Public Information

Project Title: Torrefaction and Densification of Biomass Fuels for Generating Electricity

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MILESTONE 5 REPORT

Executive Summary:

This project will research torrefaction and densification of biomass feedstocks to develop an efficient and economical biomass supply chain. The approach is to develop and optimize a torrefaction and densification regime that will improve storage capabilities, handling methods and biomass feedstock uniformity for the production of renewable baseload electricity. The project is designed to support the following goals:

- Goal 1: Generate electricity, heat or syngas from renewable biomass energy sources that are readily available in Minnesota and approaching economic feasibility
- Goal 2: Strengthen the economy of rural Minnesota through value-added processes that capture renewable biomass energy production capability
- Goal 3: Increase accessibility to information that facilitates the adoption of biomass technologies to generate electricity and reduce fossil fuel use

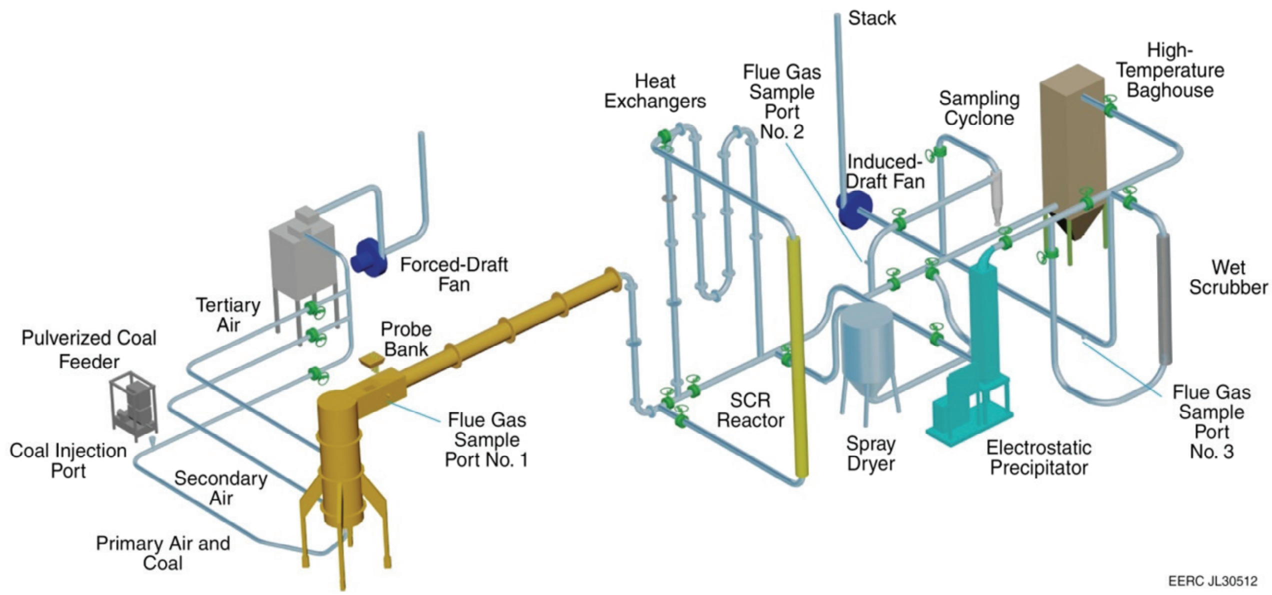
The main work activity that was conducted for Milestone 5, pilot-scale pulverized coal co-firing test combustions, addresses the project goals in the following two ways:

- Confirmation of the final product's ability to be co-fired with coal without modification.
- Validation of the final product's ability to be used in existing pulverized coal boilers to produce baseload and dispatchable renewable electricity while leveraging existing infrastructure.

The project continued with work on Milestone 5, 6, 7 & 8 during the months of November 2009 through April 2010. In August 2009, Bepex and the University of North Dakota successfully conducted the co-firing trials and have completed the final test combustion report. The team also finished planning the pilot plant upgrades, and designed, fabricated and implemented them based on our experiences from the June 2009 5 ton demonstration run. The team continued to work with the University of Minnesota to determine the co-location analysis and has continued to work on the more detailed capital and operating expense estimates for the commercial scale system. We planned and executed the 25 ton demonstration run in February 2010. Finally, the team also recently completed a 10% co-firing trial at an industrial-scale stoker grate with more than 6 tons of torrefied and densified biomass.

