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Combined Heat and Biochar Technology Assessment for a Composting Operation

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PURPOSE OF THE TECHNOLOGY ASSESSMENT

This assessment compares technology options for adding Combined Heat and Biochar (CHAB) equipment to the operations of a hypothetical composting business located in Nebraska. This assessment is a first look at technology options that are readily available from several manufacturers who are prepared to deliver and help commission a CHAB system that can provide useful thermal energy and a biochar product for a composting enterprise or any similar operation. This assessment is not a full feasibility study. This study is undertaken with the help of the vendors who provided information about their systems, and it relies on the expertise of the US Biochar Initiative, Wilson Biochar Associates and TR Miles Technical Consultants, Inc. This assessment was partially funded by the Nebraska Forest Service. The remainder of the funding was provided by USBI.

DISCLAIMER

This document is intended to serve as a summary and does not constitute an offer or recommendation to invest in any technology or project. This summary contains forward-looking statements that are based on our expectations, assumptions, estimates and projections about the technologies reviewed. These forward-looking statements include among other things, statements qualified by words such as "expect", "anticipate", "can", "intend", "believe", "estimate", "should" and other similar words indicating future events. These forward-looking statements are subject to numerous risks and uncertainties that could cause actual results to differ materially from those described in this report.

I. Introduction

Organic waste management enterprises perform vital public services for many communities. Processing organic waste such as green waste, manure and food waste keeps waste out of landfills while producing valuable soil amendment and fertilizer products. This technology assessment analyzes the contribution that a Combined Heat and Biochar System could make to the profitability of a composting operation that produces vermicompost in a system that requires heat during the winter months to keep the worms as productive as possible. If nursery operations are integrated into the enterprise, heat could also be used for greenhouses.

The volume of urban greenwaste in Nebraska and other states is growing as trees succumb to threats such as Emerald Ash Borer (EAB), pine bark beetles, other pathogens and drought. Food waste diversion from landfill provides an increasing source of organic waste. Manure can be a disposal problem for many livestock owners. These ingredients are all used in the hypothetical composting operation.

Composting of food waste presents odor issues that can be mitigated with biochar. Composting systems require aeration, which can be accomplished by adding biochar to compost. Biochar holds air in its pores, preventing anaerobic conditions, while reducing or eliminating the need for turning and active aeration systems.

In the process of making biochar from biomass, thermal energy is produced that can be used for heating and cooling. Heat is needed in the winter for vermicompost processes, and cooling is needed in summer. Energy costs are growing, and savings over natural gas can be realized by using biomass energy for heating and cooling. Advanced biomass gasification and pyrolysis systems are now available that can provide thermal energy with very low emissions.

Installing a Combined Heat and Biochar (CHAB) system could be a robust solution to all of the problems listed above, as it can use free or low-cost fuel (EAB wood chips and other biomass) to provide heat and cooling for buildings, and biochar for improving and adding value to organic waste management processes and products.

II. Methods

This technology assessment does not include a complete economic and feasibility analysis, rather, it uses the requirements of a hypothetical compost operation to assess available CHAB technologies to meet those needs.

We reached out to manufacturers through Linked In contacts and collected information on CHAB units from five manufacturers. We then interviewed them to learn more about the strengths and weakness of their products.

We compared features of the different systems such as feedstock flexibility, thermal energy offtake options and biochar production outputs, and analyzed them in the context of the needs of a vermicomposting operation for biochar and thermal energy. We analyzed two different scales of operation, a beginning scale (1x) and an expanded scale (10x) reflecting the need for a new enterprise to start small while having a path forward for expansion. We also took a first cut look at capital and operating costs, based on standard engineering assumptions.

III. CHAB and a Composting Operation

Incorporating biochar into a composting operation will increase waste processing capacity by providing odor control and aeration, and will supply a carbon source for compost and vermicompost. In recent years, an explosion of research on the use of biochar in organic waste management and compost has established that biochar provides aeration and moisture retention to compost, accelerating the composting process, and sometimes cutting the time in half.[1] This allows a greater volume of compost production on the same footprint. Biochar also helps control odors, VOC emissions (Volatile Organic Compounds such as ammonia), and leachate from compost, mitigating two of the biggest environmental impacts of compost operations.[2] Such emissions also represent the loss of valuable nutrients, especially nitrogen. Researchers are finding that the use of biochar in composting manures and other high nitrogen materials results in greater nutrient content of the compost.[3] In addition, compost products made with biochar tend to have a greater fungi-to-bacteria ratio and a greater degree of humification – all indicators of improved compost quality.[4] Biochar thus adds value to compost and soil amendment products, and if properly marketed, may increase revenues.

Biochar is especially valuable for composting food waste. This material spoils quickly and generates strong odors. Many composting facilities that began taking food waste in recent years had to back off or were shut down by regulators because of odor and pest problems.[5] Biochar is effective in reducing odors, especially when it is mixed into food waste at the receiving area as soon as it arrives, or even at the collection point before it is delivered to the site. Odor control is critical, and biochar could make the difference between success and failure.

There are other possible benefits of incorporating a CHAB system into a vermicompost operation, depending on the specific CHAB technology chosen. Some technologies include an option to produce condensates that can be refined to make wood vinegar. Wood vinegar is valuable in agriculture as a plant growth stimulant at high dilutions, and as a natural pesticide at stronger concentrations.[6] Another by-product is CO_2 rich flue gas that could be used to enrich a greenhouse atmosphere for plant growth. Extra heat could also be used for process heat needed for water heating or product drying.

Two factors are key for choosing a CHAB technology: 1) the heating needs of the operation (worm farm housing, greenhouses) and 2) the desired volume of biochar for use in the composting operation. To understand the contribution of a CHAB unit to a compost operation, it is first necessary to understand the processing steps and material flows for making compost and vermicompost, and how those might change when integrating a CHAB unit.

1. Compost Operation Material Flows

The hypothetical compost operation includes a materials receiving and sorting area, a compost yard with windrows to prepare compost bedding for the worm bins, and a warehouse that contains the worm bins and office, requiring heat in the winter and cooling in the summer. An expanded operation might include additional vermicomposting facilities, greenhouses and a nursery that produces vegetables or bedding plants for sale, using the vermicompost and potting soil made on site.

