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BIOMASS DENSIFICATION DOCUMENT OF EVALUATION

Prepared for:

Agricultural Utilization Research Institute

Minnesota Corn Research & Promotion Council

Minnesota Soybean Research & Promotion Council

Submitted by:
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- Briquetting Systems
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Section 1 – Introduction

American Ag Energy (AAE) retained Zachry Engineering in August 2008 to complete the necessary tasks to prepare a Document of Evaluation of densification equipment for biomass applications.

There is a strong regional interest in Minnesota and elsewhere for the promotion and development of agricultural and wood biomass fuel pellets for industrial boilers. The primary agricultural residues of interest for fuel pellets includes corn stover, straws (wheat, rye grass, etc.), and grasses (blue stem, etc.). Although laboratory research continues for agricultural residue densification, to date there is very limited production level data available. As such, this study document will primarily focus on densification processes applicable to softwood (e.g., pine, birch, and aspen) as a baseline of evaluation. However, reasonable judgment will be used to extend the report findings for agricultural residue densification considerations.

For evaluation purposes, this study considers a mid-size densification plant of 80,000 tons of densified product per year (14 tons per hour) operating 24 hours per day and 6 days per week. A capacity factor of 80 percent was assumed, allowing for downtime, outages, etc. The incoming feedstock is considered to be softwood (e.g., pine, birch, aspen) received in 2 inches minus sizing (chips, sawdust) with a moisture content of 25 percent. As a production plant's feedstock in-feeding and final product out-loading are generally common among various densification processes, they are outside the scope of this study. The densification process evaluation shall be limited to the production process beginning with the feedstock's initial grinding size reduction to and including the screening/cooling section.

1.1 Objective

The objective of this Document of Evaluation is to address the following points of interest:

- Is the densification process designed for biomass densification?
- Identify the most efficient and cost-effective biomass densification technologies available today.
- Assess biomass densification technologies to be available in the near future.
- Identify material handling and process differences between densification systems.
- What are the expected throughputs in tons per hour for the densification systems?
- Assess differences in biomass conditioning requirements pre-densification.

- Assess differences in biomass handling and cooling requirements post-densification.
- Provide indicative equipment costs.
- Address concerns related to individual densification systems (pelleting or briquetting).
- Compare the biomass densification systems.

1.2 Approach

This report is organized into the following sections:

- **Section 2.0 – Densification Processes Suitability for Biomass –** This section describes several densification processes in general and their suitability for biomass densification. A brief discussion of general considerations and feedstock parameters is also discussed.
- **Section 3.0 – Biomass Densification Technologies Available Today –** This section describes currently available densification processes, including pelleting and briquetting.
- **Section 4.0 – Biomass Densification Technologies Expected in the Future –** This section identifies and describes emerging biomass densification technologies that may be suitable to be implemented for commercial production in the future.
- **Section 5.0 – Material Handling and Process Differences** – This section describes equipment, material handling, and process requirements/differences among the available densification processes.
- **Section 6.0 – Expected Throughputs and Required Horsepower** – This section describes varying throughputs and energy requirements among the available densification processes.
- **Section 7.0 – Biomass Pre-Densification Conditioning** – This section describes varying feedstock pre-densification conditioning requirements among the available densification processes.
- **Section 8.0 – Biomass Post-Densification Handling and Cooling –** This section describes varying post-densification handling and cooling requirements among the available densification processes.
- **Section 9.0 –Capital Costs and Design–** This section summarizes the basic designs and capital costs among the available densification processes.

- **Section 10.0 – Densification Systems Concerns –** This section addresses the concerns related to individual densification systems.
- **Section 11.0 – Densification Systems Comparison –** This section compares the densification systems based on throughput, indicative equipment costs, and efficiency.

1.3 Summary

The information outlined in this document is limited to the actual densification process line, and is not intended to address the production plant's full requirements. These plant requirements would include, but not be limited to, site procurement and development, reliable feedstock contracts, material receiving and on-site storage, finished product storage and load-out, and environmental concerns. In addition, the production plant's requirements will be influenced by feedstock proximity and seasonal availability, available infrastructure such as roads and utilities, and ultimately the intended market for a particular form of densified materials.

The information presented in this document is intended for general guidance only for a representative densification production line. The facility's requirements, equipment, and costs can vary greatly from one facility to the next.

As such, Zachry Engineering recommends that the development of a particular production plant's economic feasibility be based upon the specific requirements of location, available feedstock, and target end user market. The initial stages of a plant development must include feedstock testing which will assist in correct selection of material processing and densification equipment. Engineering firms and equipment Vendors experienced in plant design and operation, material handling, and process engineering should be retained to perform initial feasibility study and investigation. A marketability study, including material test burns, should be performed to establish reasonable revenue expectations for a particular plant and densified product form.

Information presented in this document indicates several densification technologies, including pelleting and briquetting, are suitable and potentially viable. Pelleting and briquetting have different advantages and disadvantages and system requirements. Both technologies require suitable material handling, feedstock size reduction, and moisture control.

Pelleting has the apparent advantages of feedstock flexibility (with conditioning), lower initial capital equipment costs and higher densified material density. The true installed capital cost must be evaluated for the remaining plant requirements such as material storage and handling needs, electrical equipment, buildings, etc. Some disadvantages of pelleting include more stringent feedstock size reduction, pre-densification conditioning requirements, additional auxiliary equipment (e.g., steam boiler, cooling equipment). In addition, it appears there is potential for even greater (estimated at 60 percent) densification throughput when the feedstock is changed from wood to agricultural residues.