Technical Progress: Co-Firing Test Combustion

One of the key aspects of this project is to test the final torrefied and densified biomass product in a pulverized coal boiler to determine how easily the product can be used to produce renewable and carbon neutral electricity at existing coal-powered electrical power plants. To accomplish this objective, we worked with the Combustion Test Facility (CTF) at the University of North Dakota Energy & Environmental Research Center. A computer rendering of the CTF system, provided by the EERC, is below. The CTF is designed to operate between 550,000 – 750,000 btu/hour and is a pilot-scaled pulverized coal boiler system. The system, while having additional capabilities, was set up for our purposes to have an integrated primary, secondary and tertiary air system, simulated steam tubes to test for fouling propensity, two sets of emissions monitors, and an electrostatic precipitator (ESP) with baghouse collection system.

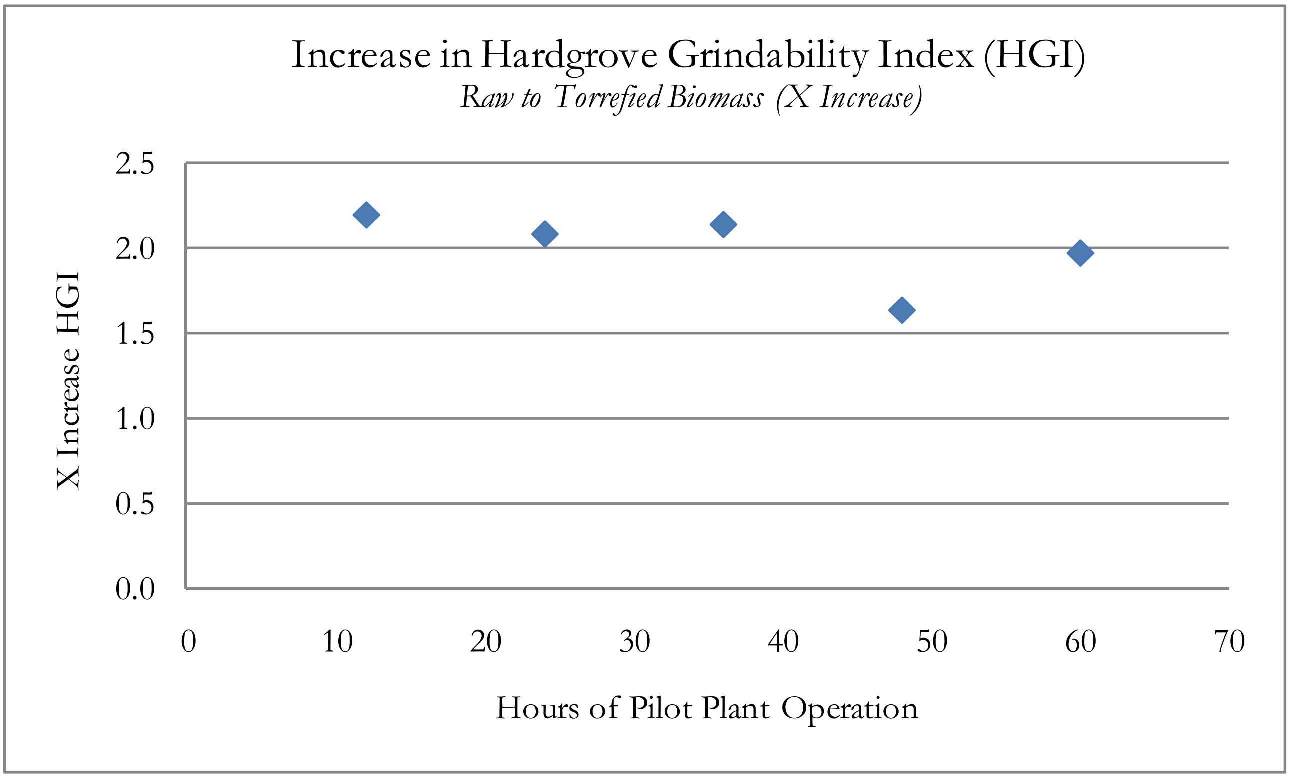


<u>Hardgrove Grindiablity Index</u>

One of the benefits of pre-processing the raw biomass via the torrefaction process is that the final torrefied product has an increased Hardgrove Grindability Index – or HGI. HGI is an industry standard for the pulverized coal industry with an HGI of "50" being the benchmark "normal" value. For example, if a solid fuel had an HGI of 45, or a 10% reduction from 50, it would take approximately 10% more energy to grind that solid fuel to the required 200 mesh minus (75 microns) prior to being blown into the coal boiler for subsequent combustion. With many raw biomass feedstock's having a HGI of around 17, and our product having an HGI between 35 – 45 depending on the targeted process conditions, we see an average 2.0x increase in HGI. This improvement in grindability dramatically augments the ability of existing pulverized coal power plants to use torrefied and densified solid fuel as a direct replacement for traditional fossil fuel coal to produce carbon neutral, renewable electricity.

During the 5 ton demonstration run conducted in June 2009, the team collected raw and finished product samples representing every 12 hours of operation and charted the increase in hardgrove grindability index over this production run. As is quickly seen in the run chart below, the process averaged a 2.0X increase in

HGI from raw to finished product, while achieving an average Hardgrove Grindability Index of 35.6 HGI for the biocoal produced from corn stover.



Solid Fuel Analysis: Proximate, Ultimate & Blending Ratios