The vermicompost process flow begins with receiving the materials that will be utilized in the compost, and ends with the vermicompost product packaged in cubic yard tote bags for shipping, or storage for use in soil blends. Integrating a CHAB unit into the operation will require additional wood chip fuel to produce the heat and biochar needed for the enhanced vermicompost product. Below we describe the steps for making vermicompost in a conventional compost yard, followed by the steps used for a compost yard that includes a CHAB unit:

Vermicompost Process Steps - Conventional

1. Sort and screen wood chips to remove over-sized chunks
2. Mix wood chips with high nitrogen food waste, greenwaste and manure
3. Mixed ingredients are moved to compost windrows
4. Compost is processed by frequent turning or aeration
5. Transfer finished compost to worm bins
6. Process by worms for approximately 6 weeks
7. Finished vermicompost is harvested and packaged in totes

Vermicompost Process Steps with CHAB

1. Sort and screen wood chips into compost piles and fuel piles
2. Process (grind) and dry fuel for storage or immediate use
3. Convey fuel to CHAB unit
4. Make biochar and heat in CHAB unit
5. Quench and store biochar appropriately
6. Mix biochar with food waste and manure first, then add wood chips
7. Mixed ingredients are moved to compost windrows
8. With biochar added, aeration and frequent turning are not required
9. Transfer finished biochar compost to worm bins
10. Process by worms for approximately 6 weeks (biochar will not speed up vermicomposting)
11. Biochar-enhanced vermicompost is harvested and packaged in totes

Biochar adds value to the composting process by reducing odors and emissions and by speeding the composting time. It also adds value to the final products. Biochar will end up as part of the worm castings and products such as worm casting liquid extract, and will also become part of soil blends that can be manufactured with worm castings as an ingredient. If a nursery operation is integrated, some portion of the soil blends will be used in the greenhouses on site, improving productivity of vegetables or bedding plants.

2. Biochar Production Needs

Biochar needs are tied to the volume of compost ingredients. We assume that, to start with, the operation receives 500 cubic yards of food waste and 1000 cubic yards of wood chips per month to use as compost ingredients. Additional wood chips are needed to fuel the CHAB unit. Based on the thermal conversion efficiency of the CHAB unit, the operation must receive enough wood chips to produce the amount of biochar needed for the compost. Many composting studies have shown positive results and benefits from biochar added at a rate of about 5% by volume to compost.[7] However, food waste composting can benefit from a biochar rate of 10% or more. The more food waste that is added to the compost, the more biochar should be added to balance the carbon to nitrogen ratio (C:N). We assume a desired rate of 10% for the composting operation.

For the starting operation, this would require the CHAB unit to produce 150 cubic yards of biochar per month. For the 10x scale operation, it would be 1500 cubic yards per month.

3. Heating and Cooling Needs

We assume the heating requirement is for a worm farm housed in a 5000 square foot warehouse with minimal insulation, and that the desired temperature differential is 80 F, to maintain 65 F when outside temperatures are -15 F. A rough estimate would indicate peak heating needs of between 500,000 and 750,000 btu/h.

Similarly, rough calculations show that cooling needs of the warehouse could be met with between 30 and 50 tons of cooling, which can easily be provided by a heat output of .5 MMbtu/h. Several manufacturers make single stage sorption chillers in the 30 to 50-ton range that use low pressure hot water at between 190 F and 200 F.

For the analysis of the scaled-up operation, we assume that heating and cooling needs increase by a factor of ten

4. CHAB Fuel Needs

The volume of wood chips needed for the CHAB unit is based on the biochar production efficiency of the system, which may vary between 16% and 35% by dry mass of wood chip input to dry mass of biochar output, depending on the CHAB technology and operating conditions. Bulk densities of both wood chips and biochar are difficult to determine accurately, but for purposes of this analysis, we use a dry bulk density of 243 lbs/cy for wood chips and a dry bulk density of 200 lbs/cy for biochar. The volumetric efficiency of the various CHAB technologies ranges from approximately 18% to 40%. Below we illustrate the range of biochar outputs that can be produced by the smallest and largest of the five CHAB technologies we analyzed. While the smallest CHAB unit is likely to meet most of the heat energy needs of the 1x scale operation, it falls short of the biochar needs, if adding biochar at the rate of 10% to compost. The largest system comes very close to meeting the desired goal of providing a biochar addition at the rate of 10% to a volume of compost that is 10x greater than current volumes (see Table 2).

Processing Volumes with CHAB System (1x scale)

- Food waste – 50,000 pounds per month (500 cy)
- Wood chips for compost – 1000 cy per month
- Wood chips for fuel – 444 cy per month
- Estimated maximum heating load – .75MMbtu/h
- Heat output (Organilock BB1000) – 1MMbtu/h
- Desired biochar for 10% addition to compost – 150 cy per month
- Estimated biochar output (Organilock BB1000) – 86 cy per month

Processing Volumes with CHAB System (10x scale)

- Food waste – 500,000 pounds per month (5000 cy)
- Wood chips for compost – 10,000 cy per month
- Wood chips for fuel – 5431 cy per month
- Estimated maximum heating load – 7.5MMbtu/h
- Heat output (ICM BC-30) – 8.3 MMbtu/h
- Desired biochar for 10% addition to compost – 1500 cy per month
- Estimated biochar output (ICM BC-30) – 1452 cy per month

4. Fuel Flexibility

Some locales many not have an adequate supply of wood chips for the operation, or there may be seasonal variations with other kinds of biomass being more available at times. Should the local supply of wood chips fail to keep up at some point, it would be helpful to understand what the other options are. This analysis also looks at fuel flexibility to see if some of the CHAB technologies are capable of using other fuels such as corn stover or hemp waste. In the preliminary economic analysis, we assume that increased wood chip deliveries will come with a cost for transporting the wood chips to the composting site.

IV. CHAB Technologies Overview

Combined Heat and Biochar technologies are based on methods of staged combustion of biomass. Unlike a gaseous fuel, a solid fuel burns in several stages that include drying, pyrolysis, gasification and char combustion. Utilizing solid biomass as a fuel requires a reactor that may be configured as a furnace, a gasifier or a pyrolysis kiln. Regardless of the terminology, all technologies that produce biochar and heat from biomass utilize some form of staged combustion that separates volatile gases from a high carbon residue that undergoes thermochemical conversion to become charcoal or biochar. Key to producing biochar is the ability to stop the combustion process before the char is oxidized completely to ash.