Briquetting has the advantages of less stringent and one-step feedstock size reduction, no pre-densification conditioning requirements, feedstock flexibility, lower power needs, and no need for additional briquette cooling equipment. However, the potential disadvantage is the slightly higher initial capital equipment cost. This capital equipment cost may be offset by remaining plant requirements such as material storage and handling needs, electrical equipment, buildings, etc. True installed cost should be fully considered for a particular plant. In addition, the resulting densified material has a lower density and its form of pucks or logs may present material handling or usage concerns for the end user.

Section 2 – Densification Processes Suitability for Biomass

The processes suitable for woody biomass densification on a production scale can be classified as two types: pelletizing (pelleting) and extrusion briquetting. Extrusion briquetting may employ either reciprocating ram/piston press or screw press technology. As it is more prevalent for commercial production, this study has considered the reciprocating ram/piston press type of extrusion briquetting equipment. A third type of densification is roll briquetting which is showing promising results in the lab, but has not yet been implemented on a commercial production scale.

This report includes a general schematic which shows the basic process flow for two pelleting and one briquetting arrangement. Refer to the sketch attached in Appendix A.

Pelleting and extrusion briquetting are described in further detail below.

2.1 General Densification Process Variables

Densification process variables that influence densification results include:

- Temperature
- Pressure and pressure application rate
- Hold time
- Die geometry

Although critical to densification results, the process variables will not be discussed in detail. The process requirements vary according to the specific feedstock control and the entire production line. We recommend laboratory testing be performed during the specification and design of densification plant equipment. Test results provide valuable information for establishing equipment and process requirements. As densification is a combination of art and science, process flexibility should be built into the plant to maintain desired throughput.

2.2 Feedstock Parameters

Feedstock variables that influence densification results include:

- Moisture content
- Particle size

- Biochemical characteristics
- Conditioning

Feedstock moisture content requirements are a function of the feedstock material and the densification process used. Although there may be variances between different Manufacturers' equipment, acceptable moisture content for densification of soft wood residues are 9 to 12 percent for pelleting, and 10 to 15 percent for extrusion briquetting. As woody biomass has a high moisture content (25 to 50 percent), drying equipment is required prior to the presses to control woody feedstock moisture content entering the densification section. If properly handled and controlled, some agricultural residues could possibly be received with a moisture content of about 10 percent. Due to harvest cycles, extended on-site storage of agricultural residues would likely be required, necessitating covered storage and / or process drying equipment.

Required feedstock particle size is again a function of the densification process used and varies with the specific equipment geometry (e.g., die size). Size reduction is accomplished by processing the delivered feedstock in one or two steps using grinders, choppers, and hammer mills. Screens are used to ensure satisfactory maximum particle size. For pelleting, the feedstock reaching the pellet mill must pass screen holes at least 1/16-inch smaller than the pellet diameter. For most ram/piston press briquetting, feedstock in 1/2-inch to 3/4-inch minus size is generally considered suitable. For agricultural residues received in bale form, size reduction would be accomplished with a combination of bale grinders and hammer mills.

Woody plants contain lignin which contributes to the strength characteristics of densified pellets and briquettes. The heat produced during densification, along with the heat added in some conditioning, assists the release of lignin which then acts as a natural binder for the material. Partial breakdown of lignin may occur during particle size reduction, also promoting binding. Depending on feedstock and production efficiencies, additional binding agents may be added during the pre-densification conditioning.

Although heated water may be used; generally, feedstock for pelleting is conditioned with high quality steam. The added heat promotes the release of lignin for material binding. The controlled addition of moisture also provides feedstock lubrication for ease of pellet extrusion and reduced die wear.

2.3 Pelleting

Pelleting is an extrusion type thermoplastic molding process by which ground material is forced by an internal roller through cylindrical dies in a rotating external ring, producing compact pellets. Some Manufacturers use a flat fixed die with a roller rotating over the die to force the material through the die holes. As it is more widely used, this study's discussion shall be limited to the internal roller/cylindrical die equipment. The incoming feedstock must be of proper size, moisture content, and temperature to ensure pellet quality. Pelleting of soft wood materials should result in bulk densities of 35 to 40 lb/ft^3, moisture contents ranging from 8 to 10 percent and good durability. The produced pellet is 1/4 to 5/16 inch in diameter and up to 1 1/2 inches long.

2.4 Extrusion Briquetting

Extrusion briquetting uses a reciprocating ram/piston press to force the ground material through a tapered die. As discussed above, the incoming feedstock must be of proper size, moisture content, and temperature to ensure briquette quality. Good briquetting of wood materials should result in bulk densities of 20 to 35 lb/ft^3, moisture content ranging from 10 to 12 percent, and good durability. The briquettes produced can be in the form of pucks, logs, etc. of varying diameters and thicknesses depending upon equipment and die geometry selected. Although this evaluation is based upon pucks approximately 3 inches in diameter and 1/2 inch in thickness, the process discussions and considerations are applicable to various size briquettes produced by the ram/piston press densification process.

Section 3 – Biomass Densification Technologies Available Today

The technologies available today for large-scale production of densified biomass, specifically wood, are pelleting and briquetting.

