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An Update on Solid Grass Biomass Fuels in Vermont

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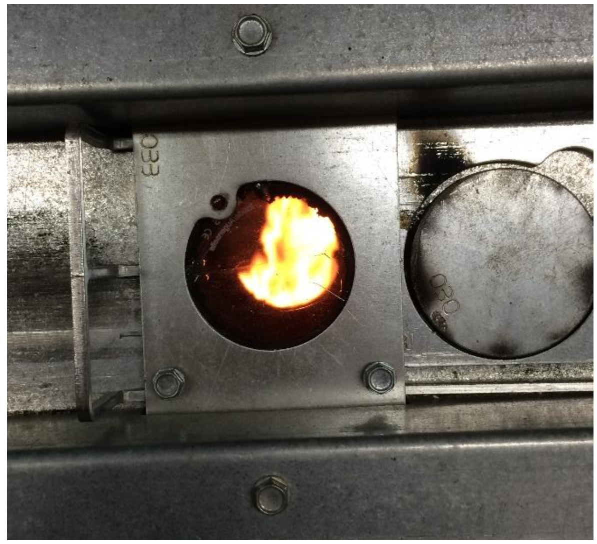

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Meach Cove Farms

Summary

This report documents recent testing involving the densification and combustion of solid, grass biomass fuels in a small commercial boiler (342,100 BTU/hr output rating). Fuel briquettes (or "pucks") were made from Switchgrass, Miscanthus, Reed Canary, Mulch Hay and "Ag Biomass" / Field Residue as well as mixtures of these feedstocks with ground wood chips. Our findings were:

1. On-farm, small scale densification of grass and agricultural biomass solid fuels via pucking is feasible with a conversion (densification) cost of $49-148 per ton and a finished fuel cost in the range of $85-228 per ton ($5.2 – 14.4 per million BTU).
2. Sustained, reliable combustion of densified grass and agricultural biomass solid fuels in a light commercial boiler (EvoWorld HC100 Eco) is feasible with 73-90% combustion efficiency, and with no ash fusion or clinker development. Longer, sustained overnight runs did result in some combustion chamber clogging with ash and fuel residue which may be resolved with further boiler tuning and clean out cycle timing adjustment.
3. The test of the Ag Biomass / Field Residue fuel demonstrated feasibility at a current delivered price of $214 per ton ($13.2 per million BTU) supporting a potential payback period of 3.6 years on the boiler. At higher production volume projects a path to $85 per ton ($5.2 per million BTU) and a potential payback period of 2.4 years.

Background

The use of solid, densified cellulosic biomass fuels has been well demonstrated with wood pellets in residential and light commercial systems and wood chips in larger, often centralized systems. The Grass Energy Partnership of the Vermont Bioenergy Initiative has been exploring an alternative form of fuel; grasses densified in a specially developed processor to take the form of 1.5"-2.0" round cylindrical pucks. Grass fuels may be produced on otherwise marginal agricultural land, sometimes in perennial production and even in buffer strips offering environmental benefit. Additionally, fuel can be made by densifying agricultural residue or biomass harvested from idle pasture or fields. We have referred to this fuel as "Ag Biomass". The testing summarized in this report has demonstrated the technical and economic feasibility of such fuels.

Earlier tests were done using pellets of various feedstocks (mulch hay, reed canary grass, and switch grass) and combinations of feedstocks (mixed with wood) (Sherman, 2011). This testing was done in a Solagen boiler (500,000 BTU/hr) designed for wood pellets. The primary findings of this work confirmed reasonable heating value of the fuels, relatively high ash content of the grass fuels (4.3-6.7%), different combustion air and mixing requirements of the fuel with potential for fusion (clinkers), and relatively high levels of chlorine in the grass fuels which is suspected to accelerate corrosion of internal appliance surfaces. This report also noted that the challenges associated with high ash content and clinker formation could be alleviated with appliance design considerations such as automated ash removal and a moving floor or cleanout cycle. Detailed emissions profiling was also conducted as part of this prior work.

A review of the potential for a grass energy industry in Vermont has also been conducted earlier (Wilson Engineering, 2014). This work focused on assessing several production and marketing models (Closed Loop No Processing, Small Scale On-Farm Processing, Regional Processing, Consumer Pellet Market). The report concluded that Small Scale On-Farm Processing presents the greatest challenges and that Closed Loop No Processing would be the easiest to implement.

