU	$ 33.00	$ 33.00	$ 33.00	$ 33.00	$ **2.54**	$ **2.54**	$ **2.54**	$ **2.54**	$ **2.54**	$ **2.54**	/million BTU
Alc conversion cost	$ 0.59	/gal	$ 0.59	$ 0.59	$ 0.59	$ 0.59	$ 0.05	$ 0.05	$ 0.05	$ 0.05	$ 0.05	$ 0.05	/gal
Production rate	75	gal/hr	75	75	75	75	75	75	75	75	75	75	gal/hr
Labor rate	$ 15.00	/hr	$ 15.00	$ 15.00	$ 15.00	$ 15.00	$ 15.00	$ 15.00	$ 15.00	$ 15.00	$ 15.00	$ 15.00	/hr
Labor cost	$ 0.20	/gal	$ 0.20	$ 0.20	$ 0.20	$ 0.20	$ 0.20	$ 0.20	$ 0.20	$ 0.20	$ 0.20	$ 0.20	/gal
Total Variable Cost (production, conversion, labor)	**$ 1.57**	**/gal**	**$ 1.67**	**$ 1.61**	**$ 1.48**	**$ 1.37**	**$ 1.41**	**$ 0.83**	**$ 1.10**	**$ 1.00**	**$ 1.00**	**$ 0.88**	**/gal**
Fixed Costs													
Annual Production	6,200	gallons /yr	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	10,000	gallons /yr
Capital investment	$ 300,000		$ 300,000	$ 300,000	$ 300,000	$ 300,000	$ 300,000	$ 300,000	$ 300,000	$ **200,000**	$ **200,000**	$ **200,000**	
Life of investment	30	years	30	30	30	30	30	30	30	30	30	30	years
Annual capital ammortization	$ 10,000	/year	$ 10,000	$ 10,000	$ 10,000	$ 10,000	$ 10,000	$ 10,000	$ 10,000	$ 6,667	$ 6,667	$ 6,667	/year
Loan interest rate	5.0%		5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%	
Loan term	7	years	7	7	7	7	7	7	7	7	7	7	years
Cost of capital	$ 17,916	/year	$ 17,916	$ 17,916	$ 17,916	$ 17,916	$ 17,916	$ 17,916	$ 17,916	$ 11,944	$ 11,944	$ 11,944	/year
Total Fixed Costs	**$ 4.50**	**/gal**	**$ 2.79**	**$ 2.79**	**$ 2.79**	**$ 2.79**	**$ 2.79**	**$ 2.79**	**$ 2.79**	**$ 1.86**	**$ 1.86**	**$ 1.86**	**/gal**
Breakeven cost	**$ 6.07**	**/gal**	**$ 4.46**	**$ 4.41**	**$ 4.27**	**$ 4.17**	**$ 4.20**	**$ 3.62**	**$ 3.89**	**$ 2.86**	**$ 2.86**	**$ 2.75**	**/gal**
Retail price assumption (value)	$ 3.00	/gal	$ 3.00	$ 3.00	$ 3.00	$ 3.00	$ 3.00	$ 3.00	$ 3.00	$ 3.00	$ **4.00**	$ **4.00**	/gal
Simple Payback Gallons	**-97,643**	**gallons**	**-205,950**	**-213,459**	**-236,447**	**-257,223**	**-250,262**	**-485,419**	**-337,448**	**1,411,388**	**175,177**	**159,435**	**gallons**
Simple Payback Period	**-16**	**years**	**-21**	**-21**	**-24**	**-26**	**-25**	**-49**	**-34**	**141**	**18**	**16**	**years**

Table 6 – Summary calculation of per gallon costs of ethanol from sweet sorghum. This is a spreadsheet that can be adjusted based on different assumptions. The "Example" column is based on 2009 field trial data, production of only enough ethanol to support State Line biodiesel production, and a capital investment of $300k. The right hand columns illustrate several potential scenarios of high and low costs of production together with high and low yields. The cases become progressively more attractive going from left to right. Most significant are far right columns (scenarios H-J) which show the impact of ethanol cost, production volume and retail price on payback when associated with fueling the ethanol using sweet sorghum bagasse. This approach reduces the energy cost to $1.24 per million BTU from $33.00 per million BTU using fuel oil ($8.00 per 900 lb bale (dry) and 7,162 BTU/lb dry bagasse). Scenarios G-J also assume a relatively low capital investment which would require identification of a low cost biomass steam boiler.