Wood pelleting technology is well established through decades of commercial production. Annual global wood pellet production capacity is estimated in excess of 10 million metric tons. Current annual production in the United States and Canada is estimated in excess of 3 million metric tons. The technology is well established and production capacity growth is expected to continue. Specific process requirements are discussed in the following sections.

Extrusion wood briquetting technology is well established, although at a much smaller commercial scale than pelleting. The technology has been in use for decades. Briquetting provides the option of a mobile densification system, which may be taken to the feedstock to be densified for potential transport cost savings.

Although not well established on a commercial scale for densification of agricultural residues, both pelleting and extrusion briquetting technologies are considered suitable. Although in-feed systems are not part of this study scope, the feedstock in-feed system should be configured as required for receipt and pre-processing of agricultural residues. These in-feed system adjustments may include, but not be limited to, bale conveyors, bale tub grinders, and hammer mills. Feedstock drying equipment may possibly be eliminated due to the lower moisture content for ag byproducts. However, covered storage would be required to prevent moisture introduction into the feedstock. Some supplemental drying equipment may or may not be required, depending on feedstock type and handling operations.

We assumed higher throughputs for the presses for the same process when densifying agricultural residue, compared to woody feedstock, based on input from equipment Manufacturers. Increased throughputs for agricultural residues (as compared to woody feedstock) are assumed at 60 percent for pelleting and 20 percent for extrusion briquetting. This increase requires larger handling and storage equipment, such as conveyors, bins, and silos.

Section 4 – Biomass Densification Technologies Expected in the Future

We expect strong growth in wood pelleting will continue for the foreseeable future. Use of extrusion briquetting densification will continue, although on a smaller scale than pelleting.

There is significant interest in the use of roll press briquetting for biomass densification. Although there are currently no commercial installations, initial promising laboratory test results indicate roll press briquetting of biomass has potential to be a low-cost, low-energy, high-capacity densification approach. As with any densification process, reliable control of process variables and feedstock properties is essential to good results.

Roll press briquetting is a well established technology for the densification of powdery granular materials, such as minerals, food products, detergents, coal, sludge, etc. The basic process is to use a screw feeder to direct materials between two opposing rotating presses. The presses include pockets in order to produce the desired briquette and deliver the required press for densification.

With the increased advancement of renewable energy and biomass technology, we assume the above densification technologies will advance the use of agricultural residues.

Section 5 – Material Handling and Process Differences

This section discusses material handling and process differences between pelleting and ram/piston press briquetting.

Effective and reliable control of critical process variables and feedstock parameters are essential to maintaining high production capacities and consistent final product quality. The most important variables and processes are:

- Feedstock size reduction (grinding)
- Feedstock moisture content (drying)
- Pre-densification conditioning
- Densification
- Interim feedstock storage (surge bins)
- Material handling

We assumed, for evaluation purposes, incoming feedstock is soft wood (e.g. pine, birch, aspen) residues supplied as 2 inches minus sizes (chips, sawdust). We also assumed a maximum moisture content of 25 percent. Additional drying equipment or capacity is needed for “green” feedstock with moisture contents up to 50 percent. The wide variance of moisture content for woody biomass requires feedstock handling and size reduction equipment be sized for the higher moisture content.

Requirements for feedstock receiving and on-site handling are a function of the feedstock, its source proximity to the densification plant, locally available transportation systems, and the operating plan for the facility. Although feedstock delivery via rail or walking floor trailers may occur, it is normally shipped in dump trucks, tipping trailers, or box trailers. The dump trucks or tipping trailers may or may not be covered depending upon feedstock source proximity or transport considerations. The material is unloaded to an on-site stockpile (preferably covered) or receiving bins. The dump trucks or tipping trailers unload unattended. Box trailers require an on-site tipping deck to unload. The material receiving system would include truck scales. These elements are independent of the densification process.

To begin the production process, receiving bins are loaded with feedstock via truck deliveries, on-site front-end loaders, or conveyors. It may be possible to transport incoming feedstock pneumatically if the densification plant is located adjacent to a feedstock source (e.g., lumber mill, furniture Manufacturer, etc.)

SECTION 5 – MATERIAL HANDLING AND PROCESS DIFFERENCES

Regardless of the densification process selected, initial grinding equipment would follow a receiving bin or receiving conveyor. The bin includes either a walking floor or belt conveyor to move the material from the receiving bin into the initial grinding section, or a conveyor (bucket elevator or drag) which in turn transports the material to the initial grinding section. For briquetting, and depending on site operations, it may be possible to eliminate the receiving bin and load the feedstock directly into the input hopper of a wood grinder for size reduction.

Once the receiving bins are loaded, the production process begins and subsequent operations vary by the densification process. These differences are discussed in the following sections.

5.1 Pelleting

This discussion is limited to pellet mills that use internal rollers and external cylindrical ring dies to produce densified pellets. Some Manufacturers use a flat fixed die with a roller rotating over the die to force material through the holes. This study's discussion is limited to internal roller/cylindrical die equipment. The pellets are 1/4 inch to 5/16 inch diameter, 1/2 inch to 1 inch length, moisture content of about 10 percent and bulk density from 35 to 40 lb/ft^3. The process requires that 100 percent passes a screen 1/16 inch smaller than pellet diameter and a moisture content of 10 to 12 percent, depending on Manufacturer's requirements. Material must be free of heavy particles and metallic materials. Effective incoming material control to the pellet mill is essential for reliable production and consistent product quality.