The work covered by the current report has demonstrated:

1. On-farm, small scale densification of grass and agricultural biomass solid fuels via pucking is feasible with a conversion (densification) cost of $49-148 per ton and a finished fuel cost in the range of $85-228 per ton ($5.2 – 14.4 per million BTU).
2. Sustained, reliable combustion of densified grass and agricultural biomass solid fuels in a light commercial boiler (EvoWorld HC100 Eco) is feasible with 73-90% combustion efficiency, and with no ash fusion or clinker development. Longer, sustained overnight runs did result in some combustion chamber clogging with ash and fuel residue which may be resolved with further boiler tuning and clean out cycle adjustment.

Methods

The following list of fuels were tested between 10/13 and 11/30/2015:

- 100% Switchgrass 2" Puck
- 50/50% Switchgrass/Wood 2" Puck
- 100% Reed Canary 2" Puck
- 50/50% Reed Canary/Wood 2" Puck
- 100% Miscanthus 2" Puck
- 50/50% Miscanthus/Wood 2" Puck
- 100% Mulch Hay 2" Puck
- 50/50% Mulch Hay/Wood 2" Puck
- 100% "Ag Biomass" Field Residue 2" Puck

The fuel was produced by Renewable Energy Resources (RER) using a custom-made densification machine ("slugger"). RER have built two machines, a smaller unit capable of 700 lb/hr throughput and a larger machine capable of 4,000 lb/hr throughput. Thus far, the main machine used has been the smaller one due to the relatively low volume demand for the fuel from the market. For this testing, fuel was made on the smaller unit in relatively small test batches given the number of different fuels being made.

The feedstock was sourced from Meach Cove Trust (Shelburne, VT), a farm that has been active in research and demonstration of solid biomass fuels from perennial grasses. Meach Cove Trust also hosted the combustion testing of these fuels in their EvoWorld HC100 Eco boiler. This boiler allows a high degree of fuel feed rate and combustion air tuning and also incorporates automated combustion floor cleaning and ash removal. Due to schedule and budget limitations, the combustion testing was also combined with basic tuning. This tuning mainly focused on fuel feed rates and combustion air settings with the goal of minimizing carbon monoxide (CO) and smoke number and maximizing combustion efficiency.

Each feedstock and feedstock combination (i.e. mixes with wood) noted in the list above was densified in batches of approximately 700 lbs by RER and stored in ½ ton sling bags with an average of 14 %wt moisture content.

The fuels were measured into 5 gal buckets, weighed and fed to the boiler via the primary feed auger during a timed combustion test lasting generally one hour. During the combustion testing, the heat distribution system was isolated and depowered so that only the water contained in the boiler and the storage tank would be heated (aside from heat loss). At the start of each test, the temperature of the boiler and the top and bottom of the hot water storage tank were noted. Heat was removed from the hot water storage tank as needed to allow for a full test run using a hydronic unit heater and forcing a call for heat. By measuring the temperature change of the boiler and tank water volume and the amount of fuel fed to the boiler over a measured period of time the input and output heat rates were determined allowing an estimate of gross thermal efficiency. A combustion analyzer (Wöhler A500) was used to measure exhaust oxygen (O_2, %), carbon monoxide (CO, PPM), nitrogen oxide (NO, PPM), sulfur dioxide (SO_2, PPM), and stack temperature (°F). Carbon dioxide (CO_2, %) is calculated by the combustion analyzer based on the fuel used and the measurement of oxygen. Additionally, smoke number was obtained using a standard hand pump and filter paper. Smoke numbers were determined by a single observer for consistency.

A sample of each fuel used in this testing was sent for analysis to Twin Ports Testing, Inc. (Superior, WI). The fuels were analyzed for moisture content, ash content, calorific value (heating value), carbon, hydrogen, nitrogen, oxygen, sulfur, SO_2, and chlorine.

Results

Feedstock Densification / Making Fuel Pucks

Fuel production was variably successful. Each fuel could be densified, but the process was not able to be optimized in the time allowed for this test period. Some of the fuels included a high proportion of chaff or loose feedstock and others included very dense and large pucks that were not able to be fed into the boiler. Occasionally smaller, denser pucks were found to block the feed mechanism and result in a shutdown of the boiler. Future work on optimizing the fuel production process (mixing and mix moisture content control, densifier rate/pressure/temperature adjustment), including fuel quality control processes and even filtering or screening fuel as it enters the boiler fuel bin and feed system would likely resolve these issues.