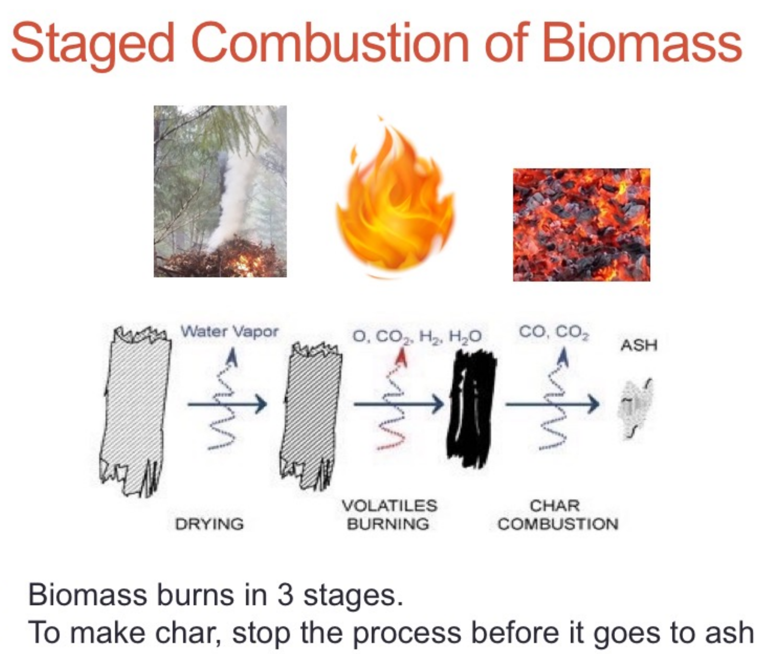

Figure 1. Biomass burns in stages.

Charcoal and biochar are different terms for the high carbon residue. Because high carbon residue from staged combustion can have different properties depending on the processing temperature, pressure, and other factors, the term "biochar" is used to indicate charcoal that has properties that make it suitable for use in soil and other biological systems. Biochar is charcoal that promotes life. The main requirement for biochar is that it should not contain compounds or elements, such as lead, in amounts that are toxic to life.

1. Biochar Characteristics

Biochar characteristics can vary widely depending on feedstock characteristics and thermal conversion factors such as temperature, pressure, treatment time and quenching method. The most important characteristics of biochar are the degree of carbonization and the ash content. This can be expressed through "proximate analysis" – a common method for analyzing fuels such as coal. Proximate analysis of a fuel provides the percentage of the material that burns in a gaseous state (volatile matter), in the solid state (fixed carbon), and the percentage of inorganic waste material (ash). When applied to biochar materials, proximate analysis indicates how much carbon is fixed as charcoal, and how much hydrocarbon material remains in a volatile form that will be easily degraded by microbial action. The ash percentage is simply the non-volatile mineral content of the biomass that remains after thermal conversion. Specific biochar characteristics are less important in composting applications than in some other more exacting applications such filtration or animal feed. Furthermore, it is important to recognize that changes in feedstock type, moisture content, and operating temperatures will result in variations in biochar characteristics. Purchasers of CHAB equipment should request test runs of their specific feedstocks in order to determine if the biochar products will meet their needs.

2. Biomass Energy and CHAB economics

Utilization of waste biomass to provide renewable energy for heating and power is a long-held societal goal, but given the current low prices for fossil fuels, the economics of biomass energy are challenging. Still, under the right conditions, biomass heat can be an economical substitute for fossil fuels. Producing biochar as a co-product with heat energy will reduce the amount of heat energy proportionally to the amount of biochar produced. However, in all of the technologies considered here, there is still plenty of heat available for thermal applications, including feedstock drying. For instance, the ICM gasifier we examined is capable of producing 9.08 MMbtu/h of heat without making biochar. When producing biochar, the heat output is reduced to 8.39 MMbtu/h, which is 92.4% of the heat produced without a biochar co-product.

Value is realized by the reduced cost of heating fuel (wood chips can be either free or very low cost) and by the value of the biochar product for many applications. Increased costs are incurred by the capital investment in the CHAB equipment and in the labor and maintenance costs of the system. Additional values that should be added to the equation include carbon sequestration from the biochar product, and avoided carbon emissions by switching to renewable biomass fuels. The additional values provided by biochar could make the difference between a successful biomass energy project and a failed biomass energy project. The additional value of the heat energy released in biochar production could make the difference between a successful biochar production project to a failed biochar production project. These values need to be considered from both a monetary and a climate mitigation standpoint. Mechanisms to monetize climate benefits are still in development. When climate benefits are fully monetized, CHAB technologies will be a no-brainer.

3. CHAB Conversion Technologies

Many different kinds of biomass combustion systems are capable of making biochar. In this assessment we looked at three main categories of technology: furnace systems, retort systems, and gasifiers. The five technologies that we looked at in depth all fall within one of these basic technology types. Table 1. lists the basic parameters of the five technologies, including the feedstock processing capacity and outputs of biochar and thermal energy for the several models being offered.

Table 1. Basic parameters of CHAB systems

Manufacturer	Model	Tech type	biomass in (dry pounds/h)	biochar out (dry pounds/h)	biochar efficiency	Thermal output, MMbtu/h	Process temperature range	Process residence time, typical wood chip
ARTi Char	ARTi 2.0	Pyrolysis Retort with Heated Auger	667 per train Up to 5 trains in one container	167-250 per train	25% - 35%	5 MMbtu/h per train	400-800 C	15 minutes
Biomass Energy Techniques	BET 49-S	Biomass Furnace	372	60	16%	3.5	1200-1600 F	5-10 minutes
ICM, Inc.	ICM BC-30	Up Draft Gasifier	1833	403	22%	8.4	1000-1300 F	15 minutes
Organilock	BB1000	Biomass Furnace with integrated dryer	150	24	16%	1	1200-2200 F	5-10 minutes
Pyrocal	Pyrocal CCT 12	Biomass Furnace - Multiple Hearth	550	138	25%	2.8	500-650 C	100 to 200 seconds
	Pyrocal CCT 18		1400	350	25%	6.8	500-650 C	100 to 200 seconds

Furnace Systems

Three of the CHAB technologies are based on furnace systems. A furnace is simply an insulated burn chamber, with or without an integrated heat exchanger or boiler, that accepts biomass loaded manually or through automated systems. Wood stoves are common examples. Industrial wood-fired furnaces are often equipped with boilers to generate hot water or steam and there are many different designs and sizes. Smaller furnaces mostly have fixed beds, while large furnaces often have fluidized beds to allow clean combustion of large amounts of fuel. Below we describe each CHAB furnace in detail.

Biomass Energy Techniques (BET)

The BET furnace can be described as "heat forward." The basic furnace design exists in dozens of installations, mostly at sawmills, to provide heat for lumber drying kilns. In its CHAB configuration, it is an inclined grate and fixed hearth furnace with a char removal auger below the grate. The long, highly insulated burn chamber and limited primary combustion air produce gasification conditions that are claimed to promote water gas reactions that liberate burnable hydrogen from water. This allows use of feedstocks with higher moisture content. In this furnace, green wood chips provide more heat energy than fully dried wood chips, and optimum moisture content is a minimum of 25%. The open grate is designed so that as the wood chips char and shrink, they will fall through the grate to a char removal auger before they burn completely to ash. An induced draft fan controls air flow. The furnace is designed for very low air flow which means low transport of particulates and clean flue gas. No emission controls are required in most locations. The furnace can be supplied with an integrated boiler or a flue gas-to-air heat exchanger.