The team sourced Montana Powder River Basin (PRB) sub-bituminous coal from the Xcel Energy Sherco power plant in Sherburne County. Prior to submitting the coal samples to the University of North Dakota for subsequent blending and size reduction, the team submitted several samples to SGS North America for Proximate and Ultimate analysis in order to conduct accurate blending ratios and post analysis. The final blend ratios of the three fuel blends are provided below. The blending ratios are on a btu basis and the results in the below chart is a weighted average calculation based on the average proximate and ultimate analysis of the two fuels – coal and biocoal – used during the co-firing trial.

	Ash %	Volatile Matter %	Fixed Carbon %	Sulfur %	Gross Calorific Value (btu/lb)
Co-Firing Ratio (0%) 100% Coal	8.24%	28.66%	34.59%	0.67%	8313
Co-Firing Ratio (10%) - 90% Coal	8.17%	32.11%	33.84%	0.61%	8350
Co-Firing Ratio (30%) - 70% Coal	8.04%	39.09%	32.32%	0.49%	8426

Solid Fuel Particle Size Distribution (PSD)

With the coal and torrefied and densified corn stover delivered to the University of North Dakota EERC CTF, the EERC blended and pre-processed the solid fuel into a 70% 200 mesh minus powder that could be subsequently blown into the pilot scale pulverized coal boiler, or CTF. The EERC used a hammermill to pulverize the coal / biocoal blends. During the actual co-firing trial the CTF system collected a continuous stream of pulverized solid fuel so that subsequent particle size distribution analysis could be conducted.

Bepex conducted particle size distribution (PSD) analysis on the pulverized solid fuel samples (results are provided below) using an INSITEC PSD analyzer. As shown in the results below, the PSD analysis reveals that while the biocoal is significantly easier to grind as compared to raw biomass, the coal still grinds easier than the biocoal., This is indicated by the increasing percentage of cumulative weight not passing through the 200 mesh screen as we increase the biocoal loading in the solid fuel. However, it should be emphasized that a hammermill and not a coal pulverizer was used for the solid fuel size reduction at the EERC. Additionally, since torrefied biomass has a higher volatile matter than most traditional coals, it burns quicker, thereby reducing the combustion impact of larger particle size. However, further testing using standard coal pulverization technology should be conducted to gain further insights into this aspect of torrefied and densified solid fuels.

