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Techno-economic analysis of decentralized biomass processing depots

Patrick Lamers [a,*], Mohammad S. Roni [a], Jaya S. Tumuluru [a], Jacob J. Jacobson [a], Kara G. Cafferty [a], Jason K. Hansen [a], Kevin Kenney [a], Farzaneh Teymouri [b], Bryan Bals [b]

[a] Idaho National Laboratory, Idaho Falls, ID 83415, USA
[b] Michigan Biotechnology Institute, 3815 Technology Blvd., Lansing, MI 48910, USA

HIGHLIGHTS

- Biomass depots are necessary to scale-up the biorefinery industry.
- There are two distinct depot concepts: addressing feedstock stability and quality.
- Within these concepts, several technical configurations are possible.
- Biomass depots can entail conventional pelleting up to sophisticated pretreatment.
- Depot processing costs range from ~US$30 to US$63 per dry metric tonne.

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ABSTRACT

Decentralized biomass processing facilities, known as biomass depots, may be necessary to achieve feedstock cost, quantity, and quality required to grow the future U.S. bioeconomy. In this paper, we assess three distinct depot configurations for technical difference and economic performance. The depot designs were chosen to compare and contrast a suite of capabilities that a depot could perform ranging from conventional pelleting to sophisticated pretreatment technologies. Our economic analyses indicate that depot processing costs are likely to range from ~US$30 to US$63 per dry metric tonne (Mg), depending upon the specific technology implemented and the energy consumption for processing equipment such as grinders and dryers. We conclude that the benefits of integrating depots into the overall biomass feedstock supply chain will outweigh depot processing costs and that incorporation of this technology should be aggressively pursued.

1. Introduction

Currently, the U.S. cellulosic biofuel industry relies on a conventional biomass supply system, hereinafter referred to as the conventional system, where corn stover, pulpwood, energy crops or other herbaceous and woody residues are procured through contracts with local growers, harvested, stored locally, and delivered in bale or low density bulk format to the conversion facility. The conventional system has been demonstrated to work in a local supply context within high yield regions (Bonner et al., 2014), e.g., the U.S. Corn Belt or southeast forests, but scaling up the biorefinery industry will require increasing biomass volumes at decreasing costs. The U.S. Department of Energy's (DOE) Bioenergy Technologies Office (BETO) has a logistics cost target to the throat of the conversion facility (including grower payment and logistics) of US$80 per dry short ton, equivalent to US$88 per metric tonne (Mg), to reach a fuel target of US$3 per gallon of gasoline equivalent (GGE) (or US$0.79 per liter of gasoline equivalent) by 2022 (DOE, 2013).

Multiple analyses (Argo et al., 2013; Hess et al., 2009; Muth et al., 2014) have shown that the conventional system may not be able to reach this target outside of highly productive regions and will even struggle in some years within high yield areas due to inclement weather during production and harvest seasons or extreme events such as floods or droughts. These supply uncertainties tend to classify the biorefining industry as a high risk investment and limit the concept from being broadly implemented (Hansen et al., in press). Financial institutions translate high risk ventures into higher interest rates, which have a profound impact on the overall costs to a biorefinery over its operational life span. Lamers et al., in press calculated up to US$96 million in savings of interest paid over a 10 year loan period for a mature biochemical biorefinery (total capital investment of $458 million) when annual

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[*] Corresponding author.
E-mail address: patrick.lamers@inl.gov (P. Lamers).

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interest rates were to drop by 5% (within a range of 8–30% annual interest). This translates to cost savings of US\$0.04 liter^{-1} (US\$0.15 gal^{-1}) of fuel produced.

The advanced system described by Hess et al. (2009) and Searcy and Hess (2010) provides a method to reduce feedstock quantity, price, and quality uncertainties. It is based on a network of distributed biomass processing centers (Eranki et al., 2011), so-called depots, that use one or several biomass types to generate uniform feedstock 'commodities'. These 'commodities' are intermediates with consistent physical and chemical characteristics that meet conversion quality targets and at the same time leverage the spatial variability in supply quantities and costs by improving flowability, transportability (bulk density), and stability/storability (dry matter loss reduction).

This paper presents a techno-economic evaluation of the depot concept, in addressing the following questions:

- What are the main technical and cost configuration options of a depot?
- What are the operational details (e.g., regarding material flow) of a depot?
- What are the economic impacts of these different depot concepts?

This evaluation is limited to a subset of potential depot designs and does not include upstream or downstream supply chain influences as a result of the depot. For a holistic comparison of depot costs and benefits across the entire biorefinery supply chain we refer to Lamers et al. (in press) who quantify cost reductions that can be achieved across the value chain by applying the depot concept.

This analysis is also directly related to project work undertaken by Oak Ridge National Laboratory (ORNL) that is studying optimal depot locations based on biomass availability and logistic networks (Webb et al., 2014). This paper investigates internal depot aspects and complements the ORNL analysis by providing feedback on changes in feedstock characteristics (i.e., changes in moisture content, flowability, bulk density, etc.), that affect the optimization runs for both a depot and biorefinery location.