Although there are basic material size reduction and drying requirements, there are several arrangements concerning material handling approaches, interim storage and feeding methods. These are established during plant design based on intended facility operation.

5.1.1 Feedstock Size Reduction for Pelleting (Grinding)

Size reduction will occur in two steps using appropriately sized grinding or hammer mill equipment. This will reduce feedstock size to 1/16 inch smaller than pellet diameter.

Typically, each hammer mill includes its own pre-bin (dosing, with level indicators) and in-feeding/out-feeding screws. The in-feeding screws should have variable frequency drives (VFD) to ensure constant feeding. Hammer mills should be equipped with separators for removing stones and ferrous metal materials.

SECTION 5 – MATERIAL HANDLING AND PROCESS DIFFERENCES

Size reduction equipment arrangement including grinders/mills, screening, storage hoppers, and conveyors (drag or pneumatic) should consider user preference and operation plans. Two possible arrangement examples are outlined below.

Arrangement A – Grinding, Hammer Mill

This arrangement includes a receiving bin with live bottom or conveyor, primary hammer mills, secondary (fine grinding) hammer mills, and interconnecting conveyance.

The walking floor receiving bin is equipped with a discharge screw to move feedstock to a screw or drag conveyor, transporting material to a bucket elevator which loads pre-bins for primary hammer mills.

Initial size reduction occurs in the primary grinding hammer mill, which is equipped with a pre-bin with level indicators and high- and low-level sensors to ensure adequate material availability for size reduction. A screw conveyor transports material from pre-bin to hammer mill. The conveyor system may be multi-screw for variable operation depending on hammer mill load. A separator for removing heavy and metallic materials is located prior to the hammer mill to minimize excess hammer wear and maintenance.

The primary hammer mill reduces size to 95 percent passing a 3/8-inch screen. An out-feeding screw and chute moves material from mill discharge to a bucket elevator which loads the pre-bin for the dryer. The dryer options are described in Section 5.1.2.

Final size reduction occurs in the secondary hammer mill which is equipped with the same controls as the primary mill. It provides size reduction to 95 percent passing a 3/16-inch screen. An out-feeding screw conveyor discharges from the secondary mills and material is conveyed via conveyors to a buffer silo for interim storage prior to densification.

Arrangement B – Pre-Screening and Hogging

Arrangement B includes a receiving bin with vibratory screener, primary grinding wood hog, secondary hammer mills, interconnecting conveyors (drag, screw, pneumatic), and interim surge hoppers.

The vibratory screener provides material segregation. Material retained on a 2-inch screen is directed to the primary grinder. Material passing the 3/4-inch screen bypasses the primary grinder and is directed to a drag conveyor serving the primary grinder discharge. The vibratory screener is equipped with metal detection and a magnet to provide preliminary removal of ferrous materials.

All material over 3/4 inch from the vibratory screener is directed to the primary grinder, where the material is reduced from 2 inches minus to 3/4 inch minus. Material discharging from the grinder is transported by drag conveyor to a rotary airlock and then enters a pneumatic conveying system, which in turn transports the material to a wet storage hopper. Dust collection pickup points are provided at the vibratory screener, wood hog hopper, and rotary air lock. Collected dust is transported via exhaust fan and ducting to a dryer use hopper.

The wet storage bin provides holding capacity prior to fine grinding. The bin is equipped with a hopper reclaimer and a powered collection filter. During production, material is discharged from the hopper and drag conveyed to the fine grinding section.

In the fine grinding section, feedstock is screw conveyed to a number of hammer mills where secondary size reduction occurs. Each mill is equipped with a vibratory feeder, a magnetic chute, and a bin vent filter. The mill reduces particle size as needed for pelleting. Each mill includes its own discharge screw conveyor and a rotary air lock discharging into a pneumatic conveying system, which transports material to a dryer receiving bin.

The dryer receiver provides interim storage prior to drying. The hopper has a product reclaimer and a powered dust collection filter. Material is discharged and transported by drag conveyor to the dryer in-feed hopper.

5.1.2 Feedstock Moisture Control for Pelleting (Wood Drying)

Feedstock must be dried to moisture in the 8 to 12 percent range, 10 percent nominal, following size reduction. Several suitable options for drying are available and are outlined below.

For ag byproducts, feedstock drying equipment may possibly be eliminated due to the lower moisture content. However, covered storage would be required to prevent moisture introduction into the feedstock. Some supplemental drying equipment may or may not be required, depending on feedstock type and handling operations.

Rotary Drum Drier

The most common dryer type used for biomass moisture reduction is available in a single pass or triple pass configuration. Rotary drum driers can be fired with natural gas, propane, biomass, or oil. They are usually equipped with a dedicated pre-bin (dosing) bin, with level indicators and high- and low-level sensors to ensure adequate material charge is available. A multiple screw feeder transports material from pre-bin to dryer.

SECTION 5 – MATERIAL HANDLING AND PROCESS DIFFERENCES

This study assumes a rotary drum dryer fired on recirculated biomass. The dryer's fuel is transported to the burner via conveyor. Dried material is discharged pneumatically from the rotary drum to a set of cyclones using an exhaust fan and ducting. Material is discharged from the cyclone hoppers using a discharge screw. Rotary air locks control material flow and diverters direct flow to the burner. Material is transported to the secondary hammer mill (fine grinding) or densification section via transport and bucket conveyors. Dryer retention time is a function of initial/final moisture content, agitation, and heat input. The systems also have blowers, exhaust fans, dust collection/recycle, and PLC control systems.