Particle Size Distribution of Pulverized Solid Fuel

		100% Mont. Coal	10% Stover 90% Coal	30% Stover 70% Coal
Mesh	micron	Cum.Wt. %	Cum.Wt. %	Cum.Wt. %
40	425	0.10	0.10	0.30
60	250	0.90	1.70	2.80
100	150	6.30	7.80	11.80
140	106	14.10	15.90	22.20
200	**75**	**27.20**	**28.00**	**37.30**
230	63	31.10	32.50	41.70
325	45	48.10	48.50	58.20
400	38	51.20	51.60	61.30
> 400	< 38	100.00	100.00	100.00

Test Setup: Co-Firing Ratios & Data Collection

The team, using the subsequently prepared coal and biocoal blends, ran three separate co-firing test combustions on August 10, 2009 at the University of North Dakota's Energy & Environmental Research Center Combustion Test Facility (CTF). The first test, a four hour run, was 100% Montana Powder River Basin (PRB) sub-bituminous coal. This first test created a baseline from which to judge the relative performance of the subsequent 10% and 30% co-firing trials that were to follow. The second and third tests were four hour tests, with test two being a 10% co-firing and test three being a 30% co-firing trial. The test combustion trails were successful, with all of the targeted data points collected including heat flux, fouling, flue gas emissions (SO_2, and NO_X) and ESP ash collection and analysis.

Test Combustion: CTF Operational Settings

For each of the three test conditions, the firing rate was maintained at or near 550,000 btu/hr, resulting in a target furnace exit gas temperature (FEGT) between 2000°F and 2100°F. Excess air was controlled to a flue gas oxygen concentration between 3% and 3.5%, about 17% to 20% excess air. Overall, the primary air flow was maintained between 18% and 19%, the secondary air flow between 64% and 65%, and the tertiary air flow around 17% to 18%. Additional CTF test settings and test results are provided below for reference.

Co-Firing Trial Description	Swirl Setting	Test Duration (min.)	Average Fuel Feed Rate (lbs/hour)	Fuel Consumed (lbs)
100% coal	4	180	63.36	195
90% coal, 10% biocoal stover	4	180	64.44	194
70% coal, 30% biocoal stover	4	180	61.68	185

Heat Flux Measurements

Heat flux measurements were made with a water-cooled, stainless steel heat flux probe that was inserted through a port in the radiant zone of the CTF. The heat flux probe was located 2 feet above the burner quarl on the east side of the furnace. Heat flux is calculated by measuring the inlet and outlet water temperature and the water flow rate to provide a relative indication of changes between fuels and operating conditions. A summary of the results obtained is provided below.

Co-Firing Trial Description	Lower Probe Flux (btu/f²/hour)
100% coal	60,079
90% coal, 10% biocoal stover	54,448
70% coal, 30% biocoal stover	59,393

Heat flux measurements averaged approximately 60,000 Btu/ft^2/hr during the baseline test. Although a drop in heat flux was noted during testing of the 90/10 coal/biocoal test, the heat flux was similar to the baseline in the 70/30 coal/biocoal blend test. Based on the results, there appears to be no dramatic degradation in heat transfer through the walls of the radiant zone when firing the coal/biocoal blends.

Emissions Reductions: NO_X and SO_2

One of the primary objectives of the combustion testing was to determine the emissions profile of the various solid fuel blends as compared to the baseline 100% coal benchmark. The final outcomes from the test in regards to the two primary emissions of SO_2 and NO_X are presented below. The combustion of biocoal made of corn stover not only allows the production of carbon neutral, renewable electricity, but also provides an emissions reduction incentive via the reduction of both SO_2 and NO_X when blended with traditional fossil fuel coal.

Emissions Reduction at ESP Compared to Baseline

	SO_2 ESP (ppm)	NO_x ESP (ppm)
10% Stover Biocoal	16.97%	15.57%
30% Stover Biocoal	30.0%	28.29%

Ash Fouling Potential

During each test, an ash-fouling test was conducted. The ash-fouling test consists of placing three steam-cooled probes in the post-combustion flue gas stream to allow hot fly ash grains to impinge on the heat-transfer surfaces of the probe as it leaves the radiant zone of the test furnace. The weight of ash deposited, hereafter referred to as the "deposit," on the probe bank during a standard test is used to rank the coal, or solid fuel, for its relative fouling potential. The more ash that accumulates on the probes during the test, the higher the likelihood that the ash will accumulate to the steam tubes in a full-scale utility boiler. To ensure that the pilot-scale test results are meaningful for evaluation of ash-fouling potential in full-scale utility boilers, calibration tests were previously conducted by the EERC with low-rank coals known to produce low and high fouling when used in utility boilers. The overall results of the three tests are provided below.