2. Methods

2.1. Model framework

The Biomass Logistics Model (BLM) framework (see Cafferty et al., 2013 for a detailed description) was used to conduct the economic analysis of each depot design. The BLM is part of a versatile analysis toolset developed by the Idaho National Laboratory (INL) to estimate delivered feedstock cost, energy consumption and greenhouse gas (GHG) emissions for the entire biomass supply system design from harvest and collection to delivery to the throat of the conversion facility. This analysis was focused only on the depot aspect of the supply system and did not account for the other operations. The BLM simulates a broad set of parameters and allows the user to investigate important sensitivities and uncertainties of equipment lineups, efficiencies and flow rates that are currently a primary source of feedstock risk for the biorefinery industry. The BLM model structure is shown in Fig. 1.

The BLM incorporates information from a collection of databases that provide (1) engineering performance data for hundreds of equipment systems, (2) spatially explicit labor cost datasets, and (3) local tax and regulation data. The BLM is designed to work with various thermochemical and biochemical conversion platforms and accommodates numerous biomass varieties (i.e., herbaceous residues, short-rotation woody and herbaceous energy crops, woody residues, algae, etc.), resulting in a robust and flexible systems model. The BLM simulates the flow of biomass through the entire supply chain, tracking changes in feedstock characteristics (i.e., moisture content, dry matter, ash content, and dry bulk density) as influenced by the various operations in the supply chain. By accounting for all of the equipment that comes into contact with biomass from the point of harvest to the throat of the conversion facility and the change in characteristics, the BLM enables highly detailed economic cost, energy consumption and environmental impact analyses. As a result of these highly detailed analyses, areas for improvement (i.e., equipment efficiencies, operational parameters, environmental conditions, etc.) can be identified through sensitivity analyses that can be used to enhance the design and performance of these systems. Finally, the BLM can be coupled to additional models as it is part of a greater modeling toolset used to assess sustainability, environmental impacts (GHG emissions), and feedstock quality specifications. The process information data per depot configuration was based on currently available equipment from INL's Process Demonstration Unit (PDU) and laboratory experiments. Data for the ammonia fiber expansion (AFEX™) process was provided by the Michigan Biotechnology Institute (MBI). Vendor information was used where experimental data was not available.

2.2. Scope and indicators

This techno-economic analysis is limited to depot internal processes, i.e., all flows from the depot entrance to the exit gate. To fully appreciate the advantages uniform-format feedstock has in a large-scale bioeconomy, a wider supply system comparison would be necessary, but goes beyond the scope of this analysis.

The economic calculations cover the operations of a depot only, i.e., all within-gate costs. It does not include the assessment of varying feedstock prices (due to different grower payments or transportation systems, etc.). The primary indicators are output cost in dry metric tonnes (Mg). Secondary indicators include energy use, preprocessing times, effective throughput rates, and moisture levels (see Supplementary Material for details).

The depot operations are focused on biochemical conversion routes using herbaceous residues as a feedstock. Herbaceous residues and energy crops currently face a limited market demand and their feedstock characteristics match up well with biochemical conversion technologies. Depots, if designed properly, can support more than fuel markets, such as biopower, animal feed, and bioplastics, which should help facilitate additional and constant demand. Furthermore, logistical advancements are needed within the biochemical conversion supply chain to make herbaceous material cost efficient. Also, herbaceous residues are not widely used in the heat and power market due to combustion issues (e.g., slacking and fouling). Woody biomass is expected to also have a role in biochemical conversion (via blending) but more so in thermochemical conversion processes. At the same time, wood (pulpwood and residues) pelleting operations have already proven to be economical and the evolution of a depot concept could benefit significantly from current operations in the wood sector. Any new operations in a depot operation defined under the herbaceous design would transfer into a woody depot system after the initial grinding operations.

2.3. Depot concepts

Currently, biorefineries located in high yield areas are designed to handle single feedstock of similar format such as corn stover or wheat straw bales (INL, 2013). These vertically integrated systems limit potential biorefinery locations and do not consider other business issues (e.g., labor, taxes, proximity to distribution centers, or end-use markets). More recent insights indicate that with the

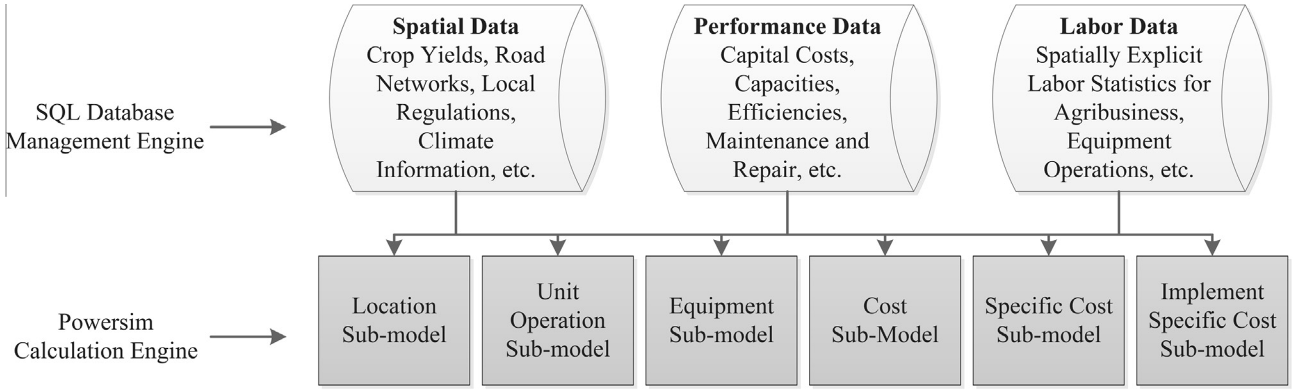

Fig. 1. The structure of the Biomass Logistics Model (Cafferty et al., 2013).