Stationary Dryer

This is another type of dryer which exposes feedstock to a rotating shaft with agitator plates and heated air. It provides further size reduction from shaft rotation and negative air flow. Fuels include natural gas, propane, or oil.

A buffer silo of adequate capacity provides for interim storage and reliable material availability for densification. The silo is equipped with a bottom reclaimer for first-in/first-out discharge. Material discharges from the silo via a transport screw. A second inclined transport screw and bucket elevator transports material to the pelleting section of the production line.

5.1.3 Pre-Densification Conditioning for Pelleting (Heat and Moisture)

Biomass (wood) densification by pelleting usually requires some sort of conditioning. Although heated water may be used, pelleting feedstock is usually conditioned with high quality steam. Added heat promotes the release of lignin for material binding. Controlled moisture addition provides feedstock lubrication for ease of pellet extrusion and reduced die wear. Conditioning occurs prior to entering the pellet mill dosing bin. Feedstock enters the conditioner mixing trough, which has a mixing shaft with adjustable paddles. Steam is injected into the trough via steam inlets with regulating valves. The agitating action and control of inletting steam allows feedstock to be uniformly conditioned. The material then discharges to the pellet mills for densification.

The conditioning section is usually equipped with a dedicated pre-bin with level indication and screw feeders with VFDs prior to entering the conditioning trough to ensure adequate charge is available and uniformly fed to the conditioning section.

5.1.4 Material Handling / Surge Bins

Conveyance options include pneumatic or mechanical means, including bucket elevators, in-feeding and discharge screws, and drag flite conveyors. Proper and adequate arrangement of storage and dosing bins with level indication is required to ensure constant feeding to the hammer mills and drying equipment. A buffer storage silo for storing sized and dried feedstock is required prior to densification. Bins and silos are equipped with rotary air locks for feeding control. Cyclone separators, blowers, and ducting are strategically located for dust control and feedstock recycle options.

5.2 Extrusion Briquetting

The extrusion briquetting process uses a reciprocating ram/piston press to force the ground material through a tapered die. The briquette is about 3 inches diameter and 1/2 inch thick, with bulk density from 20 to 35 lb/ft^3, 10 to 12 percent moisture, and good durability. For the material in-feeding to the briquette press, 100 percent should pass a 3/4-inch screen with moisture ranging from 6 to 15 percent.

5.2.1 Feedstock Size Reduction for Briquetting (Grinding)

Material size reduction occurs in the grinder. Typical size reduction system is accomplished in one step, as opposed to two steps required for pelleting. The grinder has a receiving bin with a belt conveyor to move the material in and reduces material to less than 1 inch. Material discharging from the grinder section passes over a rotating or vibrating screen. Material less than 3/4 inch (approximately 80 percent) passes through the screen and material greater than 3/4 inch is recirculated back through grinding. The screening and recirculation approach allows for smaller motors and energy efficiency. Material passing the screen is conveyed (drag or pneumatic) to a surge silo equipped with a reclaimer system.

5.2.2 Feedstock Moisture Control for Briquetting (Drying)

Reducing the feedstock moisture content to a 6 to 15 percent range occurs in the drying section. Available drying equipment is the rotary drum or stationary type as described in Section 5.1.2. The drying equipment would also be arranged similarly. The resulting feedstock moisture content is assumed to be 10 percent nominal for purposes of cost comparison.

5.2.3 Pre-Densification Conditioning for Briquetting

Generally, extrusion briquetting requires no pre-densification conditioning.

5.2.4 Material Handling / Surge Bins

Same requirements as described for pelleting.

Section 6 – Expected Throughputs and Required Horsepower

Desired densification plant throughputs are achieved by properly sizing and arranging production line process equipment. Plant throughput should not limited by the densification process selected. Reliable and locally available feedstock supply and transport economics should dictate facility sizing.

Although there may be variances according to specific plant arrangements and between equipment Manufacturers, a summary of average expected horsepower requirements is outlined below. The horsepower summary is limited to the densification production process equipment only, beginning with the feedstock's initial grinding to and including the screening/cooling section.

Production plant's feedstock in-feeding and final product out-loading are generally outside the scope of this horsepower summary. No adjustments were made for when motors operate at less than full power.

Horsepower requirements for material handling equipment are allocated to the respective densification production section that it serves, i.e., size reduction, drying, densification, and cooling/screening.

Wood Feedstock	**Power Demand - Production Line**	
Production Section	**Pelleting – HP**	**Briquetting – HP**
Feedstock In-feed / Size Reduction	750	500
Feedstock Drying	320	350
Conditioning / Densification	1380	850
Cooling / Screening	50	0
Total Horsepower	2500	1650
Power Demand per Throughput – HP / TPH	179	118

Notes:

1. Based on 14 tons/hour of densified wood per Section 1.
2. Pelleting requires an added package boiler for conditioning steam. No conditioning is required for briquetting.
3. No additional cooling equipment is required for briquetting. Product cooling is provided by the briquette press discharge cooling line, which also serves to push the product out to trucks or trailers.
4. The above horsepower requirements are reflective of densification of woody feedstock. Approximate comparison to expected horsepower for densification of agricultural residues is outlined in Section 11.
5. Not included here: Final product load-out for pelleting requires additional conveyance, storage silo, bucket elevator, and truck load-out lines.

