Public Information

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

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MILESTONE 7 REPORT

Executive Summary:

This project will research torrefaction and densification of biomass feedstocks to more fully understand the most efficient and economical biomass supply chains available. 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 conducted for Milestone 7 consisted of completing the 25 ton production run and completing the commercial-scale process flow diagrams with mass and energy balances. Additionally, the team demonstrated the torrefaction process and provided a sample of torrefied product to RDF administration. Milestone 7 addresses the project goals in the following ways:

- Operating the upgraded biomass torrefaction and densification pilot plant for more than 500 hours to prove feasibility, stability and practicality of the process for commercial scale-up.
- Conducting raw biomass and finished biocoal characterization analyses to confirm product specifications for use in industrial-scale co-firing applications for the production of heat and power.
- Increasing the availability and accessibility to information; specifically, more detailed commercial-scale biocoal production plant mass and energy balance process flow diagrams.

The project continued with work on Milestone 7, 8 and 9 during the months of December 2009 through late August 2010. The team prepared for the 25 ton production run during December 2009 and January 2010. The production run was performed in February 2010 and completed in early March 2010. After completion of the production run, the team turned its attention to post-processing the raw biomass and

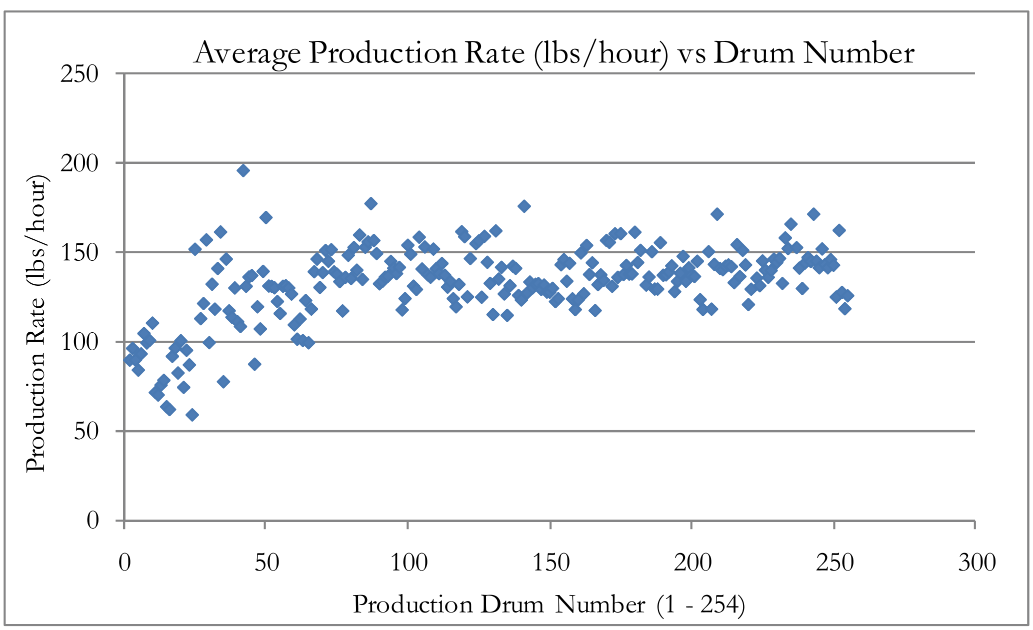
biocoal samples for this report. In parallel, the team completed the detailed commercial-scale biocoal production plant mass and energy balance process flow diagrams that are included in this report. Additionally, the team successfully completed the industrial scale 10% and 30% stoker grate co-firing trials at District Energy in April and July 2010 respectively. As a part of this effort, the team obtained the final emission test reports for the Milestone 8 Report. Finally, the team continued to coordinate a gasification trial as a part of the Milestone 9 Report.