Table 1
Comparison of depot concepts and their main characteristics.

	Standard Depot	Quality Depot
Primary function	Improve feedstock stability, storability, flowability, bulk density by creating physically (and chemically) homogeneous feedstock	In addition to the standard function: Create on-spec feedstock by actively addressing feedstock quality
Secondary function		In addition to the standard function: Create intermediates that meet specific biorefinery needs and reduce processing intensity downstream
Location	Driven by feedstock supply, logistical infrastructure, community support, social capital, potential link to existing industry (e.g., agriculture or wood processing), low energy prices	
Feedstock quality control	Only passive via blending	Active control
Technologies applied	Mechanical and thermal processing (grinding, drying, pelleting)	Mechanical and thermal processing plus chemical/ thermochemical preconversion
Status/timeline for adoption	Already applied in woody biomass industry, pilot scale for herbaceous biomass	Pilot scale (expected)
Other	Moisture control (quality aspect) is done to prevent dry matter loss and reach primary goals	Active management of feedstock specifics allows advanced depots to target different end-use markets (fodder, energy, plastics, etc.)

support of depots, biorefineries could be built almost anywhere, including lower yield areas (Argo et al., 2013), where a network of biomass depots would supply biorefineries with sufficient feedstock, possibly from different biomass sources in a variety of forms (e.g., square and/or round bales, chopped, bundled, raw, etc.). As a result, a depot could take on many forms. For example, a Standard Depot could include particle size reduction, moisture mitigation, and densification to achieve the supply system benefits discussed in earlier studies (Eranki et al., 2011; Hess et al., 2009; Kenney et al., 2013). More severe feedstock quality issues and intolerant specification at the biorefinery could provoke depots to include additional processing steps (e.g., leaching, chemical treatment, or washing). These two distinct set-ups characterize the potential structure of a depot (Table 1).

2.3.1. Standard Depot

In our analysis, the primary function of the *Standard Depot* is to improve feedstock stability (for storage), increase bulk density (for transport), improve flowability (for stable in-feed rates), and reduce material loss. Any improvement to feedstock quality is a result of these activities rather than a primary target of the operation. Indirect quality activities, for example, drying, are done to prevent degradation and material loss. Consistent moisture levels, however, also benefit conversion efficiency in thermochemical conversion pathways (Muth et al., 2014) and improve in-feed. Additionally, densification is done to improve material handling and transportability as well as provide a stable, reliable resource inventory reducing feedstock volatility influence to the supply chain which is key in de-risking the feedstock supply system (Hansen et al., in press). Passive quality management is optionally possible via feedstock blending.

2.3.2. Quality Depot

A *Quality Depot* actively addresses feedstock quality aspects specific to the end-use market it targets, e.g., cellulosic biorefineries, animal feed, or the heat and power sector. It produces enhanced feedstock (with lower contamination levels) or even process intermediates and thus reduces the pretreatment requirements at the client facility. To match its final markets, various kinds of pretreatment steps are possible within an advanced depot. Thermal pretreatment technologies (e.g., torrefaction) create feedstock with structural homogeneity and superior handling, milling, and co-firing properties. Chemical pretreatment changes the composition and structure of the biomass. This reduces the energy required to grind or densify the feedstock, improves flowability and storage stability, and removes contaminants detrimental to downstream biorefinery processes.

2.4. Assumptions and formula applied

In our analysis we assume a maximum depot capacity of 9 Mg h^{-1} (equivalent to 10 short tons h^{-1}) where 10 depots support a biorefinery demand of 725,600 Mg $year^{-1}$ (equivalent to 800,000 short tons $year^{-1}$), a scale that resembles a mature biorefining industry (Dutta et al., 2011; Humbird et al., 2011). We assume depots are modular, and can be incrementally scaled in a stepwise fashion of 9 Mg h^{-1}. We did not assume any cost savings for larger depot sizes via economies of scale, because operations are limited by finite equipment capacities, which are commercially available (i.e., grinders, dryers, pellet mills). Corn stover is used as a representative herbaceous residue feedstock, assumed at 30% moisture content (MC) (wet basis) when received at the depot.

2.4.1. Cost year indices

The cost-year of 2011 was chosen for consistency across all DOE-BETO platforms, where similar analyses were performed with respect to the designs and cost targets mentioned. Capital costs provided for other years were adjusted using the Plant Cost Index from *Chemical Engineering Magazine* (CEM, 2011) to the common basis year of 2011. The general formula for year-dollar back-casting is shown in Eq. (1):

$$\text{2011 Cost} = (\text{Base Cost})\left(\frac{\text{2011 Cost Index}}{\text{Base Year Index}}\right) \tag{1}$$

2.4.2. Total capital investment

The list of equipment can be determined by performing a detailed study of everything required to make the depot operational. A complete list of the equipment is provided in Supplementary Material, along with equipment purchased and installed costs. The equipment prices used in this analysis are obtained from local dealers. The Agricultural & Applied Economics Association (AAEA) indicates that the difference between purchase price and list price may be up to 15% (AAEA, 2000). While this quoted price may be the list price, no adjustment of this price per AAEA guidance was applied.