Section 7 – Biomass Pre-Densification Conditioning

Pre-densification conditioning requirements for pelleting and extrusion briquetting were previously discussed in Section 5.1.3 and 5.2.3, respectively.

Section 8 – Biomass Post-Densification Handling and Cooling

Densified woody material, pellets or briquettes are discharged from the densification equipment at approximately 200ºF. It is recommended that the pellets or briquettes be cooled to approximately 80ºF before handling. This cooling process also tends to reduce the final product's moisture content slightly. Following cooling, additional screening is also desired to separate dust, particles, and fragments.

For higher throughputs when densifying agricultural residues, the capacity of post-densification handling and cooling equipment needs to be increased accordingly.

8.1 Pelleting

Following densification and prior to load-out, pellets should be cooled and screened. Hot pellets leaving the pelleting press are soft, fragile, and subject to breakage. The cooling process hardens the pellets for improved handling durability. In addition, the cooling process tends to reduce the pellets moisture content by approximately 1 percent. The pellet cooler would be a counter-flow type available from a number of Manufacturers. Pellets enter the cooler through an airlock system which includes adjustable air flow ducting and distributed evenly across the cooling bed.

Air is circulated across the pellet bed to promote cooling. Pellets are discharged from the cooler through a rotary air lock and directed to a shaker screener where fine particles and dust are separated from the pellets. Fine particles are recycled back to the system for densification. The pellets are discharged from the screener ready for storage or load-out. Weather protection should be provided for pellets both in the storage and load-out systems.

8.2 Briquettes

The extrusion briquetting presses discharge the briquettes and push them down discharge cooling lines to a collector, e.g., truck or bin. No additional cooling equipment is required. Although out-loading is excluded from this study, this discharging cooling line may be directed to storage bins and eliminate the need for some out-loading conveying equipment. Weather protection should be provided for briquettes both in the storage and load-out systems.

Section 9 – Capital Costs and Design

Mechanical equipment cost is summarized below for the pelleting and briquetting densification processes of woody feedstock. The equipment list presents major mechanical equipment components and systems.

Although there may be variances according to specific plant arrangements and between equipment Manufacturers, a summary of average expected capital equipment cost requirements are outlined below. Installation labor is not included. The plant's in-feeding and final product out-loading are outside the scope of this cost summary.

Production Section – Wood Feedstock	Pelleting Mechanical Equipment Cost	Briquetting Mechanical Equipment Cost
In-feed / Size Reduction / Drying	$2,380,000	$1,730,000
Conditioning / Densification	$1,850,000	$3,400,000
Cooling / Screening	$220,000	$0
Control Systems	Included	Included
Total Plant Mech. Equipment	$4,450,000	$5,130,000
Mech. Equipment Cost per Ton	$56	$64

Notes:

1. The above costs do not include costs for engineering, land, electrical, foundations structures, installation labor, and Owner's costs. As a rough rule of thumb, total plant cost may be two or three times total mechanical equipment cost. More work should be done to obtain costs for an overall installation.
2. Pelleting requires an added package boiler for conditioning steam. No conditioning is required for briquetting.
3. No additional cooling equipment is required for briquetting. Product cooling is provided by the briquette press discharge cooling line, which also serves to push the product out to trucks or trailers.
4. Final product load-out for pelleting requires additional conveyance, storage silo, bucket elevator and truck load-out lines.
5. The above estimated costs are reflective of densification of woody feedstock. Approximate comparison to estimated costs for densification of agricultural residues is outlined in Section 11.
6. The equipment estimates are based on 2008 dollars.

SECTION 9 – CAPITAL COSTS AND DESIGN

9.1 Pelleting vs. Briquetting

The basic densification system design and typical equipment requirements for pelleting versus briquetting are outlined in the following table.

Process Section	Pelleting	Briquetting
Feedstock intake / size reduction section	Per Arrangement A or B, Section 5.1.1 Feedrate control system	Electric powered stationary grind system with conveyor belted receiving bin Vibratory screening Magnetic separator Conveyor for recycle of oversized material back through grinder Transport conveying between grinder and material storage silo Material storage silo with reclaimer and discharge screw Transport conveying between storage silo and dryer system Feedrate control system
Feedstock drying section	Either rotary drum or stationary Wet product intake Preferably biomass fired burner Fuel screening and recirculation system, including storage Cyclone collector ID fan and ducting Rotary screw discharge conveyor Burner and feedrate control system	Either rotary drum or stationary Wet product intake Preferably biomass fired burner Fuel screening and recirculation system, including storage Cyclone collector ID fan and ducting Rotary screw discharge conveyor Burner and feedrate control system

SECTION 9 – CAPITAL COSTS AND DESIGN

Process Section	Pelleting	Briquetting
Feedstock conditioning and densification section	Feedstock steam conditioning system Pellet mills with including pre-bins and screw feeding Screening and magnetic separators Required conveying systems Control system	Material surge silos with reclaimers and discharge screws Cyclone separators for material inlet to dosing silos Dosing silo to serve one or more briquetting presses Extrusion briquetting presses with feeding screws, intake bin discharge cooling lines Control system
Pellet cooling and screening section	Counter flow pellet cooler Airlock and adjustable air flow ducting Rotary airlocks Discharge shaker / screener Recycling system for fines Required conveying systems Control system	

Section 10 – Densification Systems Concerns

As discussed in Section 2, a number of process variables and feedstock parameters must be consistently controlled throughout the densification production line to ensure satisfactory densification results. These, along with other concerns, are discussed below.