Technical Progress: 25 Ton Production Run

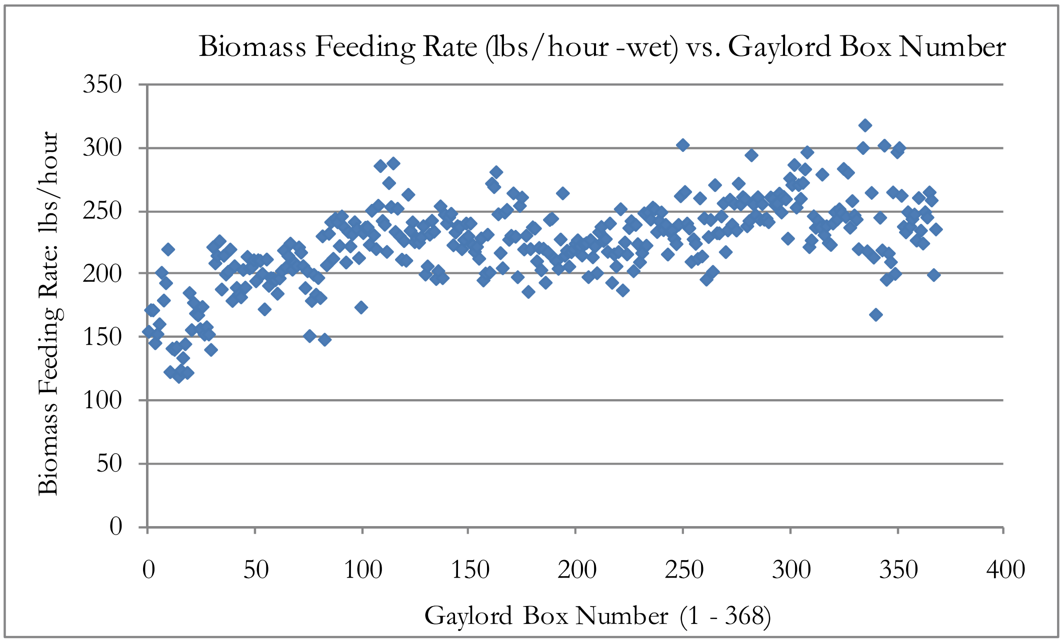
The 25 ton production run began at 12:00 a.m. on February 1, 2010. It ran 24 hours a day, 5 days per week through March 2, 2010. Corn stover material collected during the Fall of 2008 (Reference: Milestone 2 Report) and stored indoors in a warehouse in Olivia, MN was the primary source of feed to produce the 25 tons of biocoal. Additional material was sourced from Iowa State University (ISU) (Reference: Milestone 6 Report) and the Morris, MN region. Beginning on February 25, the ISU and Morris, MN corn stover was used until production completion on March 2, 2010.

The same basic torrefaction pilot plant operations and overall processes were used again for this production run and documented in detail in our Milestone 3 Report. Additionally, the same data collection systems (hardcopy and digital) were used for this run. However, modifications made to the system significantly increased system availability and decreased the amount of operator intervention throughout the production run. For a discussion on the changes made to the system please refer to the Milestone 6 Report.

The production run yielded 26.2 tons (54,400 lbs.) of biocoal product over a total operational window of 504 hours or 21 days. No product was produced on Friday, February 26, 2010. Total system availability stood at 93.7% or 473.2 hours of production during the operational window. The overall average biocoal production rate was 110.7 lbs/hour. However, the mode of finished biocoal production based on 254 drums of product collected over the 21 days of operation was 130.9 lbs/hour with a maximum and minimum production rate of 195.9 and 58.8 lbs/hour respectively. Averaging the 254 product drum averages (see graph below) came to a 132.5 lbs/hour production rate with a StDev of 21.5 lbs/hour.



As is seen in the graph in the previous page, a "learning curve" was experienced in the first several days of operation until our "average" biocoal production rate leveled off at around 140 lbs. of biocoal per hour. As suspected, a similar pattern emerges when we review the raw biomass feeding rate during the larger production run. The graph below shows how the raw biomass feeding rate changed over the 368 total Gaylord boxes of corn stover processed to complete the production run. Large Gaylord boxes filled with raw corn stover were weighed (tared), timed (elapsed time to use material in production) and then weighed again to determine average feeding rates for each Gaylord box of material used in the production cycle. These intra-production analyses helped ensure proper control during production.



During the run, a total of 45.9 tons, or 91,887 lbs. (wet basis) of raw corn stover biomass was fed into the pilot plant at an overall average rate of 194.6 lbs/hour (wet basis), or 170.8 lbs./hour (dry basis). The biomass had an average incoming moisture content of 12.19%. The mode for the 368 Gaylord boxes processed was 240 lbs./hour (wet basis) with the maximum and minimum feeding rate at 318 and 118 lbs/hour (wet basis) respectively. Based on the overall production quantity of 26.2 tons of biocoal and 40.3 tons (dry basis) of corn stover raw biomass used in the process a calculated mass loss of 34.8% was determined. This number is very close to our expected mass loss of 34.4% for the production run which was determined based on our bench and piloting activities.

With the production run completed, the team turned its attention to analyzing the samples that were collected during the demonstration run. Raw biomass and torrefied and densified biocoal samples were selected for analysis from the continuous operation that best represented the overall 500+ hours of the operational window. The five (5) samples selected consisted of biocoal product from drums 38, 78, 110, 146 and 185. These time points for sample collection were selected as they were equally spaced time periods based on the overall production run. The table below indicates the biocoal samples selected for analysis from the 25 ton production run. To increase the statistical power of the results, a combination of three (n=3) and five (n=5) intra time-point samples were taken, and the final results subsequently presented are an average of these analyses. It should be noted that three samples, each from a different time point, were eliminated due to statically relevant analytical (proximate and ultimate) inconsistencies. An astrick (*) by the sample number in the table below indicates if a sample was removed from this population.