Once the total fixed capital equipment cost has been determined in the year of interest, we add several additional equipment options (e.g., electrical installation, instrumentation and control), other direct (e.g., yard improvements, land, buildings, etc.) and indirect costs (e.g., engineering and supervision, construction expenses, contractor's fee, contingency, etc.) to determine the total capital investment. These costs are estimated based on Peters et al. (1968), and are considered part of the fixed capital investment.

2.4.3. Ownership costs

Ownership costs are made up of two cost blocks: interest and depreciation (I&D), plus insurance, housing, and taxes (IH&T).

2.4.3.1. Interest and depreciation (I&D). I&D can be calculated separately or combined, based on the value to be depreciated plus the interest on the salvage value (ASABE, 2006). The AAEA uses the second method, shown in Eq. (2). The salvage value (i.e., the remaining value) must be known or estimated to determine I&D. The method by the American Society of Agricultural and Biological Engineers (ASABE) was used to determine the salvage value (ASABE, 2006). We apply an annual interest rate of 6%:

$$\text{I\&D} = (P - S)\left[\frac{(i)(1+i)^n}{\{(1+i)^n\} - 1}\right] + S \times i \tag{2}$$

where I&D = Interest and depreciation, P = purchase price of equipment, i = annual interest rate, n = life of the equipment in years, S = salvage value (salvage value % × list price).

2.4.3.2. Insurance, housing, and taxes (IH&T). Insurance, housing (cost of shelter for equipment), and taxes (IH&T) refer to the fixed costs related to the equipment, and these costs are estimated as percentages of the purchase price (Eq. (3)). Where actual data is not available, the ASABE suggests using the following percentages: taxes 1.00%, housing 0.75%, and insurance 0.25%, for a total of 2.00%:

$$\text{IH\&T} = \frac{(I_{\text{Percentage}} + H_{\text{Percentage}} + T_{\text{Percentage}}) \times \text{average (Percentage price, salvage)}}{\text{Work hours per year} \times \text{efficiency factor}} = \frac{\$}{\text{hr}} \tag{3}$$

2.4.4. Operating costs

Operating costs consist of repair and maintenance (R&M), as well as fuel and labor cost. Expenditures are necessary to keep a machine operable due to wear, part failure, accidents, and natural deterioration. Machine repair costs are highly variable and depend on handling and management of the respective equipment. R&M costs in this study are calculated via Eq. (4):

$$\text{R\&M} = \frac{\text{list price} \times \text{repairs and maintenance percentage}}{\text{lifetime(hr)}} = \frac{\$}{\text{hr}} \tag{4}$$

The R&M percentage is estimated based on ASABE, 2006. Fuel consumption cost is calculated based on data obtained either via machinery specifications or from actual estimates and/or measurements obtained from INL's PDU. Labor rates were obtained from the Idaho Bureau of Labor Statistics, and labor hours were assumed on shift schedules. The assumed labor rate for the horizontal bale grinder, hammer mill, dryer, pellet mill, and chemical pretreatment are US\$15.88 h^{-1}, US\$19.88 h^{-1}, US\$15.51 h^{-1}, US\$15.51 h^{-1}, and US\$19.88 h^{-1}, respectively. We assume that one person is able to manage two machines (see Supplementary Material for details). Further, we account for 3 shifts per day, 40 h per week and worker, and 50 weeks per year.

3. Results and discussion

3.1. Technical comparison

Standard Depots are meant to address feedstock stability, bulk density, and flowability issues. The process flow includes particle size reduction, moisture mitigation and densification. The most basic Standard Depot configuration is a conventional pelleting process (CPP) involving two stage size reduction (grinding), drying, and pelleting. Additional modifications within a Standard Depot could be made to make the process more efficient, e.g., a high moisture pelleting process (HMPP). A HMPP varies in process sequence, dryer type and size from the CPP.

3.1.1. Standard Depot: conventional pelleting process (CPP)

Conventional biomass pellet production includes initial size reduction to a less than 50 mm particle size, followed by drying to 10–12% MC using a rotary dryer. The dried biomass is then passed through a second stage grinding process to reduce the particle size to less than 5 mm (typically to 2 mm), steam conditioned, and pelletized (Fig. 2). The steam conditioning prior to pelleting increases moisture content, which helps to gelatinize the starch, denature protein, and change the glass transition temperature of lignin (Tumuluru et al., 2014). The two sequential size-reduction steps are necessary to arrive at the final particle-size specification (INL, 2013). The first stage of the size reduction process takes the as-received biomass and converts it through grinding or chipping into a product that can be further processed. The configuration of the first-stage grinding/chipping process uses a 51–76 mm (2–3 in.) screen for coarse size reduction. This size and type of screen provides enough size reduction for subsequent drying and final grinding. The role of the second-stage grinder is to reduce the