OrganiLock

The BB 1000 from OrganiLock is also a "heat forward" furnace. Biomass is fed through a port into the furnace where it piles up on a refractory furnace floor. Combustion air comes in through various ports above the burning pile. Residence time is controlled so that the biomass gasifies but does not burn to ash. A rotating arm sweeps char from the furnace floor through a port into an airlock leading to a char removal system that quenches the char and conveys it to a storage bag or bin. An integrated boiler provides hot water for thermal heating applications. The software monitors combustion conditions and will only turn on the char option when the system is stable and the heating requirements are met. A cyclone removes particulates from the flue gas, and an induced draft fan provides negative pressure in the system. An integrated feedstock grinding and drying option, the BBS200, uses a hammermill to grind wood chips to a uniform size. The dryer uses 210 F hot water from the hot water boiler, and dryer capacity is designed to match the fuel feed rate so the system can "dry-as-you-go."

Pyrocal

The Pyrocal CCT system is a "biochar forward" system. The first prototypes of this multiple hearth furnace were developed for mobile biochar production with no application of the extra heat energy. A multiple hearth furnace consists of a number of hearth surfaces within an insulated furnace. Biomass is fed into the top chamber, where it begins to dry and release volatile gases. The biomass is moved by a system of rotating rakes that transport it through a number of chambers before it falls into an auger where it is quenched and discharged as biochar. Different sizes of holes in the hearth surfaces allow smaller biomass to move more quickly through the furnace, preventing ashing. The flaming off-gases travel up through the hearth and then to the thermal oxidizer, where they are mixed with more air and oxidized completely. The hot flue gas can then be fed to a boiler for hot water for heat applications. The manufacturer describes the process as "omnivorous" for feedstock, as it can accommodate light fluffy materials, clumping materials, chips and materials with a diverse size range. The system can be controlled to bias for either carbon product or heat yield, as needed.

Gasifiers

Like furnaces, gasifiers come in many different configurations. Fixed bed gasifiers work by dividing the fuel into zones where the different processes of drying, pyrolysis and gasification take place. Because these zones are separated, it is possible to transport the gas produced to a separate chamber where it can be burned in an engine, for example. Gasifiers may be designed for updraft or down draft, and they can have fixed or moving fuel beds. Some of the furnaces described above operate more like gasifiers than conventional furnaces, especially since they are designed to separate the gas from the carbon residue. Engineer James Joyce, designer of the Pyrocal CCT system, says it is "essentially a modified updraft gasifier." The BET furnaces also have aspects of an updraft gasifier. Only one of the technologies we examined is explicitly configured to produce a combustible gas, the ICM gasifier.

ICM, Inc.

The ICM Model BC-30 is a horizontal, cross-flow/updraft gasifier with an internal auger to control the movement of biomass through the reactor. The refractory lined reactor is divided into four zones with separate air controls for each stage of the process: drying, pyrolysis, gasification and char oxidation. In biochar production mode, char oxidation is minimized, and char is recovered at the end of the reactor. Feedstock bed depth and mass flow into the gasifier are controlled for a consistent process. The "producer gas" generated during the biochar production process is subsequently converted downstream of the gasifier into usable heat energy by a thermal oxidation reactor. Integrated heating applications can include feedstock drying, process steam, hot water, power generation via steam turbines or ORC systems, district heating and/or adsorption chillers. The ICM gasifier technology was originally developed for two main purposes: to provide heat for large scale ethanol production facilities, and to produce energy from a wide variety of wastes, including processed Municipal Solid Waste (MSW). Designed for the ability to remove large amounts of char and ash, it was a straight forward process to incorporate biochar production as a co-product. ICM's configuration allows for the use of larger and more variable biomass particle sizes.

Retort Systems

Retort systems differ from furnaces and gasifiers by physically separating the biomass from the combustion air. Heat is transferred through the walls of the retort to the biomass inside. Volatiles and moisture are driven off by the heat and exit the retort through holes or ports. The gases contain hydrocarbons and water that can be condensed into different fractions to produce tar, bio-oil and wood vinegar. They can also be directly combusted for heat energy. The carbon residue remaining in the retort becomes biochar. Retorts operated in a batch mode are used to make charcoal without energy recovery. Continuously fed retorts are suitable for production of heat energy and biochar. Retort technologies provide greater control over processing conditions and biochar characteristics than furnaces and gasifiers.

ARTi

The ARTi pyrolysis retort is a “biochar forward” system that provides fine control over biochar production conditions. An auger moves biomass through a retort tube with outlets into an annular burn chamber where pyrolysis gases are combusted to provide heat to the retort. Unburned gases are drawn into an afterburner with an induction fan where combustion is completed and clean flue gas is emitted through a stack. An optional condensing unit placed before the afterburner can condense volatiles to produce bio oil and wood vinegar fractions. Biochar is removed from the end of the retort with an auger where it is conveyed to a cooling tower with water spray for quenching, and then into tote bags or bins for storage. Thermal energy offtake is achieved via direct use of flue gas or with a flue gas-to-air heat exchanger. There is currently no boiler integrated into the unit, but the potential exists to do so. The basic package includes an integrated dryer that dries feedstock at the rate needed to feed the system. The design is modular, and up to five “trains” can be packaged into one container.

4. Feedstock and Biochar Handling and Storage

Wood with all water removed (called “bone-dry” or “oven-dry”) contains about 8,000 BTUs per pound. This is nearly the same for all wood species. Most of the CHAB units perform best using wood. While other feedstocks can be used with some of the units, in this section we will only discuss the use of wood chips. Fuel needs are specified on a dry mass basis, so to understand the volume needs, we need to know the dry bulk density of the wood chips. Because this can vary according to the species of wood, particle size, and other factors, we use an average value of 243 lbs/cy, or 9 lbs/ft^3, from the EPA.[8] Table 2 gives an estimated volume of wood chips that would be needed for each of the CHAB technologies with the corresponding output volumes of biochar (based on assumed biochar dry bulk density of 200 lbs/cy), along with the desired chip size and moisture content. Some of the technologies are capable of processing other feedstocks such as manure and corn stover.

Feedstock drying is necessary in most cases, depending on the moisture content of the delivered wood chips and the feedstock requirements of the thermal technology. Heat produced by the CHAB unit can be profitably used to dry incoming feedstocks, and some off the vendors we contacted supply an integrated dryer that uses hot flue gas and/or hot water from an integrated boiler to dry feedstock. A rough estimate for feedstock drying needs is 1500-2000 btu to remove one pound of water from wood chips (Georgia Forestry Commission). To dry wood chips from 50% moisture down to 20% moisture would require about 1 MMbtu per ton of green wood. In practice, depending on the dryer technology used, feedstock particle size, and ambient temperature and moisture conditions, feedstock drying may require between 10 and 50% of the thermal output of the CHAB unit.