Date	Drum	Samples
2/4/2010	38	3
2/10/2010	78	5*
2/12/10	110	3*
2/17/2010	146	5*
2/22/2010	185	3

To allow comparisons between raw and finished product to be made, four (4) samples of raw corn stover were selected for analysis. The feed samples selected correspond closely (based on time of sample collection) to the biocoal product samples selected for analysis as listed above. Only one sample per time-period was analyzed as the Olivia, MN raw biomass has been previously and extensively analyzed with no significant changes seen from sample to sample.

Date	Drum	Samples
2/10/2010	78	1
2/12/2010	110	1
2/17/2010	146	1
2/22/2010	185	1

All of these samples were submitted to SGS North America for proximate and ultimate analysis and the results returned to Bepex. The goal of this activity was to determine if the process produced product that was consistent over the duration of the production run. The proximate and ultimate analyses of both the raw and final product are presented in the following two pages in Figures 1-4.

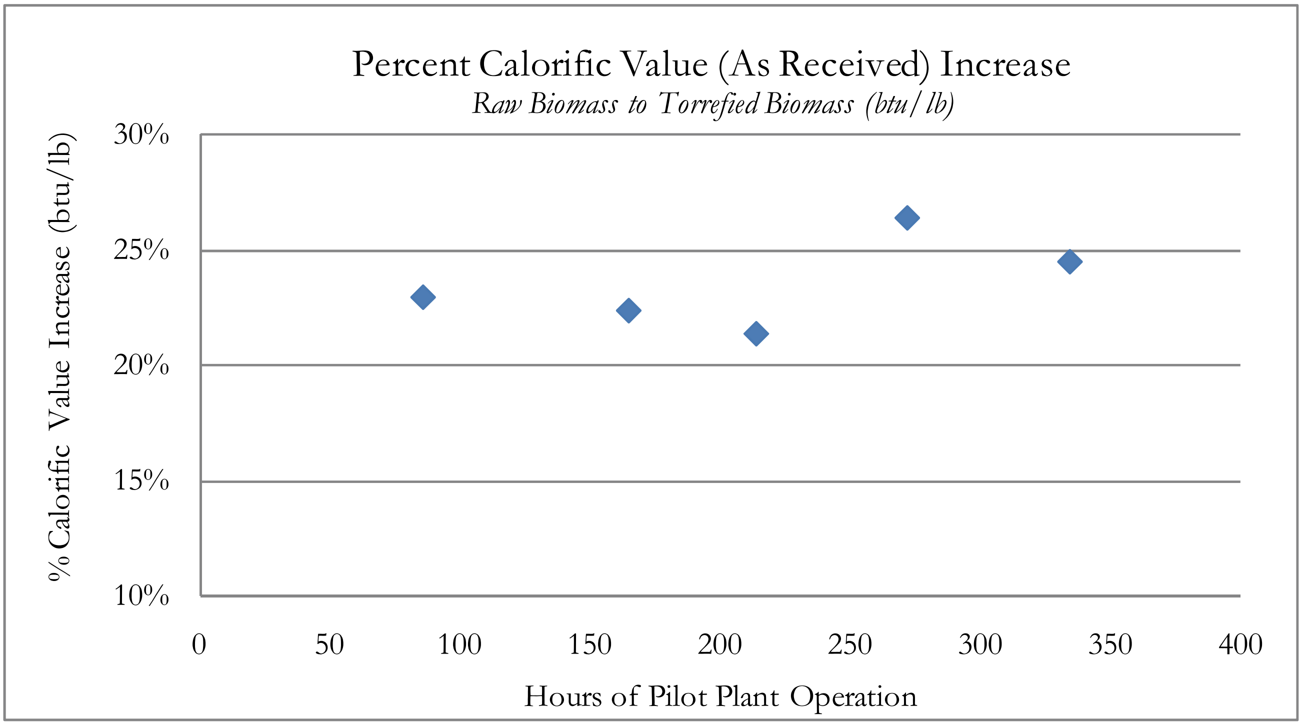


Figure 1: Percent Increase in Calorific Value

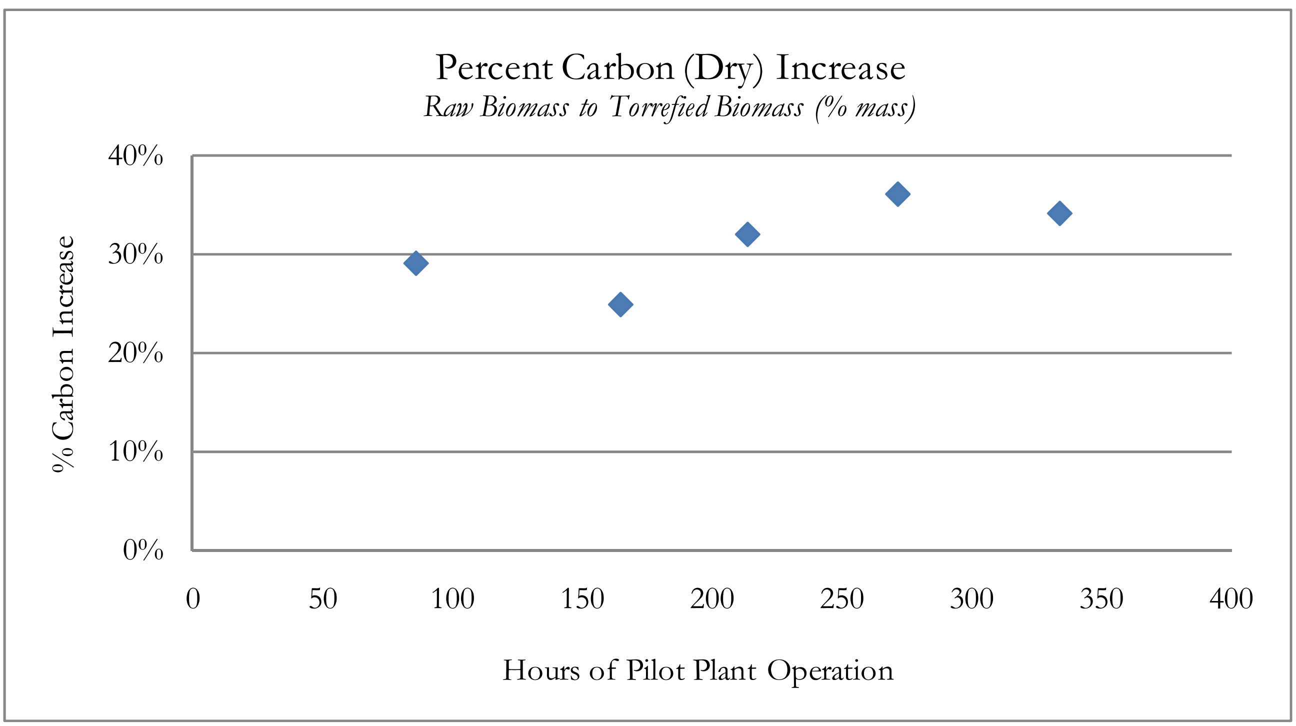


Figure 2: Percent Increase in Carbon

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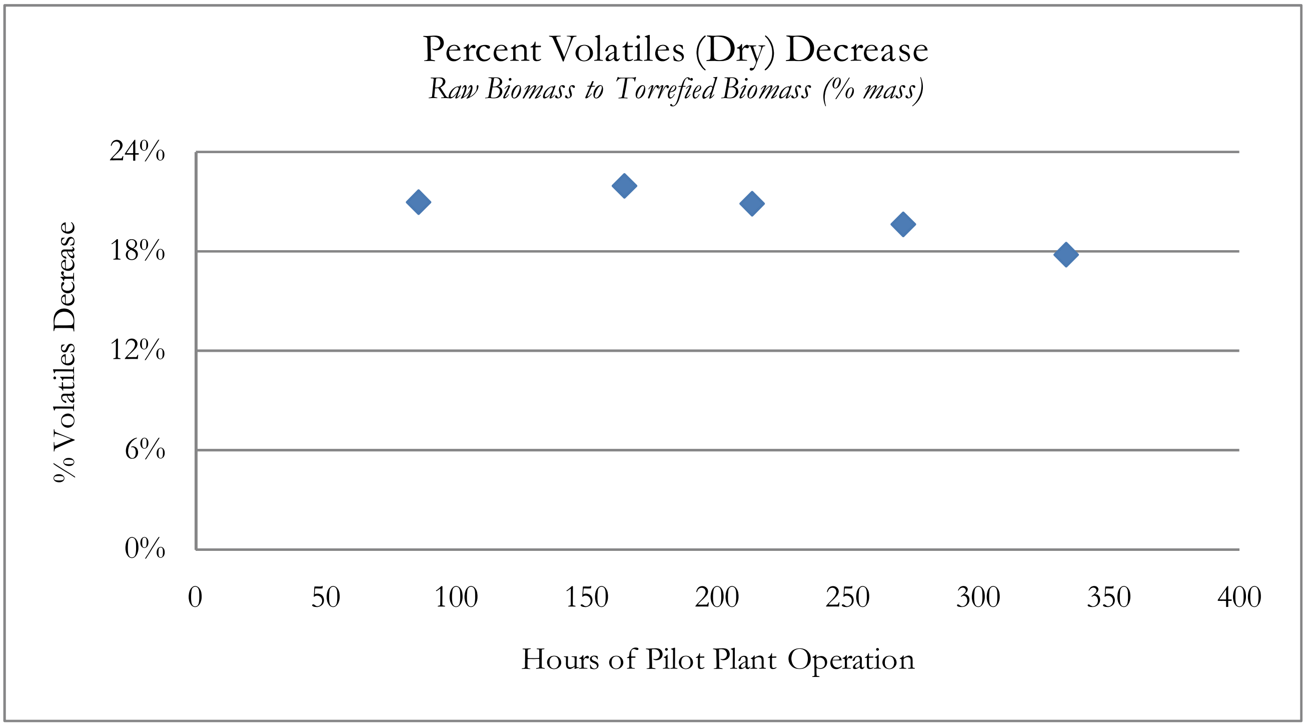