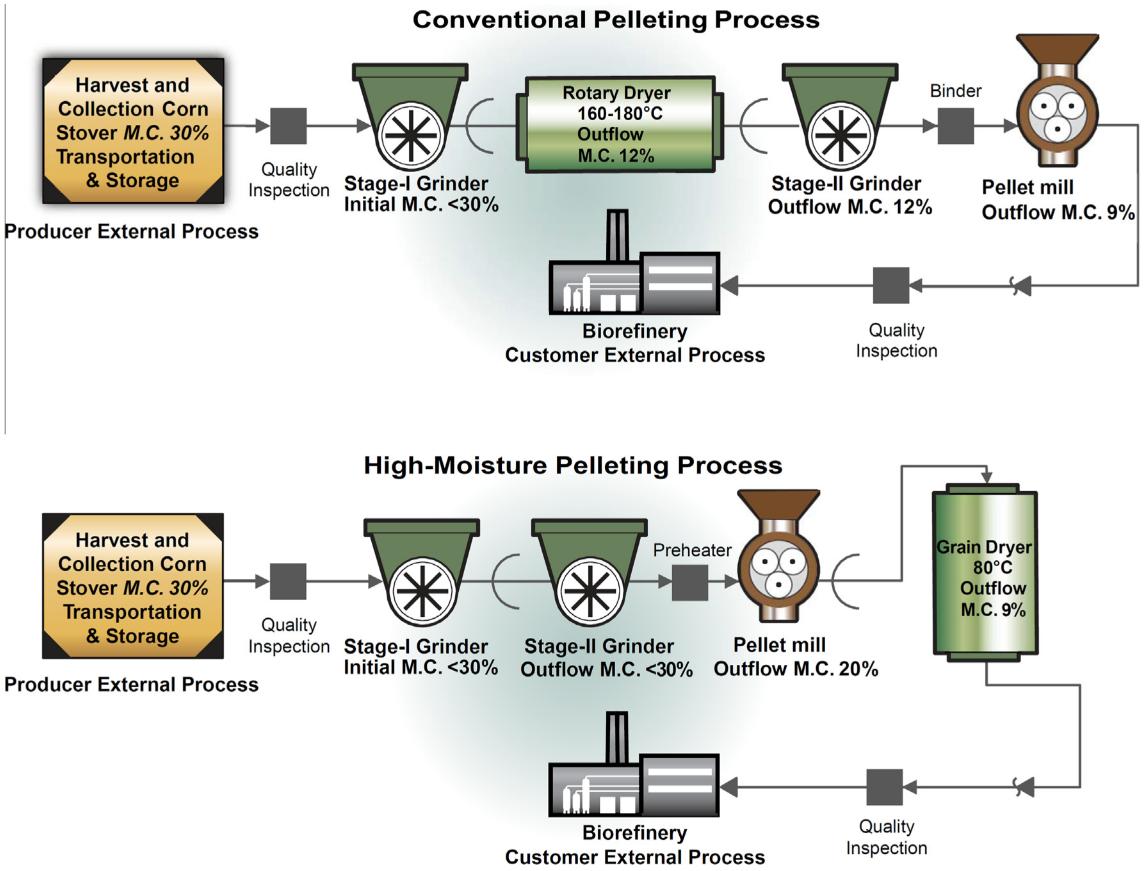

Fig. 2. Two technical configurations of the Standard Depot as analyzed. Legend: MC: moisture content.

particle size further in order to meet particle size distribution requirements for pelleting. A typical second-stage size reduction process will use a 19–25 mm (0.75–1 in.) screen to produce a mean particle size of 2.5–3.8 mm (0.1–0.15 in.). Material that flows through a screen is smaller than the actual screen size.

Drying is the major energy consumption unit operation in this process, accounting for about 70% of the total pelleting energy. Pelleting takes the material and compresses it to pellets ranging in density from 480 to 640 kg m^{-3} (30–40 lbs ft^{-3}). The pellets are hydrophobically stable and are high quality to sustain transportation with minimum losses.

In the case of woody feedstock, first stage grinding would be done during the harvesting and collection process or at the landing site. Thus, the CPP depot configuration for woody biomass would start with drying, followed by second stage grinding, etc.

3.1.2. Standard Depot: high-moisture pelleting process (HMPP)

In the HMPP depot configuration, high-moisture (30–35% MC) biomass is preheated and pelletized instead of dried prior to pelleting as in the CPP. The final pellets are then dried in a (vertical) grain dryer to reduce the moisture and stabilize the pellets. This option offers cost reductions as it eliminates the energy intensive, expensive, horizontal (i.e., larger footprint) rotary drying process prior to pelleting. The high-temperature (typically 160–180 °C) drying step is replaced with a low-temperature (approximately 80 °C), short duration (typically several minutes) preheating step. The combination of preheating with the additional frictional heat generated in the pellet die and further cooling results in a reduction of feedstock moisture content by about 5–10% to produce partially dried pellets. These partially dried pellets still have a high MC and require further drying to under 9% MC for safe storage and transportation (Tumuluru et al., 2014). This reduction in moisture in the partially dried pellets can be achieved using low-cost and energy-efficient grain or belt dryers. Fig. 2 indicates the various unit operations and energy consumption associated with each step. HMPP does not include the addition of a binder.

3.1.3. Quality Depot: ammonia fiber expansion (AFEX)

Quality Depots may include processing steps (e.g., leaching, chemical treatment, or washing) designed to enhance the quality aspects of the biomass. We demonstrate a Quality Depot using the AFEX process which is a promising pretreatment that involves an ammonia-based process resulting in physical and chemical alterations to lignocellulosic biomass that improves their susceptibility to enzymatic attack (Bals et al., 2011) (Fig. 3). AFEX pretreatment has increased glucan and xylan conversion and ethanol yields for a variety of feedstocks, including corn stover and switchgrass (Balan et al., 2009; Campbell et al., 2013; Teymouri et al., 2005).