Combustion Tests

Each of the fuels made were successfully combusted. There were no fuel mixes that did not combust and heat the water system successfully. The following observations were made during these tests.

- No “clinkers” or blocks of fused ash and fuel were observed during this testing. The boiler cleaning system successfully cleared ash and residual fuel between tests.
- Combustion efficiency was in the range of 73-90%. This is a measure of how well the boiler converts fuel energy into hot water, i.e. how much energy is removed from the combustion products vs. how much fuel was burned. Data in Table 1 is averaged for each run.
- System thermal efficiency was in the range 70-85%. This is a measure of how the fuel, boiler and tank work together with the heat distribution system isolated, i.e. how much energy was put into the tank vs. how much fuel was burned.
- CO levels (PPM) range: 87 (100% Miscanthus) – 481 (100% Switchgrass). All uncorrected PPM.
- Smoke levels (colorimetric pull on 0-9 scale): 4.0 (100% Miscanthus) - 8.5 (100% Switchgrass).

- Switchgrass and Reed Canary provided the greatest qualitative challenges, especially the 100% samples. Switchgrass pucks tended to either have high chaff or were too dense. Reed Canary was relatively challenging to combust well.
- Miscanthus and Ag Biomass / Field Residue were the easiest to combust well. The Ag Biomass / Field Residue was sourced from an abandoned pasture that was full of goldenrod, chicory, Queen-Anne's lace and oak leaves. It was cut, baled, pucked and burned. The intent of this trial was to test a non-intentional crop that results from land maintenance activities as a low-cost option for increased adoption with potential secondary benefits (open space management, nutrient management, etc.)

Summary data for each fuel tested is provided in Table 1 where the data are generally average results from test points toward the end of each 1 hour run. Higher efficiency figures were noted several times during testing, approaching 90%. Additional appliance tuning over longer runs would likely allow for sustained operation at such higher efficiencies.

	Exhaust Gas Measurements						Combustion Efficiency
Fuel	Stack Temp F	Oxygen %	CO ppm	NO ppm	SO2 ppm	Smoke #	%
Wood Pellets	386	9.53%	365	69	1	>9.0	82%
100% SG Pucks	354	13.20%	143	107	0	6.7	79%
50% SG / 50% Wood Pucks	258	17.70%	215	58	0	8.5	73%
100% Reed Canary Pucks	347	14.60%	184	107	0	7.0	75%
50% RC / 50% Wood Pucks	345	14.17%	153	123	0	6.0	77%
100% Miscanthus Pucks	347	14.00%	58	64	0	4.5	78%
50% Miscan. / 50% Wood Pucks	322	16.05%	125	70	0	6.0	74%
100% Mulch Hay Pucks	374	13.27%	206	122	0	5.3	77%
50% MH / 50% Wood Pucks	314	16.13%	219	89	3	6.0	74%
100% Ag Biomass / Field Residue	374	13.27%	206	122	0	5.3	77%

Table 1 - Summary of combustion test results. Typically, these data are an average of three readings toward the end of a one-hour test run. This is not representative of optimized performance, but rather of an initial feasibility trial.

Fuel Analysis

The results of the fuel analyses are presented in Table 2. The energy density of the main feedstocks (all 100% biomass fuels without wood) was similar to pellets on a weight basis which is to be expected (mean of 8,086 BTU/lb dry). The chlorine content (mean of 1,402 mg/kg) is similar to earlier results (mean of 864 ppm, ppm is approximately mg/kg), with one exception. The Ag Biomass / Field Residue was relatively low in chlorine (227 mg/kg). Wood pellets were analyzed previously and found to have 32 ppm Chlorine (Sherman, 2011). The concern over Chlorine in biomass fuels is that it and other halogens will accelerate corrosion of combustion and heat transfer surfaces. We did not observe this in our testing, albeit short in duration. Ash content of the main feedstocks (all 100% biomass fuels without wood) averaged 5.26% (dry) compared to 5.37% (dry) from previous work (Sherman, 2011). This is still relatively high, compared to wood pellets, but with automated removal and cleanout on startup, less of a challenge.