Figure 3: Percent Decrease in Volatiles

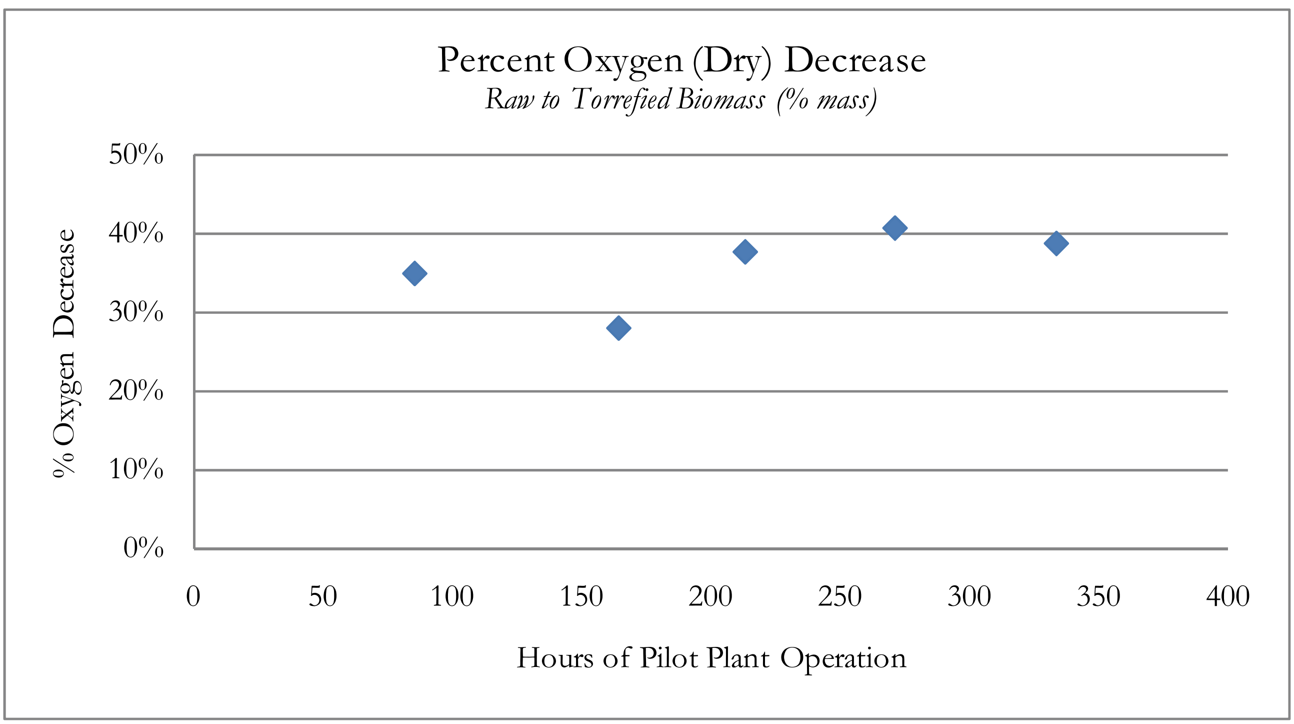

Figure 4: Percent Decrease in Oxygen

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Technical Progress: Post Production Run Product Analysis

The team collected samples from drums 38, 78, 110, 146 and 185 which represented time points in the production run of 85.5, 164.5, 213.5, 271.5, and 334 hours of the total 500+ hours of operational window. The results of these analyses are shown in Figures 1-4 above. The analyses were conducted by SGS North America and consisted of both proximate and ultimate analysis.