Table 2. Feedstocks and production volumes

Model	Biomass in (dry pounds/hr)	Max woodchip volume per day (cy)	Max woodchip volume per month (cy)	Max biochar production per month (cy)	Wood chip feedstock format	Max moisture content (wet basis)	Other Feedstock Capabilities
ARTi 2.0, one train (4 max/unit)	667	66	1,976	840	Up to 3" minus. 1" for best performance	50%, with integrated dryer. For direct feed to the reactor ideal moisture 10-25%	Manure, grain hulls, corn stover, nut shells
BET 49-S	372	37	1,102	214	3" minus with no fines or dust or sawdust	60% (25% min)	Chopped hemp stalks
ICM BC-30	1833	181	5,431	1,452	One plane 3/4" or less, or strips 6 inches long. Best performance requires 3/8" to 2".	15% - can handle up to 35% - 40%	Straw, corn stover, chicken and dairy manure mixed with wood chips
Organilock BB1000	150	15	444	86	Wood fiber through a 3/4" hammer mill screen for best performance. No bark.	35%	Manure, wood pellets, sawdust
Pyrocal CCT 12	550	54	1,630	495	Chipped or shredded up to 3/4" thick x 2" long/wide for best performance. Can accept up to 1.5" thick and 4" long .	35% - Less than 20% recommended	Manure, nut shells, MSW, hog fuel
Pyrocal CCT 18	1400	138	4,148	1,260			

The CHAB technologies vary in their requirements for feedstock particle size, but generally, the more uniform the feedstock thickness is, the better it will perform in the thermal conversion process, and perhaps more importantly, in the feedstock handling and conveying systems. Basic particle size control is achieved by screening, but for best results, feedstock grinding may be required. Feedstock grinding uses electrical energy that must be available at the site. Some of the CHAB unit vendors supply a hammermill grinder that can be integrated into the drying process so that raw wood chips are delivered directly into a hopper that leads to a hammermill and then into a feedstock dryer. As part of the site analysis for a CHAB installation, energy needs for grinding must be provided for. For instance, the Organilock

BB1000 can include an optional hammermill that uses a 5 hp electric motor. The feed tube auger into the integrated dryer uses an additional 3/4 hp motor. Additional feedstock conveying may be required to move raw wood chips from a storage bin or feed wagon to a grinder. Another set of feed augers moves the biochar product out of the furnace and into a receiving bin or bagging area.

A well-designed feedstock handling system can avoid the need for large biomass storage areas if fuel deliveries are scheduled to match the fuel needs of the system and a correctly sized dryer is installed to "dry-as-you-go". However, a CHAB installation may not have the ability to schedule fuel deliveries given seasonal operations of arborists and other wood chip suppliers. Winter can be especially challenging as wet wood chips may freeze and become difficult to handle. For these reasons, at least some covered storage is desirable so that dry wood chips can be stockpiled for use as needed. Wood chips that are extremely wet, old, or degraded can be diverted for use in the composting and vermicomposting operations. Altogether, the feedstock receiving, conveying, grinding, and drying systems will constitute a large part of the cost and the site footprint needs of the complete CHAB system.

BTEC, the Biomass Thermal Energy Council, has published standards for wood chips for use in thermal energy installations.[9] These standards provide good guidance for fuel procurement, and for handling and storage of wood chips once they arrive at the site. It is important to protect wood chip piles from flooding, rain and snow, and to avoid storing chips for too long by establishing first-in, first-out utilization techniques rather than first-in, last-out. It is also important to avoid contamination with rocks and dirt from an unpaved storage area, or a dirty loader bucket. Use magnets to remove any metal that could be found in the chips.

Biochar quenching and handling is similar in all of the systems. Hot char is removed from the reactor by an auger or a rotary arm, where it enters a cooling chamber and is sprayed with water to stop combustion and cool down. Another auger system removes the biochar from the cooling chamber and deposits it in a bin or bag. This process can be completely automated. Some make-up water is required in all of the systems, but there is no wastewater discharge as the systems are designed so that the char absorbs the quenching water.

5. Emissions

Small thermal energy technologies that are fueled by clean wood chips do not usually require extensive pollution controls beyond clean combustion technologies such as appropriate burners and thermal oxidizers, with cyclones to remove particulate matter from the flue gas as needed. Most likely, none of the technologies analyzed here would qualify as a major emissions source under Nebraska regulations and require a Class I permit for air emissions. Most of them would fall under the limit of 10 MMbtu/h of fuel energy input (about 1250 dry lbs of wood chips/h) that requires emission controls for fine particulate matter, however some of the larger systems may require a Class II operating permit. Permitting needs for a CHAB unit and any associated emissions from wood chip dryers would need to be analyzed as part of a complete feasibility study.

If additional emission controls are required, several of the vendors we contacted can provide integrated wet scrubbers, and third-party solutions are available for any of them. Table 3 lists the primary emission control strategies for each technology and any optional controls supplied by the vendor, and indicates whether or not the unit may require a higher class of permit.

Table 3. Air emission controls and requirements for CHAB units

Manufacturer	Model	Tech type	biomass in (dry pounds/hr)	Primary emission control	Optional controls provided by vendor	Possible to exceed 10MMBTU
ARTi Char	ARTi 2.0	Pyrolysis Retort with Heated Auger	667 per train Up to 5 trains in one container	thermal oxidizer		depends on # of trains
Biomass Energy Techniques	BET-49	Biomass Furnace	372	clean combustion		no
ICM, Inc.	ICM BC-30	Up Draft Gasifier	1833	thermal oxidizer		yes
Organilock	BB1000	Biomass Furnace with integrated dryer	150	clean combustion	wet scrubber	no
Pyrocal	Pyrocal CCT 12	Biomass Furnace - Multiple Hearth	550	thermal oxidizer	wet scrubber	no
	Pyrocal CCT 18	Biomass Furnace - Multiple Hearth	1400			yes

6. Heat Recovery System Options

In order to fully recover the costs of installing and operating the CHAB unit, the heat energy must be utilized efficiently. All of the CHAB units will provide adequate heat for the 1x scale vermicompost facility, and the larger units are capable of meeting the needs of a 10x scale expanded operation that includes greenhouses. All of the systems can also provide enough heat to operate a chiller for summer cooling, allowing heat value to be recovered year-round.

Heat recovery systems add additional costs, even if the only additional requirements are heat delivery units and piping for hot water or ducting for hot air. It may also be necessary to provide and maintain backup systems for heating during times when the CHAB system is down for maintenance or other outages. CHAB systems require more labor for fuel handling than fossil fuel systems, and this additional labor need adds expense and complications to the heating system that must be anticipated.