Moisture content must be monitored and controlled with moisture monitoring equipment and drying equipment throughout the process. With proper monitoring and control feedrates, dryer retention times, and other variables can be adjusted as needed. Unacceptable moisture results in poor durability, plugging, or failure to densify. Pelleting requires moisture ranging from 10 to 12 percent. Briquetting is more forgiving and acceptable moisture can range from 6 to 15 percent. We recommend drying occur after size reduction to minimize dryer size, retention time, and improve efficiency.

Adequate and correctly arranged storage silos and surge bins, along with feedrate and level control, are critical to maintaining production rates. The material must be available and fed into each production step according to equipment throughput capacity. Each grinder, hammer mill, pellet mill, or pellet press needs to be equipped with dedicated dosing capacity and material feeding equipment. Feeders should be equipped with VFDs to allow varying feedrates according to demand. Equipment fed incorrectly will produce poor results and may plug. Storage silos and surge bins should be equipped with level indication (high / low) so in-feeding / out-feeding equipment can be adjusted.

Magnetic separation equipment is necessary to remove large, ferrous materials prior to introduction into process equipment. Feedstock screening of rocks and other non-ferrous materials is also required. This will minimize equipment damage and shutdowns.

Feedstock processing, particularly grinding, conveying and discharging generate dust. Dust control should be located where needed according to the production line. Closed storage silos and bins should be equipped with vent filter and exhaust fans. Exhaust fans and ducting should be used to convey collected dust and fines back into the process.

As with any material handling and processing lines, particularly with dust generation and storage, spark detection and fire protection is required to meet National Fire Protection Association and other applicable safety and code requirements. These design requirements are specific to the production process arrangement and local regulations.

Section 11 – Densification Systems Comparison

Basic efficiency of a densification system can be established by considering the following:

- Capital equipment cost
- Operating horsepower / energy usage
- Additional capital equipment required for utilities (steam, air, water)
- Additional capital equipment required for product out-loading
- Production variances with change in feedstock

The baseline for this evaluation is soft wood. However, it is may be desired for these densification technologies to be applied to agricultural residues, such as wheat straw.

Pelleting equipment Manufacturers indicate production throughput for agricultural residues will be approximately 50 to 75 percent greater than for soft wood using the same pelleting mills. However, changes would be required for the initial size reduction equipment (use of bale grinder versus wood mill or hog). In addition, the size of material handling and production bins / silos would need to be increased for higher material throughputs. We will assume a 60 percent throughput increase for wheat straw. The pellet production line requires three pellet mills.

Briquetting equipment Manufacturers have been reluctant to estimate production throughput increases for agricultural residues without further testing. However, an increase is expected. Similar to pelleting, changes would be required for the initial size reduction equipment (use of bale grinder versus wood mill grinder). In addition, the size of material handling and production bins / silos would need to be increased for the higher material throughputs. We will assume a 20 percent throughput increase for wheat straw. The briquetting production line requires eight briquette presses.

An approximate mechanical equipment cost comparison of pelleting and extrusion briquetting, for soft wood and wheat straw, is found in the table below.

SECTION 11 – DENSIFICATION SYSTEMS COMPARISON

GENERAL EQUIPMENT SUMMARY	Softwood with Drying		Ag Residue without Drying	
	Pelleting	Briquetting	Pelleting	Briquetting
Throughput	100% of baseline wood	100% of baseline wood	160% of baseline wood	120% of baseline wood
	80,000 TPY	80,000 TPY	128,000 TPY	96,000 TPY
	14 TPH	14 TPH	22.4 TPH	16.8 TPH
Feedstock as received	Softwood	Softwood	Ag residue	Ag residue
	2" minus	2" minus	Bales	Bales
	25% moisture content	25% moisture content	10% moisture content	10% moisture content
Feedstock prior to conditioning	Softwood	Softwood	Ag residue	Ag residue
	3/16" minus	3/4" minus	3/16" minus	3/4" minus
	10 to 12% moisture content	6 to 15% moisture content	10 to 12% moisture content	6 to 15% moisture content
Primary (coarse) grinding	(1) Hammer mill or wood hog	(1) grinder	(1) bale grinder	(1) bale grinder
Secondary (fine) grinding	1 to 4 hammer mills	Not required	1 to 4 hammer mills	Not required
Feedstock drying	(1) rotary drum or stationary dryer	(1) rotary drum	Not required	Not required
Dryer fuel	Dry wood	Dry wood	N/A	N/A
Conditioning	(3) steam conditioners	Not required	(3) steam conditioners	Not required
Densification	(3) pellet presses	(8) ram presses	(3) pellet presses	(8) ram presses
Post-densification cooling	Counter flow cooler	Discharge cooling lines	Counter flow cooler	Discharge cooling lines