Figure 1 details the percentage increase in the final torrefied product's calorific value on an "as received" basis as compared to the raw biomass feedstock. On average, the process produced a product that had a 23.5% improvement in its bulk energy density on a btu/lb basis. The team observed a standard deviation of 138 btu/lb in the final product throughout the production runs 504 hours of operation. On a moisture ash-free, dry ash-free basis (MAF, DAF), the final product from the demonstration run averaged 9,544 btu/lb. By having an increased energy density, each pound of transported torrefied biomass contains more energy, thus resulting in lower transportation costs for each mmbtu transported.

Figure 2 details the percentage increase in the final torrefied product's carbon (% mass) on a dry basis as compared to the raw biomass feedstock. The final product from the production run averaged 55.9% carbon on a % mass basis. The team observed a standard deviation of 2.5% of carbon on a mass % of the final production throughout the production runs 504 hours of operation. On average, the product showed a 31.4% improvement in its carbon density on a % mass basis compared to raw biomass feedstock.

Figure 3 details the percentage decrease in the final torrefied product's volatiles (% mass) on a dry basis as compared to the raw biomass feedstock. The final product from the production run averaged 65.3% volatiles on a % mass basis. The team observed a standard deviation of 1.55% of volatiles on a mass % of the final production throughout the production runs 504 hours of operation. On average, the product showed a 20.2% improvement in its volatile matter on a % mass basis compared to raw biomass feedstock. As volatile matter decreases, typically the energy density of the final product increases. However, some volatile matter needs to remain to promote flame stability during combustion.

Figure 4 details the percentage decrease in the final torrefied product's oxygen (% mass) on a dry basis as compared to the raw biomass feedstock. The final product from the production run averaged 31.1% oxygen on a % mass basis. The team observed a standard deviation of 3.3% of oxygen on a mass % in the final production throughout the production runs 504 hours of operation. On average, the product showed a 35.9% improvement in its oxygen density on a % mass basis compared to raw biomass feedstock.

Based on our prior 5 ton demonstration run and the results presented in Milestone 4 and 5, the following final product attributes were not re-analyzed for this production run: bulk density, durability, equilibrium moisture, crush strength, hardgrove grindability index and elemental ash analysis. However, in replacement, we choose to augment our knowledge of the product by adding several new attributes, including tests for chlorine, mercury and an extreme weathering test protocol. These additional attributes and the results of the tests will be included in our Milestone 8 Report.

Technical Progress: Commercial Scale Process Flow Diagrams (PFD)

The team has successfully updated the preliminary commercial scale mass and energy balance process flow diagrams from Milestone 2 to reflect our new knowledge of the process. The process flow diagrams included in this report focus on one commercial scale plant design which was used as the basis for the economic analysis discussed in Milestone 6 and will again be leveraged in the Milestone 9 Report.

The plant scale used in this report provides for a final plant capacity of 150 kTon/annum (150,000 short tons per year of biocoal) of final product. This is a change from our preliminary process flow diagram with mass and energy balances first presented in our Milestone 2 Report which was for a 135 kTon/annum production plant.

This design is also specific for corn stover due to the inbound moisture content of the material and the biomass' relative reactivity to the torrefaction process. If other feedstocks were to be used, such as switchgrass or dedicated energy crops, the PFD and corresponding mass and energy balances would also change. It should be noted that the system, like our preliminary findings, continues to be self-sustaining in that the energy that is released from the raw biomass during torrefaction provides enough energy to drive the biomass drying and torrefaction process once commenced.

As is the case for any design, the boundary conditions and the corresponding set of assumptions will drive the final results. This situation is no different. As such, a set of assumptions that were used to help drive the model for greater accuracy is included in Appendix A to this Milestone 7 Report. The following two pages include the mass and energy balance process flow diagrams, with the respective mass and energy balances.

Process Flow Diagram: Mass Balance

Provided below is the final commercial scale mass balance process flow diagram.