	Summary Stats					Switchgrass		Miscanthus		Reed Canary		Mulch Hay		Ag Biomass	
Key	**Min**	**Avg**	**Avg Main**	**Std Dev**	**Max**	**100 SG**	**50/50 SG/WD**	**100 MSC**	**50/50 MSC/WD**	**100 RC**	**50/50 RC/WD**	**100 MH**	**50/50 MH/WD**	**100 ABM**	
Form						**2" Puck**	**2" Puck**	**2" Puck**	**2" Puck**	**2" Puck**	**2" Puck**	**2" Puck**	**2" Puck**	**2" Puck**	
Description						**100% Switchgrass**	**50% Switchgrass with 50% Wood**	**100% Miscanthus**	**50% Miscanthus with 50% Wood**	**100% Reed Canary Grass**	**50% Reed Canary Grass with 50% Wood**	**100% Mulch Hay**	**50% Mulch Hay with 50% Wood**	**100% Ag Biomass (Field Residue)**	
Moisture	10.23	13.99	12.45	2.56	17.27	15.22	17.27	13.61	16.53	10.70	14.27	10.23	16.76	12.51	wt%
Ash	3.32	5.26	4.95	1.36	7.20	3.31	3.32	3.45	5.22	7.20	6.98	6.11	5.12	4.69	wt% (dry)
Gross Calorific Value	7,898	8,073	8,086	143	8,344	8,353	8,344	8,105	8,079	7,898	7,900	7,952	8,180	8,123	BTU/lb (dry)
Carbon	39.21	40.25	41.11	0.90	41.45	41.15	39.85	41.09	39.22	40.69	39.21	41.18	39.29	41.45	wt% (dry)
Hydrogen	4.75	4.95	5.06	0.15	5.17	4.92	4.81	5.06	4.78	5.10	4.88	5.17	4.75	5.06	wt% (dry)
Nitrogen	0.26	0.61	0.66	0.22	0.90	0.33	0.33	<0.17	0.26	0.70	0.83	0.90	0.58	0.69	wt% (dry)
Oxygen	33.43	34.68	35.58	1.01	36.29	35.03	34.39	>36.59	33.95	35.47	33.69	36.29	33.43	35.53	wt% (dry)
Sulfur	0.024	0.078	0.079	0.046	0.143	0.048	0.031	0.024	0.035	0.137	0.143	0.119	0.069	0.067	wt% (dry)
SO2	0.065	0.214	0.212	0.124	0.401	0.129	0.085	0.065	0.099	0.370	0.401	0.317	0.192	0.180	lb/MMBTU (calc'd)
Chlorine	227	1,434	1,402	1,151	3,312	973	899	352	341	3,312	2,983	2,146	1,211	227	mg/kg

Table 2 - Summary of fuel analysis results for the fuels tested in this trial. Testing was conducted by Twin Ports Testing, Inc. (Superior, WI).

Economics

The consideration of a biomass heating system as an alternative to fossil fuel systems generally comes down to investing greater capital in the conversion system or appliance and recouping that investment in recurring savings via less expensive fuels. Recently depressed fossil fuel prices pose a significant challenge to biomass systems demonstrating feasibility or at least economic attraction.

However, this testing has demonstrated the feasibility of an alternate fuel source and form in an advanced heating appliance. The cost of the fuel varied depending on the feedstock, but was in the range of $85-228 per ton ($5.2 – 14.4 per million BTU). Even at relatively low prices today, propane at $2.75 per gallon has a normalized cost of $29.85 per million BTU and fuel oil at $2.014 per gallon has a normalized cost of $14.58 per million BTU (US DOE EIA, 3/12/2016). The normalized savings possible when using densified grass biomass fuels ranges from nearly zero to $24.65 per million BTU depending on the fuels being compared and current pricing and assuming comparable appliance efficiencies which is reasonable when considering modern designs.

The assessment of basic economic feasibility and benefit of an alternate system must consider 1) feedstock costs, 2) densification costs and 3) appliance cost premium all in the context of current standard fuel costs. These items are reviewed in the following sections.

Feedstock Costs

Perennial Grasses

Prior work has helped to estimate the establishment and recurring production costs of perennial grass crops (Bosworth, 2009; Ciolkosz, 2015). The result of this previous work concludes that an average cost of $60-80/ton is a reasonable expectation for most perennial grasses.