Some of the manufacturers provide integrated heating systems that use either a hot water boiler or a flue gas-to-air heat exchanger. None of them provide a steam boiler, but a third-party steam boiler could be integrated into some of the systems. If greenhouses are to be heated, flue gas can be used directly where it can also provide a CO_2-enriched atmosphere for growing plants, (provided the plants can survive the small amounts of carbon monoxide that may be present in the combusted gas). Flue gas can also be used in a biomass dryer. Due to heat losses through the piping or ducting, buildings or greenhouses should be located within 100 feet of the CHAB unit. For a larger operation with many buildings or greenhouses, a steam boiler may be the only workable option.

The costs of the different options increase as you move from direct flue gas, to gas-to-air heat exchangers or hot water boilers, to steam boilers. Any of the units can be configured to also generate electricity from either hot water using an Organic Rankine Cycle (ORC) generator, or steam, using a steam turbine, but these are very expensive options and not likely to be economically viable at a small scale. Biomass Energy Techniques is currently testing the feasibility of a Stirling engine generation for electricity, but the costs are still to be determined. Table 4 lists the different heat offtake options for each system. It also lists the labor and maintenance needs of each system. This information is important to be able to assess the thermal offtake performance and reliability of the heating systems so that the customer can anticipate needs, provide appropriate back up heating systems, and not get caught in a situation where needed heat is unavailable.

Automation systems are also described in Table 4. There are major advantages to a system than can run automatically for 8-12 hours to avoid night time work shifts versus one that requires attended operation for 24 hours a day. Another important consideration is turn-down ratio, so that when the full capacity of heat is not needed, the unit can be run with a lower throughput of feedstock. On the other hand, if the heating needs are primary and the heat demand is close to the capacity of the system, some of the systems are able to prioritize heat provision by reducing char production in order to provide more heat.

Table 4. Thermal offtake performance characteristics

Model	Thermal output, MMbtu/h	Thermal offtake types	Integrated thermal options provided by vendor	Turn-down ability	Automation and controls	Maintenance schedule	labor requirements for daily operations
ARTi 2.0	5 MMbtu/h per train	Direct flue gas for dryers or greenhouses, flue gas-to-air heat exchangers, hot water boiler, steam boiler	integrated dryer using flue gas	Control T with combustion air in primary combustion chamber. All trains must run, even if turned down, if using multi-train configuration.	Multiple options, soft automation and full automation. Data logging, vpn, remote viewing or operation, cloud storage, event alarms text message and emails, and reports. IP cameras also available.	Quarterly - shut down and clean inside - remove ash coating. Grease bearings. Grinder screens and hammers cleaned and replaced as needed.	1.0 FTE
BET 49-S	3.5	Direct flue gas for dryers or greenhouses, flue gas-to-air heat exchangers, hot water boiler, steam boiler	flue gas-to-air heat exchanger or hot water boiler	Air damper and fuel feed rate can be varied	Basic manual controls to fully automated /computerized controls	clean grates every 8 hrs clean out stack every 2-3 weeks	.25 FTE
ICM BC-30	8.4	Direct flue gas for dryers or greenhouses, flue gas-to-air heat exchangers, hot water boiler, steam boiler. Can have one duct that can feed a boiler and another duct that goes to a dryer.	none	Very large turn down ratio - 30% of design rate at minimum. Can flare gas if desired.	Have an automation group that can design controls, control logics or enclosed packaged DCS distributed control systems		2.0 FTE
Organilock BB1000	1	Direct flue gas for dryers or greenhouses, flue gas-to-air heat exchangers, hot water boiler. Company is working on an integrated chiller option.	Integrated boiler consists of a 350 gallon tube heat exch. 1700 F flue gas going in, 300 F exhaust T. Integrated dryers can use both flue gas and hot water	Up to half by controlling air and fuel feed rates	Fully integrated controls. Can be monitored and run remotely. Feedstock dryer will shut down if the HX water drops below a pre-programmed level. It will turn itself back on when the water temp is high enough to handle both applications.	Clean fly ash from HX tubes and cyclone – 30 minutes/week. Very little maintenance needed in the combustion chamber because 'ash' is being constantly removed in the form of biochar	.25 FTE
Pyrocal CCT 12	2.8	Hot combustion flue gas at temperatures of 700 to 850 deg C, suitable for all conventional boiler types as well as dryers. .	none	The temperature and oxygen profiles in the hearth are controlled to achieve the desired char yield and char quality. Unit can be turned down to 25% of design rate.	Fully PLC automated for unattended operation. Unitronics touchscreen PLC with over 100 I/O. Remote access. The entire system is controlled by a PLC programmed to specific installation requirements.	The hearth unit internals overhauled every 8000 hours. Every 2 weeks, inspect for accumulation of foreign matter and service the start-up burners. If the unit has flue gas filters they would typically be changed out.	.25 FTE
Pyrocal CCT 18	6.8						

7. System Configurations and Costs

System size, modularity, unit costs and installed cost all need to be considered as part of the technology assessment. Table 5 compares important implementation information for each technology, including site footprint and quoted costs. Note that cost information provided by vendors is for August 2019 prices only.

Table 5. CHAB technologies configurations and costs

Model	Modular or relocatable?	Footprint	Capital cost, $ and what is included (August 2019 prices)	commissioning includes	Installed units?
ARTi 2.0	Modular and relocatable	Reactor, dryer and grinder fit in shipping container of 40x8x8 ft and requires concrete pad for machinery about 20 ft around.	$250k per train (including 1 pyrolysis train, and dryer), grinder is 25k, condensate unit is 80k, includes commissioning	Initial meeting to determine site conditions, ship equipment in shipping container, one week with technician to get set up and running	Sold or licensed 12 units. Four in operation currently.
BET 49-S	Modular	64"x192"	$216,000 - includes automated feed system and feed wagon, controls with remote notifications, hot water boiler	One full day of onsite training	Three units currently operating, five on order.
ICM BC-30	Modular	Reactor unit and TO retention duct. 100' x 50' pad	$1.5 to 2 million - includes commissioning	Supervise installation training during start up - about 3-4 weeks to get it running 24-7. Does not include site work, electric install, utilities.	One prototype and one larger unit currently being commissioned.
Organilock BB1000	Modular	16' x 29'	$155K - includes BB1000, bulk fuel bin, hammermill and BPS200 dryer	Most customers can handle the installation with phone assistance only. The BPS1000 large dryer requires our help and installation fees can be between 3-6K.	Two current operating, two new orders about to ship.
Pyrocal CCT 12	Relocatable	40 ft cube shipping container	USD $0.6M delivered, installed and commissioned in US	Client prepared site, excluding boiler and flue gas filters (not normally required to meet emissions standards)	20 installed units in different configurations, including mobile prototypes.
Pyrocal CCT 18	Modular and relocatable	Floor footprint 30 metres x 12 metres. If covered 8 sq.metres of space is required over the oxidiser modules.	USD $1.0M delivered, installed and commissioned in US		

Some of the technologies are configured to be modular, that is, several identical units can be grouped together in one installation and share common feedstock handling, heat energy offtake and other ancillary systems needed for operation. Modularity could facilitate the eventual expansion of an operation that wants to begin at one level of biochar and heat production and grow into a larger operation. A few of the technologies are also re-locatable.