SECTION 11 – DENSIFICATION SYSTEMS COMPARISON

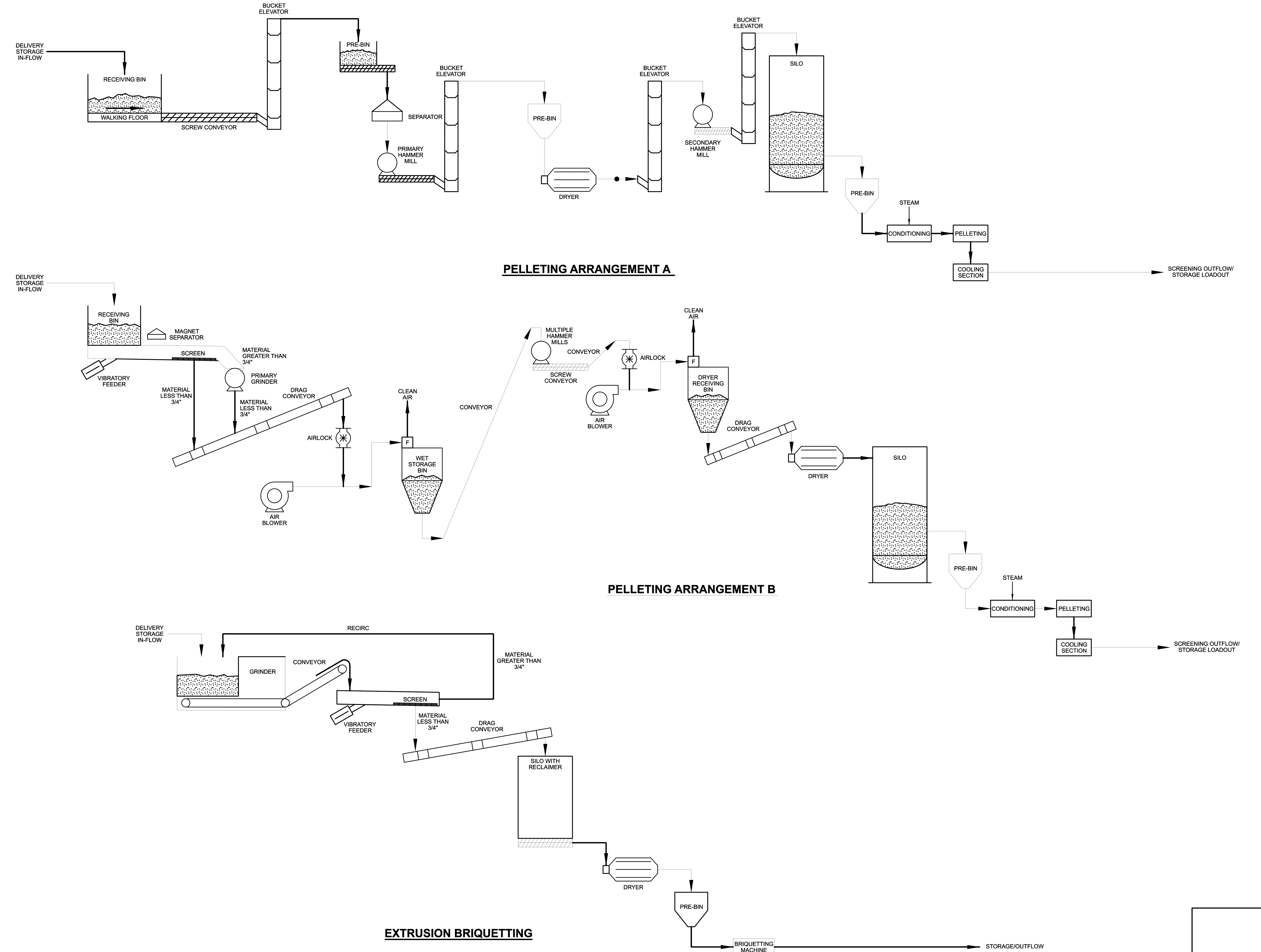
BASIC EQUIPMENT CAPITAL COSTS	Softwood with Drying		Ag Residue without Drying	
	Pelleting	Briquetting	Pelleting	Briquetting
Feedstock In-feed / size reduction	$1,400,000	$750,000	$1,730,000	$825,000
Feedstock drying	$980,000	$980,000	$0	$0
Conditioning / densification	$1,850,000	$3,400,000	$2,109,000	$3,465,000
Cooling / screening	$220,000	$0	$275,000	$0
Subtotal	$4,450,000	$5,130,000	$4,114,000	$4,290,000
Add for Package Boiler	$40,000	$0	$40,000	$0
Adjusted Capital Equipment Costs	$4,490,000	$5,130,000	$4,154,000	$4,290,000
Estimated Capital Cost per Ton	**$56**	**$64**	**$32**	**$45**

BASIC EQUIPMENT HORSEPOWER	Softwood with Drying		Ag Residue without Drying	
	Pelleting	Briquetting	Pelleting	Briquetting
Feedstock In-feed / size reduction	750	500	900	600
Feedstock drying	320	320	0	0
Conditioning / densification	1,380	830	1,500	900
Cooling / screening	50	0	100	0
Total	2,500	1,650	2,500	1,500
Estimated HP per TPH	**179**	**118**	**112**	**89**

Additional considerations relating to the specific plant design and operation plan are outside the scope of this study. These include, but are not limited to, the following items:

- Additional capital equipment required for feedstock in-feeding, on-site storage, and outfeeding
- Operation and maintenance costs
- Remaining plant requirements including engineering, balance of plant systems, building, and other capital costs
- End user product requirements

Appendix A – Biomass Densification Process Flow Diagram



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