Ag Biomass / Field Residue

Hay can be cut, raked, baled and stored for $2.00 per bale for small squares with a weight of 60 lbs per bale and $15.40 per bale for large round bales at an average weight of 863 lbs per bale (Pike, 2014). These rates have been used to estimate the cost of the “Ag Biomass / Field Residue” used in this testing. This feedstock was gathered in small square bales. At the rates noted, this feedstock is estimated to cost $35-67 per ton. In this case, the crop was somewhat unintentional; it was not planted and it was not fertilized. But this is representative of many acres in the Northeast and elsewhere which could be harvested for this purpose and also potentially serve a secondary benefit of sequestering nutrients that would otherwise impact local water ecology.

Densification Costs

The cost of densification as briquettes or pucks (distinct from pellets) has been estimated based on the experiences of RER building and operating two scales of “slugger” densifying machines. The small machine uses a two tubes & pistons and has a full load capacity of 700 lb/hr making 1.5” or 2” pucks. The large machine is made up of eight tubes & pistons and has a full load capacity of 4,000 lb/hr making 2” pucks. Accounting for normal work shifts, cost of labor, cost of energy for operation, maintenance, insurance and debt service the costs of densification for the small and large machine are estimated to be $148 and $49 per ton respectively at 50% and 63% machine utilization respectively (Table 3). This cost decreases with higher utilization (i.e. higher output of tons/year as shown in Figure 1).

	Small Machine	Large machine	Units
Maximums			
Max Output	700	4,000	lb/hr
Max Operation	80	80	hours/week
	50	50	weeks/year
	0.8	0.8	uptime
Max Volume	1,120	6,400	ton/year
Actuals			
Work Time	10	10	hr/day
Product Volume	7,000	40,000	lbs/day
	3.5	20	tons/day
Annual Volume	**560**	**4,000**	**tons/yr**
Utlization	**50%**	**63%**	%
Labor			
Staff	2	4	people
Work days	160	200	days/yr
Labor cost	$15.00	$15.00	$/hr
	$300	$600	$/day
	$86	$30	$/ton
Labor Cost	**$48,000**	**$120,000**	$/yr
Fuel			
Gasoline Used	2	5	gal/hr
Unit Cost	$3	$3	$/gal
Fuel Cost	**$9,600**	**$30,000**	**$/yr**
	$17	$8	$/ton
Maintenance Cost	**$5,000**	**$10,000**	**$/yr**
Insurance Cost	**$2,500**	**$2,500**	**$/yr**
Equipment			
Initial Cost	$100,000	$200,000	$
Term	7	7	yrs
Interest	5.50%	5.50%	%
Equipment Cost	**$17,596**	**$35,193**	**$/yr**
Total Costs of Densification	**$82,696**	**$197,693**	$/yr
Unit Cost of Densification	**$148**	**$49**	**$/ton**
at volume of	560	4000	ton/year
Fixed	$25,096	$47,693	$/yr
Variable	$103	$38	$/ton

Table 3 – Summary of grass fuel densification costs based on RER experience with two scales of processing machines.