Similar to the Standard Depot, AFEX material needs to be pelleted prior to transport/distribution to biorefineries.[1] Campbell et al. (2013) indicate that high-quality pellets (in terms of density and durability) can be produced after the AFEX process. While outside the scope of this analysis, Hoover et al. (2014) and Bals et al. (2014) suggest that AFEX pelleting could have additional advantages beyond improved logistical handling of biomass.

The grinding, milling, drying, and pelleting steps in the AFEX pretreatment are aligned with those of the CPP. We did not apply a HMPP to the AFEX process due to a lack of data. At the same time, these combinations may prove beneficial to the overall process

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[1] AFEX material for animal feed operations is typically not pelleted (Bals and Dale, 2012).

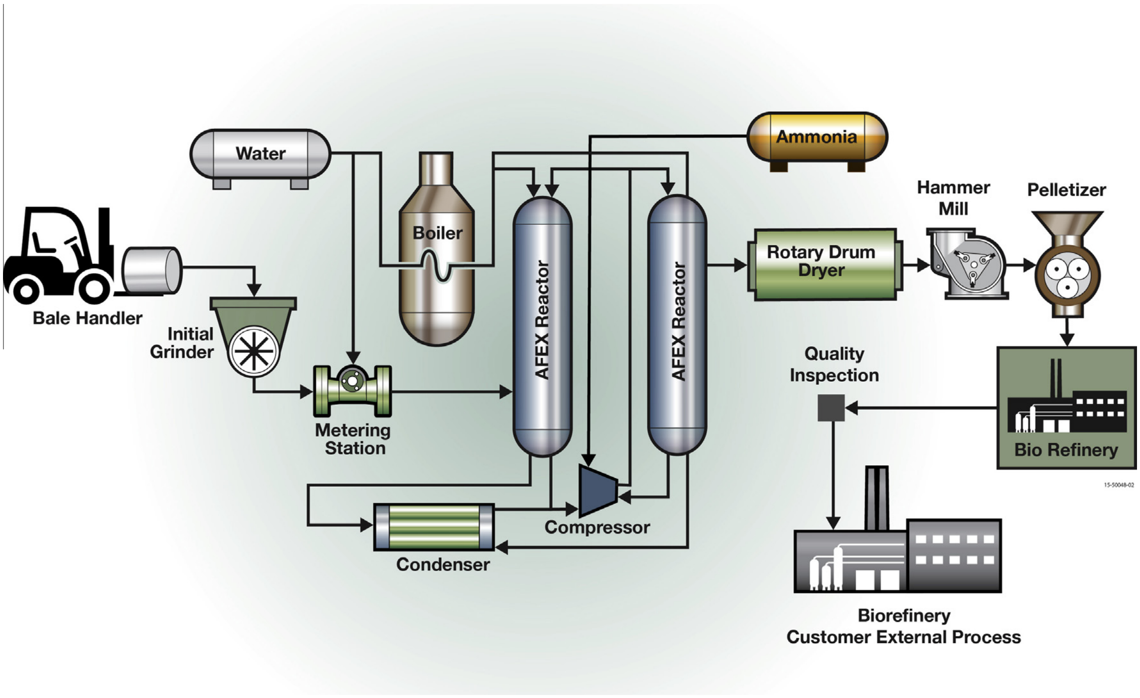

Fig. 3. Ammonia fiber expansion (AFEX) process flow diagram.

performance and AFEX pellet quality, and should be investigated further.

3.1.4. Quality Depot: dilute-acid pretreatment

A second example of the Quality Depot could include dilute-acid pretreatment, which is a pretreatment step currently applied in the biological conversion route of sugars to hydrocarbons (and the prior enzymatic deconstruction of biomass to sugars) (Davis et al., 2013). However, investment costs for this pretreatment step are substantial. In a biorefinery, dilute-acid pretreatment costs up to US$51,400,000 installed plus a waste water treatment (WWT) facility to manage effluents from both steps for an additional US$60,100,000 (installed) (Davis et al., 2013). Despite the significant difference in size to a depot, the requirement of a WWT facility will not prove cost efficient for a single-depot. Unless effluents can be recycled within the process, much like the AFEX pretreatment step, several depots are combined, or directly connected to an existing WWT (e.g., at a biorefinery), the inclusion of this pretreatment step in decentralized depots appears unreasonable and therefore was not included for further analysis. For an economic and environmental comparison of different pretreatment options, we refer to Tao et al. (2014).

3.2. Economic comparison

The economic analyses of all the depot configurations reveals medium (Standard Depot) to high (Quality Depot) initial investment costs and highly variable production costs with the HMPP being the lowest (US$30.80 Mg^{-1}), and CPP and AFEX representing the middle and higher cost ranges (US$47.80 and US$62.50 Mg^{-1}, respectively) (Fig. 4). Each configuration is shown to be heavily dependent on electricity prices, due to the energy consumption levels for grinders and dryers, particularly in the CPP and AFEX configurations.

Table 2 summarizes the economics of each depot configuration for total investment costs. Fig. 4 details the specific cost blocks per unit output. As these overviews show, cost savings of 35% can be achieved by moving from the conventional (CPP) to the high-moisture (HMPP) depot configurations in cost per unit output. The cost reductions are achieved by several improvements. First, the transition from a rotary dryer in CPP to a cross flow pellet dryer in HMPP. Secondly, by increasing the effective machine throughput, reducing the number of equipment operations necessary to process material, consequently lowering capital costs. Note that the capacity of the first stage grinder for CPP is 1.8 Mg h^{-1} and 4.5 Mg h^{-1} for the HMPP (see Supplementary Material for details).