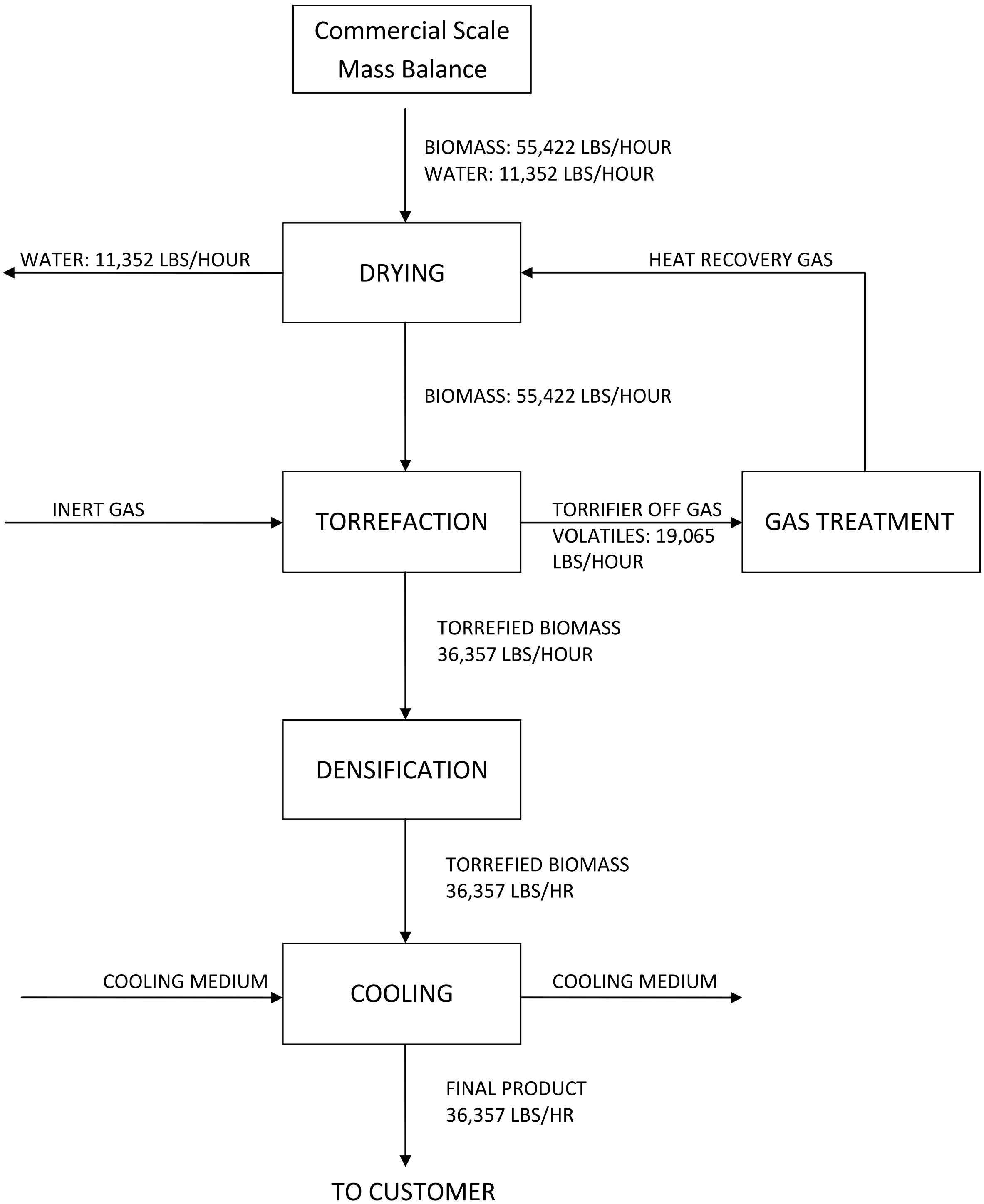

Figure 5: Commercial Scale Mass Balance PFD

Process Flow Diagram: Energy Balance

Provided below is the final commercial scale energy balance process flow diagram.