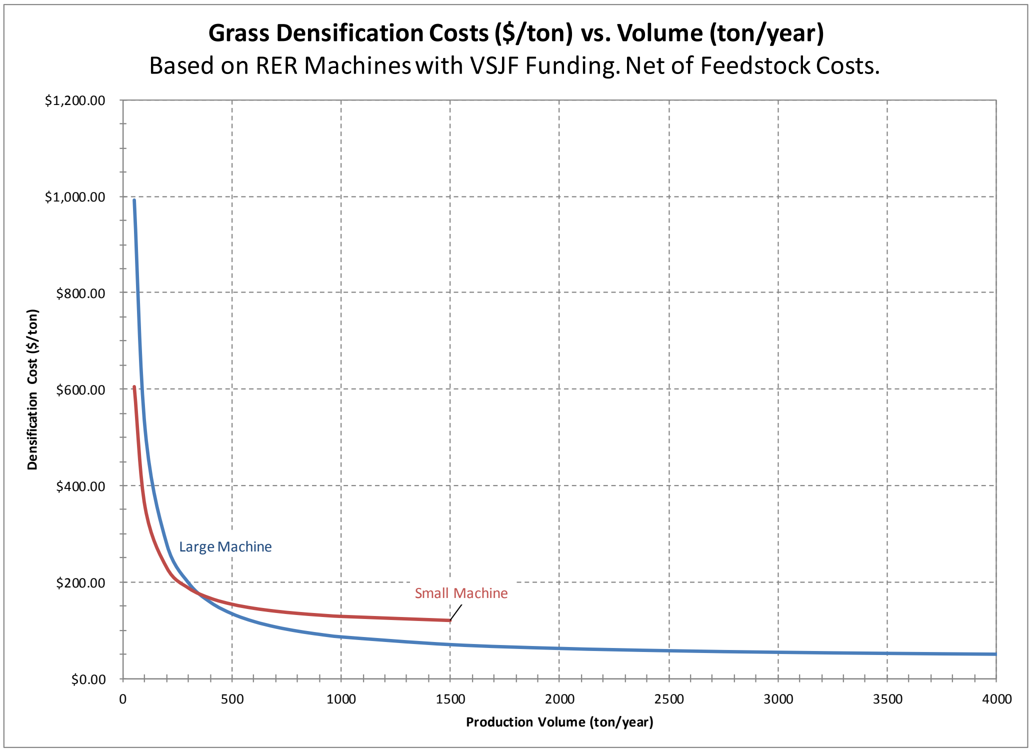

Figure 1 - Effect of fuel production volume on cost of densification for the two scales of machines built by RER. This analysis shows a pathway to $120 per ton on the small machine and $45 per ton on the large machine when operated at full volume of 1500 ton/year and 4000 ton/year respectively. Note, this is not full fuel cost, it is net of feedstock.

Fuel Costs

Knowing the production and densification costs of grass biomass fuels we can make a comparison to other common fuels in order to determine potential savings in operational costs. A summary of fuel costs, in normalized terms at current pricing, is presented in Table 4.

Fuel	Cost	Cost Units	Energy Content	Energy Units	Normalized Fuel Cost $/million BTU
Propane	2.75	$/gal	92000	BTU/gal	29.8
Fuel Oil	2.01	$/gal	129500	BTU/gal	15.6
Wood Pellets	225.00	$/ton	8600	BTU/lb	13.1
Wood Chips	56.00	$/ton (green)	9.9	mill BTU/ton	5.7
Ag Biomass	85-214	$/ton	8123	BTU/lb	5.2-13.2
Switchgrass	129-228	$/ton	8353	BTU/lb	7.7-13.6
Miscanthus	129-228	$/ton	8105	BTU/lb	8.0-14.0
Reed Canary	129-228	$/ton	7898	BTU/lb	8.2-14.4
Mulch Hay	129-228	$/ton	7952	BTU/lb	8.1-14.3

Table 4 - Comparison of fuel costs in normalized terms.

Potential Fuel Savings

Given the assumed fuel costs above and the potential for modern biomass appliances to operate at efficiencies similar to standard fossil-fueled appliances it is possible to achieve 7-82% savings when using densified grass biomass as a combustion fuel. This is a wide range given the variability in grass biomass production costs and fossil fuel prices. It is likely that propane will be at least $3 per gallon ($32.60 per million BTU) in the future when a mature grass biomass fuel can be produced for $130 per ton ($7.93 per million BTU. This suggests a future scenario of 75% fuel cost savings potential. The impact of that savings depends significantly on the cost premium of the appliance and the amount of heating load the site has.

Appliance Premium

The EvoWorld HC100 Eco has an output heat rating of 341,200 BTU/hr and costs approximately $53,500 (net of balance of plant and fuel bin). We will constrain our consideration of appliances to this rating since it is what the current testing was focused on. A propane unit heater with the same rating costs approximately $3,000[1]. An oil-fired boiler with the same rating costs approximately $4,500[2]. The cost premium of the advanced biomass boiler in this case is approximately $50,000.

Cost / Benefit

A building with a peak design load that matches the 341,200 BTU/hr of the EvoWorld boiler in this study would have an overall heat transfer coefficient and area product of 4,550 BTU/hr-F (-10 degF design temperature for Burlington, VT & 65 F inside temperature assumed.) This information allows us to estimate annual fuel usage by applying heating degree days.