All of the CHAB reactors are fairly compact units, many of them fitting into a shipping container or smaller space. This is important for hot water heating because it means the reactors can be located close to the spaces that will use the heat, avoiding excessive energy loss through piping or ducting. The reactors themselves require only a small fraction of the total area that is needed for the entire operation, mostly for feedstock processing and storage.

Similarly, the unit cost of the reactor itself may also be a fraction of the cost of the entire system that includes feedstock handling, heat recovery equipment, automation controls, and other ancillary equipment needed to run the plant. Some of the systems include integrated dryers, boilers, heat exchangers or full automation in the quoted purchase price, while others provide only the reactor itself.

Clients who purchase CHAB equipment also need to understand all of the costs associated with installing and commissioning the plant. Most of the vendors we interviewed indicated that they would provide either onsite commissioning assistance or phone support as part of the purchase price. Those offering the larger, more complex units were willing to include significant amounts of commissioning assistance. However, the CHAB vendor may not be willing to take responsibility for integrating and commissioning subsystems involving feedstock handling, thermal energy offtake and pollution controls.

IV. CHAB Features and Decision Tools

In this section we provide several tables to compare technology features and aid in decision-making. However, this technology assessment is only a first look at these systems and no decision for an actual project should be made without a full feasibility study.

Capital and operations & maintenance costs are certainly critical, but it is not possible within the scope of this analysis to understand these costs in relation to the possible benefits provided. Instead, we focus on comparing some of the other important decision points for selecting a technology. The ones we compare are: feedstock flexibility, biochar production volumes and co-products, scale and scalability, and the completeness of system integration that the vendor can provide. Depending on the actual needs and limitations of the site, there are likely to be other critical factors that are not examined here.

For further information, contact the vendors. Section VI includes contact information and websites for the vendors.

1. Feedstock Flexibility

Feedstocks are rarely uniform, consistent or delivered at an optimum moisture content. While wood chips are widely available, other potential feedstocks include materials such as corn stover and hemp waste. The ability to process those feedstocks could be important for long term feedstock sustainability of an operation.

Some of the CHAB units are capable of using feedstocks other than wood. The units from ARTi, ICM and Pyrocal are the most capable of processing other feedstocks. These are also the units that have the most control over temperature and residence time. Most of the CHAB reactors require uniform feedstock size. All of the technologies will perform better with smaller, more uniform feedstock, but the Pyrocal multiple hearth furnace is uniquely capable of processing feedstocks that are variable in particle size and density. The ICM gasifier can also handle wood chips with variable sizes, potentially eliminating the need for grinding. The BET furnaces are unique in their ability to utilize wetter feedstocks, especially green wood chips at up to 60% mc, but the BET furnaces do require uniform particle sizes, so while a dryer may not be required, a grinder is probably needed. The ICM gasifier can also perform adequately with feedstocks up to 40% moisture content. The ICM gasifier might be able to utilize unprocessed wood chips if they are less than 40% mc. All the other technologies require moisture content in the 20-25% range or less. Table 6 compares different metrics of feedstock flexibility for the systems.

Table 6. Feedstock flexibility comparison

Model	Technology	Handles non-uniform particle size	fibrous or fluffy feedstocks	high moisture feedstocks (>35%)
ARTi 2.0	Pyrolysis Retort with Heated Auger			
BET 49-S	Biomass Furnace			X
ICM BC-30	Up Draft Gasifier	X		X
Organilock BB1000	Biomass Furnace with integrated dryer			
Pyrocal CCT 12 and CCT 18	Biomass Furnace - Multiple Hearth	X	X	

2. Biochar Production and Co-products

Matching the CHAB system to the biochar production needs of the composting operation is the best approach, because the thermal energy produced will likely be more than adequate for feedstock drying and the utilization of thermal energy can be adjusted by improving building insulation or adding expanded capacity of vermicompost bins or greenhouses to match the thermal outputs. For the systems to be economically feasible, it is essential that all of the thermal energy output is used productively. See section V. Preliminary Economic Comparisons for this analysis.

The systems differ in their biochar conversion efficiencies. The simple furnaces from BET and Organilock are less efficient than the other technologies, however, they may also be simpler to operate and better integrated for providing heat energy to the application. They also have a lower capital cost than the other units. As far as biochar quality, as long as the biochar is used only in compost and not for other applications, tight control over biochar characteristics is not so important. However, if the client wants to produce specialty biochars for filtration or remediation applications, then such control could become important.

Finally, the ARTi system is capable of producing condensates with an optional flue gas condenser. Condensates allow the production of wood vinegar, which is becoming known as a valuable agricultural chemical. Table 7 compares biochar production metrics for the different systems.

Table 7. Biochar products and co-products

Model	**Conversion efficiency (dry mass basis)**	**Max biochar production per month (cy)**	**Precision control of biochar characteristics**	**Other co-products**
ARTi 2.0	25-35%	840	yes	Condensates and wood vinegar
BET 49-S	16%	214	no	none
ICM BC-30	22%	1,452	yes	none
Organilock BB1000	16%	86	no	none
Pyrocal CCT 12	25%	495	yes	none
Pyrocal CCT 18	25%	1,260		

3. Scale and Scalability

All of these technologies are scalable in one way or another. The ARTi 2.0 is uniquely scalable in the same foot print by adding up to three additional retort trains. BET can group several furnaces together in parallel in one installation. Organilock's BB1000 is the largest of their line, but it is always possible, and may be preferable, to start with one furnace to meet the current need, and simply add another furnace, perhaps in a different location, as the operation expands. This could be the best option if heating needs are too far apart for effective hydronic heating from one centrally located unit. Both ICM and Pyrocal can provide dual, side-by-side units that double capacity while utilizing common feed and off take systems. Table 8 compares the scale and modularity of the systems, indicating which systems match most closely with the 1x and 10x vermicompost production scales.