The chemical pretreatment in the AFEX configuration drives total fixed investment costs to about US$6 million which is then also reflected in the higher direct and indirect costs (Table 2). Compared to the Standard Depot configurations, the AFEX pretreatment option requires more process steps, and thus more equipment, which increases the total investment costs. The eventual costs per Mg output, however, are relatively competitive to the CPP due to higher throughput rates and lower repair and maintenance costs per Mg output.

3.3. Sensitivity analysis

A sensitivity analysis was performed for depot size, electricity price, and energy consumption as these indicators potentially influence depot ownership and operating costs. We assumed triangular distributions for each variable for simplification. For this exploratory analysis, it generates sufficient randomness to identify sensitive parameters. A triangular distribution requires the median (most likely), minimum and maximum expected values.

Of the parameters chosen for the sensitivity analysis, the electricity price had the greatest influence on total and operation costs across all configurations (Supplementary Material). Changing the electricity price from US$0.04 kWh^{-1} to US$0.14 kWh^{-1}, the depot fixed and operation costs increase from US$40 Mg^{-1} to US$88 Mg^{-1} for CPP, from US$27 Mg^{-1} to US$49 Mg^{-1} for HMPP,

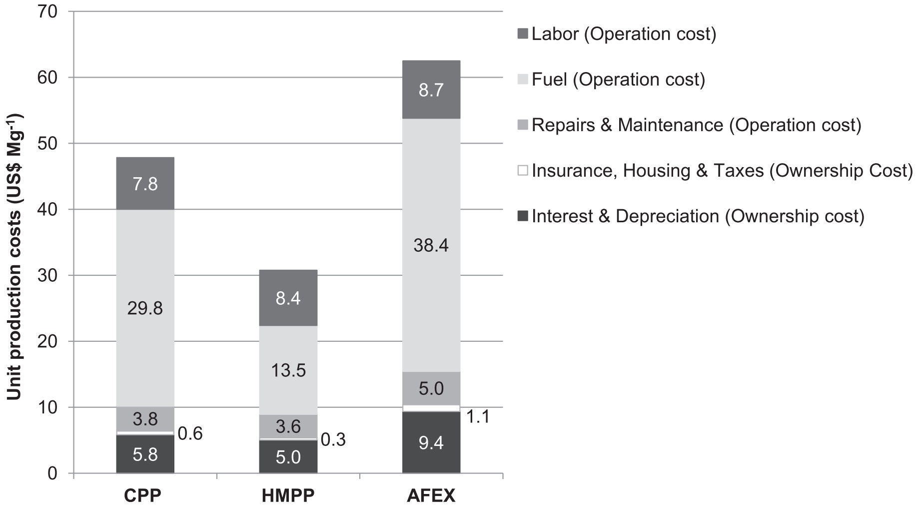

Fig. 4. Total cost comparison between the depot configurations. Legend: CPP: conventional pelleting process; HMPP: high moisture pelleting process; AFEX: ammonia fiber expansion.

Table 2
Total fixed capital costs and total capital investment (US$) for a depot sized at 200 Mg day^{-1} capacity.

	Conventional pelleting process (CPP)	High moisture pelleting process (HMPP)	Ammonia fiber expansion (AFEX)
Grinder	[I] 324,000[a]	[I] 324,000[a,b]	[I] 324,000[a]
Chemical pretreatment			[II] 2,564,800
Dryer	[II] 1,579,200	[IV] 64,000[c]	[III] 1,579,200
Hammer mill	[III] 206,400	[II] 515,200[d]	[IV] 206,400
Pellet mill	[IV] 630,400	[III] 630,400	[V] 630,400
Conveyor equipment	268,800	268,800	268,800
Dust collection equipment	286,400	286,400	286,400
Surge bin	96,800	96,800	96,800
Miscellaneous equipment[e]	84,000	84,000	84,000
Total fixed capital costs (US$)	3,476,000	2,269,600	6,040,800
Total other direct cost (21% of total fixed capital cost)	729,960	476,616	1,268,568
Total indirect cost (15% total fixed capital cost)	521,400	340,440	906,120
Total capital investment (US$)	4,727,360	3,086,656	8,215,488

[I–V] the roman letters indicate the process flow sequence.

[a] The AFEX process is based on the CPP machinery set (see Supplementary Material for details).

[b] Reduction in cost due to increased machine throughput reducing the number of equipment necessary to process material consequently lowering capital costs (Note that the throughput rate of the first stage grind for CPP and HMPP are 1.8 Mg h^{-1} and 4.5 Mg h^{-1}, respectively).

[c] Cost reduction achieved by the transition from a rotary dryer in CPP to a cross flow pellet dryer in HMPP.

[d] Cost reduction achieved by increasing the machine capacity caused by increasing the screen size of stage-one grinder in HMPP.

[e] Miscellaneous equipment includes: twine remover, moisture meter, electro magnet, bale ejecter.

and from US$53 Mg^{-1} to US$110 Mg^{-1} for AFEX (Figs. S1–S3). The second largest variations were observed in configurations with higher energy consumption, to which drying and thus dryer type is the most critical influencing parameter.

We also assessed the impact of variations of all sensitivity parameters simultaneously on depot fixed and operations cost at different depot configurations (Fig. 5). This was done by generating random variations of different sensitivity parameters from the triangular distribution and running the model 1000 times with randomly selected different combinations of sensitivity parameters.