Using Burlington, VT heating degree days of 6,457 (65 F basis), annual heat loss is estimated to be 705 million BTU which translates to 830 million BTU of fuel input with an assumed heating appliance efficiency of 85%.

At this rate of fuel use, grass biomass densified as pucks has the potential to support a minimum payback period of 2.5 years on a $50,000 appliance premium (with biomass fuel delivered at a savings of $24.6 per million BTU, i.e. 82% savings, best case based on propane at $2.75 and Ag Biomass at $85/ton in puck form)[3]. Even with a mid-range delivered fuel price of $9.8 per million BTU ($159 per ton) a payback period of 3 years is estimated. The test of the Ag Biomass / Field Residue fuel demonstrated feasibility at a current delivered price of $214 per ton supporting a payback period of 3.6 years on the boiler. At higher production volume projects a path to $85 per ton and a payback period of 2.5 years.

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[1] Dayton Model#WP14783. Online Quote via Grainger. 2016 03 11.

[2] Weil-McLain Model#481. Online Quote via eComfort. 2016 03 11.

[3] Premium is $50,000. Annual savings = $29.8 per million BTU (Propane at $2.75 per gallon) less $5.2 per million BTU (Ag Biomass at $85 per ton) = $24.6 savings per million BTU. Simple Payback Period = $50,000 premium / (830 million BTU of fuel per year x $24.6 savings per million BTU) = 2.45 years

References

Bosworth, S. (2009). Cost of Grass Biomass Establishment, Maintenance and Harvest Estimator [Microsoft Excel]. Burlington, VT: UVM Extension. Retrieved from http://pss.uvm.edu/grassenergy/Articles/Grass_Biomass__Production_and_Harvest_Cost_Estimator.xlsx

Ciolkosz, D. (2015, January 22). On-Farm Production of Biomass Pellets. USDA NE-SARE Farm Energy IQ Project. Retrieved from http://articles.extension.org/sites/default/files/Fact%20Sheet%20-%20On%20Farm%20Production%20of%20Pellets.pdf

Pike, A. (2014, April). 2014 Machinery Custom Rates. USDA NASS. Retrieved from http://www.nass.usda.gov/Statistics_by_State/Pennsylvania/Publications/Machinery_Custom_Rates/CustomRates%202014.pdf

Sherman, A. (2011, January). Technical Assessment of Grass Pellets as Boiler Fuel in Vermont. VSJF. Retrieved from http://www.biomasscenter.org/images/stories/grasspelletrpt_0111.pdf

Wilson Engineering. (2014, May). Grass Energy in Vermont and the Northeast. Vermont Sustainable Jobs Fund. Retrieved from http://vermontbioenergy.com/wp-content/uploads/2013/03/Grass-Energy-in-Vermont-and-the-Northeast.pdf

Figure 2- Small bales of "Ag Biomass / Field Resiude. This feedstock was cut and baled from a fallow field that is generally brush-hogged annually. The material included goldenrod, oak leaves, chicory, and other native weeds.

Figure 3 - A representative "dense" puck that was noted to cause feed jamming. Generally, a puck that could be cleaved in half radially in one hand was of reasonable density for the feed system.

Figure 4 - A variety of potential biomass fuels that can be used in the EvoWorld HC100 Eco (Left to Right: Wood chips, Ag Biomass Pucks, Wood Pellets).

Figure 5 - Reed Canary Pucks, showing a relatively high proportion of loose chaff due to densifying challenges with this feedstock.

Figure 6 - The primary feed auger on the EvoWorld HC100. The green tube is a parallel wood pellet feed system. Both of these systems feed into a "hand off box" below where they join. The combustion feeder moves fuel from the hand off box to the combustion chamber. The hand-off box has a fire damper to separate the combustion area from the primary feed (and fuel storage) area.

Figure 7- The EvoWorld HC100 Eco boiler at Meach Cove Trust in Shelburne, VT. Intended for wood chip fuels, the boiler was demonstrated on a variety of coarse biomass fuels due to a wide range of adjustment in fuel feed, air flow (exhaust, primary and secondary combustion air) and automated cleanout..

Figure 8 - A Wohler A500 combustion analyzer was used to measure the content and conditions of the combustion exhaust.

Figure 9 - A view of the exhaust stack on a clear day under full load. No visible smoke.

Figure 10 - Smoke number tests from three runs.