Ash Fouling Propensity and Strength Rating Factor (SRF)

Co-Firing Trial Description	Fouling	SRF
100% coal	Medium	2
90% coal, 10% biocoal stover	Medium-High	2
70% coal, 30% biocoal stover	High	5

While ash fouling potential, as provided above as Medium – High, is a good early predictor of the overall deposition rate of ash deposits, it does not provide an indication of the ease of removal of deposits by soot blowing. To understand how easily a given ash deposit can be removed by traditional soot blowing technology, we have to look at the deposit tenacity and strength. Methods to measure deposit tenacity and strength have been reviewed at the EERC, and strength test methods have been developed that appear to provide reliable, reproducible results. The result of this test is called the Strength Rating Factor or "SRF."

The SRF is a subjective observation made by a pilot plant operator during removal of ash deposits from the above mentioned probe bank at the completion of a co-firing test. Deposit hardness and breakability are rated from 1 to 10, with "1" indicating "soft and crumbly" and "10" meaning "hard and un-fragmented."

The lack of strength development (SRF = 2) in the baseline deposit and the 90/10 blend tend to indicate a low fouling potential at the operating conditions used here. Each of these deposits would be easily removed by normal soot blowing methods. The deposit formed during combustion of the 70/30 coal/biocoal stover showed increased strength development relative to the baseline (SRF = 5); however, it was also very friable and would present no difficulty for a utility operator using normal soot blowing methods.

<u>Post Combustion Electrostatic Precipitator Ash Analysis</u>

With the co-firing tests successfully completed, the team turned to analyzing the post-combustion ash from the electrostatic precipitator. We were looking for signs of non-burned or unspent solid fuel that might have made its way through the boiler and into the ash stream. This analysis is important as it is common in raw biomass co-firing applications to see an increase in Calorific Value in the ash due to very large raw biomass particles (due to their relatively low HGI) not completely burning and ending up in the ash stream post-combustion. Using the ash collected from the co-firing trials proximate analysis tests were conducted to determine the percentage of fuel that might have gone unused.

Post-Combustion ESP Co-Firing Ash Analysis

Co-Firing (%)		0%	10%	30%
Datapoint	Unit	As Received	As Received	As Received
Moisture, Total %	%	0.30%	0.05%	0.40%
Ash %	%	99.54%	99.54%	98.97%
Volatile Matter %	%	0.63%	1.41%	1.61%
Fixed Carbon (by diff) %	%	< 0.01	< 0.01	< 0.01
Calorific Value (btu/lb.)	%	< 100	< 100	< 100

The results above clearly show that the co-firing blends produced an ash stream with very little unspent fuel. There was no detectable btu/lb in the ash for all three co-firing trials, indicating complete combustion of the various blends. We did see, as expected, a relative increase in the percentage of Volatile Matter in the ash stream for increasing co-firing blends due to the relatively high percentage of volatile matter that is present in raw biomass and subsequently in torrefied biomass as compared to traditional coals.

Co-Firing Test Combustion: Summary

Overall the co-fire testing of the biocoal with coal was successful with the biocoal pulverizing, feeding, and combusting similarly to coal while maintaining a stable flame throughout the testing. Heat flux measurements showed similar thermal output throughout the various co-firing tests. Emissions for NO_X and SO_2 were reduced from the baseline while ash fouling propensities, on average, saw an increased severity over that of the baseline.

Biomass Harvest: 5 Tons – Ames, Iowa

During the month of October 2009 Iowa State University (ISU) successfully collected 5 tons of corn stover in Ames, Iowa. This material, along with material collected during the Fall of 2008, was preprocessed and was used as feedstock for the 25 ton production run that occurred in February 2010. Additionally, the team is continuing to work with Iowa State University to develop and complete its Fall 2009 biomass harvest report to support our Milestone 6 Report.