CONCLUSIONS

Based on the research and field trials summarized above, we can draw the following conclusions:

1. Sweet sorghum based anhydrous (dry) ethanol appears promising in Vermont as a sustainable source of alcohol and lye to be used in the conversion of vegetable oil to biodiesel. The crop is grown with limited inputs on marginal land and yields both juice and *bagasse* (the byproduct of juice extraction). Together with oilseed crops, sweet sorghum makes an excellent companion in an integrated model of small-scale biodiesel production.
2. The production of sweet sorghum has been demonstrated in southern Vermont with average yields of 1714 gallons of juice / acre (range 1315-2151) with average Brix sugar measurements of 16.0 (range 15.2-16.7). These data correspond to an average alcohol yield of 148 gal/acre (range 107-185) at an estimated production cost of $212.00/acre with manual harvest methods. Mechanization of harvest is projected to reduce this cost to $114.50/acre.
3. Sweet sorghum bagasse (byproduct of pressing juice from the cane) represents a significant fuel crop with an estimated fuel value of 45.6 million BTU/acre which can be harvested at an estimated cost of $1.24 / million BTU (vs. $33.00 / million BTU for biodiesel @ $4.00 / gal.) On a per-acre basis there is a large surplus of energy from bagasse when compared to that required for distillation of the ethanol.
4. Sweet sorghum bagasse also represents a source of potassium hydroxide (KOH) for use in the biodiesel conversion process. The team estimates that 18.8 lbs (43%) of the 44 lbs KOH required for the 532 gal biodiesel production supported by 148 gal sweet sorghum ethanol can be provided from the associated bagasse.
5. Investment of $200,000 in an anhydrous still for production of ethanol from sweet sorghum shows the potential for a 17 year payback when run at a capacity of 10,000 gal/yr assuming a retail value of anhydrous ethanol of $3.00/gal. This is reduced to 9 years if a retail price of $4.00 per gallon is assumed.
6. The estimated breakeven cost per gallon of ethanol produced at a rate of 6,200 gal/yr and with sweet sorghum juice produced at 1714 gal/acre and a cost of $114.50 / acre is $6.07/gal. This cost includes crop production costs, ethanol production costs, labor, fixed asset amortization and cost of capital. The assumptions resulting in this breakeven price match demonstrated crop production from State Line Farm in 2009 and assume a $300,000 capital investment in a distillation facility fueled by biodiesel. The breakeven cost is reduced to $5.50 per gallon if bagasse is used as the fuel. This indicates a need for greater volume of production and lower capital costs in order to compete with retail pricing of $3.00-4.00 per gallon.

RECOMMENDATIONS and NEXT STEPS

One of the key issues identified by this project was the synergy between sweet sorghum bagasse, the energy required for distillation and the potassium hydroxide required for biodiesel production. While this synergy has been discussed above, more detailed research is required to fully assess the logistics and energy balance associated with this model.

To this end, the research team is pursuing a Northeast Sun Grant to support the further development of a sustainable anhydrous ethanol production plant at State Line Farm. The following scope of work has been identified.

1. Determine best practices for use of ethanol and potash lye in small scale biodiesel production
2. Determine the most regionally appropriate sugar crops to serve as feedstock for farm-based ethanol production
3. Evaluate harvesting, handling, pressing and storage technologies for sugar crops
4. Demonstrate farm-scale fermentation of sugars to alcohol
5. Demonstrate farm-scale distillation and production of anhydrous ethanol
6. Demonstrate farm-scale production of potash lye from wood ash
7. Integrate on-farm oilseed, ethanol and lye production into on-farm biodiesel production

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