Table 8. Scale, fit and scalability of the CHAB systems

Model	Thermal output, MMbtu/h	Max biochar production per month (cy)	Matched to 1x scale	Matched to 10x scale	Scalable by adding units in parallel
ARTi 2.0	5 MMbtu/h per train	840	no	yes	yes
BET 49-S	3.5	214	yes	no	yes
ICM BC-30	8.4	1,452	no	yes	yes
Organilock BB1000	1	86	yes	no	no
Pyrocal CCT 12	2.8	495	no	no	no
Pyrocal CCT 18	6.8	1,260	no	yes	yes

4. Completeness of Vendor Supplied System Integration

CHAB systems are supplied with different levels of vendor-integrated components for accomplishing feedstock handling, thermal energy offtake, and pollution controls. Most of the systems can accommodate third-party versions of various components. Table 9 compares the type of integrated components offered by each vendor for the basic purchase price quoted.

Table 9. System integrated components

Model	Feedstock handling integration	Thermal offtake integration	Advanced automation
ARTi 2.0	X		X
BET 49-S	X	X	
ICM BC-30			X
Organilock BB1000	X	X	X
Pyrocal CCT 12 and CCT 18			X

V. Preliminary Economic Comparisons

Preliminary capital and operating costs were estimated for each of the systems in order to estimate the cost of biochar production and evaluate the benefits from heat savings. Results are shown in Table 10. A decision about which system to select would have to be made with more detailed planning, engineering and analysis.

It is difficult to estimate the cost of a system without at least a substantial amount of the engineering complete. Preliminary cost estimates can be made with about 20% of the engineering and with contingencies and allowance for unlisted items of 20%, hoping to fall in a probably range of error of 30%, or in a range of -10% to +25%. Standard engineering assumptions were used to estimate costs of civil, structural, mechanical, electrical, fire and safety, installation, maintenance, and insurance, and indirect costs for engineering and permits. Capital costs included preliminary estimates of additional equipment and services that could be needed to integrate each system into the compost operation. Costs for stormwater planning, environmental permits and compliance testing are not included. Wood costs were assumed to be $20/dry ton or $10/green ton. Labor was at the employer's cost of $20/hour. Natural gas is $6.50/MCF (MMBtu).

If the assumptions are correct, the cost of biochar production after heat savings can range from -$7/cy to $77/cy depending on the capacity of the system and the ability to use the heat. Heat savings can contribute from 40% to 100% of the total annual cost of producing heat and biochar. Lower capital costs and large heat production make the BET system an interesting choice in the 1 to 4 MMbtu/h, 800-2,000 cy/year production range. In the 5,000 to 6,000 cy/year range at 2.8 to 5 MMbtu/h, both the small Pyrocal and ARTIChar systems have reasonable biochar costs at $17-$41/cy. At the larger scale of 13,000-15,000 cy/year and 6.8 to 8.4 MMbtu/h, the Pyrocal and ICM system have reasonable costs of $17-$30/cy net of heat savings.

The main conclusions of this preliminary economic evaluation are:

- There are CHAB systems available for economically feasible production at all scales, depending on the ability to use the excess heat as a substitute for natural gas or propane.

- Heat savings are important at all capacities, but especially at the small scale to reduce biochar costs.

- While the larger systems benefit from the economies of scale, the heat savings appear to lower the production costs to acceptable levels.

- The cost of biochar could range from an income value of $7.46/cy to a production cost of biochar of $77.12/cy, if the thermal energy is fully valued. These prices are either below or within the range of current commercial biochar prices.

Table 10. Preliminary Cost Comparisons of CHAB Systems

COMBINED HEAT AND BIOCHAR PRODUCTION

Description	Organilock	BET	ARTiChar	Pyrocal	Pyrocal	ICM
Heat Capacity MMBtuh	1	3.5	5	2.8	6.8	8.4
Annual Heat Production, MMBtu	7,200	25,200	36,000	20,160	48,960	60,480
Annual wood consumption, dry tons	540	1,339	2,401	1,980	5,040	6,599
Annual Biochar Production, CY	864	2,143	6,003	4,950	12,600	14,517
Annual revenues						
Heat savings	$46,800	$163,800	$234,000	$131,040	$318,240	$393,120
Biochar value added	$69,120	$171,418	$480,240	$396,000	$1,008,000	$1,161,389
Capital Costs						
Equipment direct costs	$157,000	$225,000	$402,500	$522,000	$795,400	$1,130,400
Total Project Costs (incl civil, mech, elec, etc)	$263,300	$394,900	$715,800	$933,500	$1,531,800	$2,049,700
Operating Costs						
Labor	$36,000	$36,000	$144,000	$36,000	$36,000	$288,000
Feedstock	$810	$26,784	$48,024	$39,600	$100,800	$131,976
Electricity	$5,940	$10,260	$10,260	$13,500	$30,240	$28,080
Maintenance	$4,710	$6,750	$12,075	$15,660	$23,862	$33,912
Insurance	$12,560	$18,000	$32,200	$41,760	$63,632	$90,432
Debt	$53,412	$50,021	$90,668	$189,367	$310,737	$259,629
Total Annual Cost	$113,432	$147,815	$337,227	$335,887	$565,271	$832,029
Less heat savings	$46,800	$163,800	$234,000	$131,040	$318,240	$393,120
Biochar cost	$66,632	-$15,985	$103,227	$204,847	$247,031	$438,909
$/CY	$ 77.12	$ (7.46)	$ 17.20	$ 41.38	$ 19.61	$ 30.23

VI. Conclusions

Biochar and biomass thermal energy as co-products can help communities and enterprises capture value from waste biomass, while sequestering carbon and reducing the need for fossil fuels. A composting operation is the type of enterprise that is well-positioned to take advantage of biomass energy and biochar for use in its operations. This technology assessment looked at CHAB systems that are currently available in the US market from vendors that have a track record of successful installations.

We identified six models from five vendors that could meet the needs of a composting operation for heat and biochar, at several scales. The preliminary economic analysis shows that all of these systems could be profitable if the thermal energy is fully utilized.

The next step for any enterprise wishing to bring a CHAB system online would be a full feasibility study. A full feasibility study would include:

- Business plan for the current and expanded operations
- Market analysis for biochar and biochar-enhanced products
- Energy audit for the current facility
- Energy needs analysis for the expanded facilities
- Long term biomass fuel supply and cost analysis
- Fuel handling and storage needs
- Permitting needs: construction, site, operating
- System and Balance of System capital cost
- Engineering and commissioning cost
- O&M needs
- Staffing needs
- Backup heating needs
- Sensitivity analysis for main factors of fossil fuel costs, biomass costs, debt cost and biochar market price

The information provided in this assessment should be helpful to any entity that wishes to pursue the opportunity to utilize a CHAB system to capture value from waste biomass.

VI. Vendor Information

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