As the depot size increases, fixed and operation costs decrease (Fig. 6). Total cost reduction however remain fairly small. As the depot size increases from 5 to 18 Mg h^{-1}, the fixed and operations costs drop from US$49.67 Mg^{-1} to US$47.94 Mg^{-1} for CPP, from US$32.10 Mg^{-1} to US$30.79 Mg^{-1} for HMPP, and from US$66.08 Mg^{-1} to US$63.41 Mg^{-1} for AFEX. The slight increase in the AFEX configuration between 10 and 11 Mg h^{-1} is due to an increase in adding another dryer in whole increments.

4. Conclusions

Decentralized biomass processing facilities (depots) may be necessary to achieve feedstock costs, quantity, and quality required to grow the future U.S. bioeconomy. Depending on the depot configuration, processing costs range from US$30.80 Mg^{-1} to US$62.50 Mg^{-1}, but are expected to be outweighed by overall supply system benefits. Multiple depot set-ups are possible. Feedstock stability, bulk density, and improved flowability can be met via Standard Depots, while Quality Depots encompass additional processing steps such as leaching or chemical treatment. The economic burden of each design depends greatly on the energy consumption of the respective processing equipment.

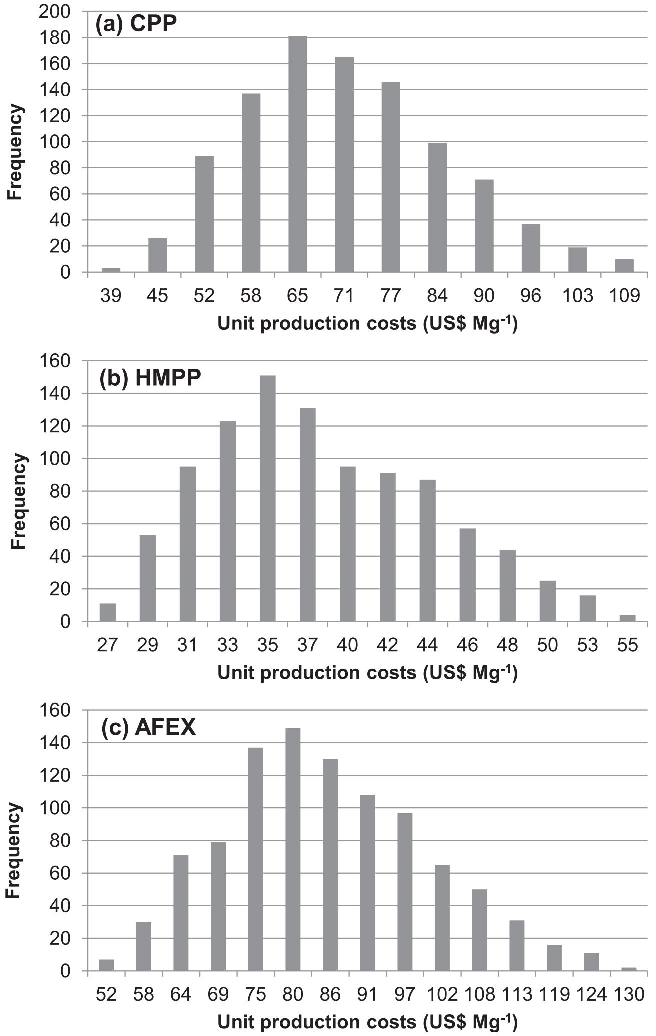

Fig. 5. Impact of all sensitivity parameters on depot production costs per unit output for CPP (a), HMPP (b), AFEX (c). Legend: CPP: conventional pelleting process; HMPP: high moisture pelleting process; AFEX: ammonia fiber expansion.

Disclaimer

Financial & competing interests disclosure

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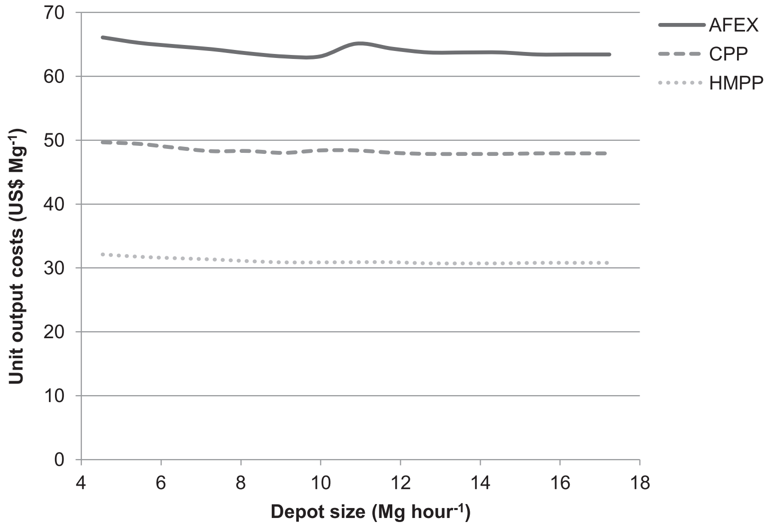

Fig. 6. Impact of depot size on production costs for the different configurations. Legend: CPP: conventional pelleting process; HMPP: high moisture pelleting process; AFEX: ammonia fiber expansion.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biortech.2015.07.009.

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