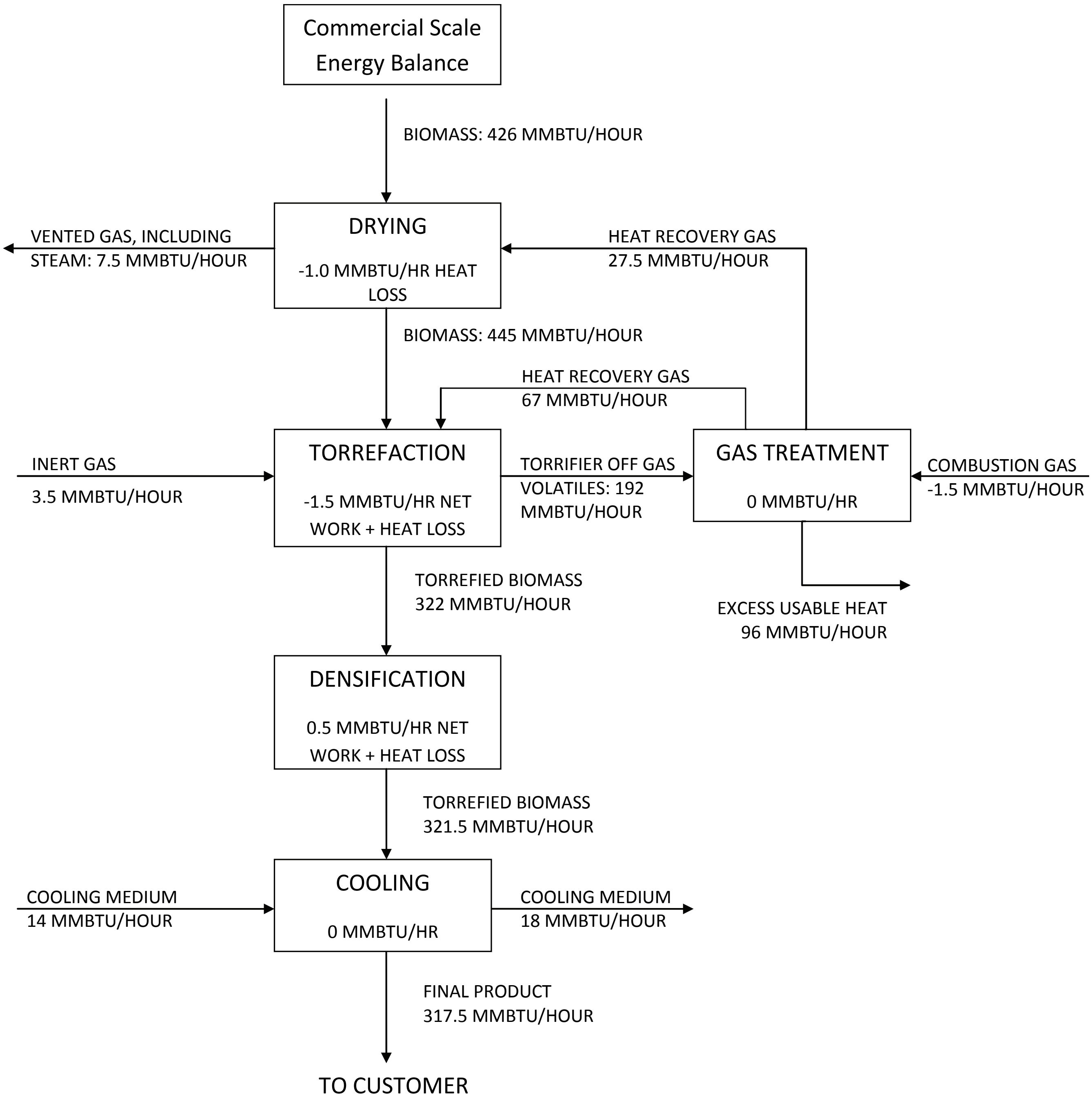

Figure 6: Commercial Scale Energy Balance PFD

Milestones:
We are currently working on Milestones 8 and 9.

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.

Milestone 9 consists of conducting a test gasification with biocoal to collect stack emissions profiles while demonstrating the test gasification to RDF administration. Also, it consists of completing the feasibility and economic analysis.

Project Status:

The project has successfully completed the requirements for Milestone 7. The team has successfully completed the industrial scale 10% and 30% co-firing trials as part of our Milestone 8 requirements and has received the final emission test reports from these trials. Finally, the team is in active discussions to execute the gasification trial as a part of our Milestone 9 requirements.

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APPENDIX A: Commercial Scale Biomass Torrefaction & Densification Scenario Assumptions

Summary: Below are some of the assumptions made for the specific commercial scale 150,000 ton / year biocoal production plant scenario developed by the Bepex team for the Xcel Energy RD3-4 activities. Assumptions made during the scope of work for this effort were determined as a team and then documented via additions / updates to this document as the effort moved forward.

List of Assumptions:

- Operational Uptime: 95.0% Operational Uptime / Year
- Operational Hours: 8327 Hours of Operation / Year (365.25*24*.95 = 8327 Hours)
- Plant Elevation: 1,200 feet
- Ambient Air Temperatures:
  - Average January: 11 °F (-11.7 °C)
  - Average July: 71°F (22°C)
  - Winter Low: -20°F
  - Summer High: 95°F
- Relative Humidity: 55% Worst Case Summer
- Commercial Scale Production Volume: 150,000 tons of biocoal / year (dry basis)
- Raw Feedstock: Corn Stover
- Raw Feedstock Incoming Moisture Content: 17.0% Moisture
- Raw Feedstock Incoming Particle Size: Particle Size is assumed to be optimized for Process
- Raw Feedstock Incoming Temperature: 0 °F (-17.8 °C)
- Raw Feedstock Feeding Rate: 66,774 lbs/hour - (wet basis)
- Raw Feedstock Feeding Rate: 55,422.42 lbs/hours (dry basis)
- Raw Feedstock Required: 278,035.217 tons / year (wet basis)
- Torrefaction Mass Loss: 34.4%
- Finished Product Production Rate: 36,357 lbs/hour
- Finished Product Bulk Density: 40 lbs./ft^3
- Finished Product Specific Gravity: 1.2 g/cm^3 (75 lbs/ft^3)

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