Technical Progress: Process Research & Development (PR&D)

During the 5 ton demonstration run, the team was able to learn about our existing continuous-phase biomass torrefaction and densification pilot plant. Leveraging these experiences, the team planned the pilot plant upgrades during the months of October – November 2009 to allow the 25 ton demonstration run to run as smoothly as possible. These upgrades included new features that allowed the pilot plant to more accurately feed the raw biomass into the plant, densify the torrefied biomass, and collect and subsequently combust the volatiles from the process.

As a result, elements of the pilot plant were fitted with larger motors, more accurate sensors, and other upgrades. Combined these modifications allowed the team to complete the final process research and development objectives for this effort. These upgrades were implemented during the months of December 2009 and January 2010 with a shakedown test being conducted during the last week of January 2010 prior to the commencement of the second demonstration run.

A full discussion of the completed PR&D will be included as a part of our Milestone 6 Report.

Technical Progress: Economic Analysis

We have continued to work on the next level of detail surrounding our commercial scale economic analysis. Specifically, the team has reviewed the commercial scale process flow diagram and has broken out each flow such that a more detailed mass and energy balance can be conducted. With this greater detail a more detailed external quoting process is currently being conducted for non-Bepex specific equipment, which will provide more accurate capital, operating and maintenance expense estimates.

While obtaining the greater detail will take a considerable amount of time to complete, we believe it is required if a commercial scale facility is to be built. To date the team has completed the more detailed process flow diagram, and the detailed mass and energy balances associated with the updated process flow diagram.

Additionally, the team is continuing to work with the University of Minnesota on developing a co-location analysis with existing corn based ethanol plants here in the Midwest. There are possible strategic advantages of co-locating an industrial scale biomass torrefaction and densifcation production plant at these facilities. The analysis reviews the energy balances and possible opportunities for these plants to reduce their carbon intensity while adding another revenue stream to the plant.

We expected that the economic analysis for the commercial scale system will take Bepex until early May to complete due to the amount of effort and external contact with various vendors required. The results of this and the co-location analysis with the University of Minnesota effort will support our Milestone 6 and 7 Reports.

Demonstration Run: 25 Ton Run

The team met in early September 2009 to begin to schedule the 25 ton demonstration run due to the complexity and duration of this run. The demonstration run commenced at midnight on Monday, February 1, 2010 and ran continuously for five days a week, 24 hours per day until the production run was completed in early March 2010.

The full results of the 25 ton production run will be included as a part of our Milestone 7 Report.

<u>Milestones:</u>

We are currently working on Milestones 6, 7 and 8.

Milestone 6 consists of completing the economic analysis, PR&D, designing and fabricating the upgraded torrefaction equipment, and completing the biomass harvest for the second harvest season. Additionally, this milestone consists of completing the optimization of the torrefaction regime for the upcoming larger scale trial.

Milestone 7 consists of completing the process flow diagrams with mass and energy balances of the demonstration and providing a sample of torrefied product to RDF administration. Additionally, this milestone consists of demonstrating the torrefication process to RDF administration.

Milestone 8 consists of conducting a second bulk storage and transportation test sequence, and conducting independent co-firing test burns and emission tests at an industrial scale while demonstrating the test burns to RDF administration.

Project Status:

The project has successfully completed the test burn required of Milestone 5. The team has completed the biomass harvest for the second harvest season and is working with Iowa State University to develop its final report from this biomass harvest for our Milestone 6 Report. The team has also completed a more detailed commercial-scale process flow diagram with associated mass and energy balances. The team has designed and fabricated the upgraded torrefaction equipment to both complete our process research & development activities for this grant, and effect the 25 ton demonstration run as a part of our Milestone 6 and 7 requirements. Additionally, the team has continued the process of working with the University of Minnesota to develop a more detailed co-location economic analysis model with existing corn-based ethanol plants. Finally, the team has successfully completed an industrial scale 10% co-firing trial at a stoker grate as part of our Milestone 8 requirements.