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Comparing pelletization and torrefaction depots: Optimization of depot capacity and biomass moisture to determine the minimum production cost

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HIGHLIGHTS

- Moist climates justify more severe torrefaction, while dry climates support less severe torrefaction.
- Torrefied pellets are less costly than conventional pellets at the optimum depot scale and biomass moisture content.
- High biomass availability and access to well-maintained roadways allow larger biomass upgrading depots.

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ABSTRACT

In the present study, the biomass upgrading depot capacity and biomass feedstock moisture were optimized to obtain the minimum production cost at the depot gate for the production of woody biofuels. Three technology scenarios are considered in this study: (1) conventional pellets (CP), (2) modestly torrefied pellets (TP1) and (3) severely torrefied pellets (TP2). TP1 has the lowest cost of $\$7.03/GJ_{LHV}$ at a moisture of 33 wt.% and a depot size of 84 MW_{LHV}. The effects of climatic conditions and biomass field conditions were also studied for three scenarios. In humid regions of Michigan, TP2 is more economical than other scenarios because of the increased production of combustible gas. The three scenarios have similar sensitivities to biomass field conditions.

1. Introduction

Renewable feedstocks and conversion strategies are needed for making solid fuels that can displace coal for heat and power production [1]. Several states within the U.S.A. have enacted renewable fuel standards that mandate renewable energy comprise a fraction of the electrical power grid energy [2]. Forest biomass is an important potential source of renewable energy because of its abundance and availability. Further, woody biomass can be efficiently grown on marginal lands in plantations. Harvested biomass can be chipped and piled in the field to increase its value, however, the low bulk density and low heating value of raw woody biomass constrains its commercial use [3]. Upgrading, either by densification or torrefaction followed by densification, is needed to improve biomass properties.

Direct biomass densification improves handling, storage and transportation characteristics. Pelletization is one of the most common densification technologies for solid fuel production [4] as it can increase the bulk density of raw biomass by up to 5 times [5]. It was demonstrated that combustion properties of raw biomass, such as HHV and O/C ratio can be improved significantly by torrefaction [6–9]. Torrefaction is a preprocessing technology that typically precedes densification to improve the physicochemical properties of raw biomass [10,11]. In torrefaction, heat is added in the absence of oxygen to perform a mild pyrolysis of the structural components of biomass [12]. Operating conditions include temperatures ranging from 220 °C to 300 °C and residence times from 5 to 60 min [13,14]. Generally, 61–82% of the starting mass is retained in the torrefied wood, which contains 73–92% of the starting energy because bound oxygen is liberated as water and carbon oxides in the product gas [7,13–15]. Heat required by the torrefaction reactor and for biomass drying can be supplied by combusting this gas, a mode known as autothermal operation when external fuel is not needed [16]. After torrefaction, biomass

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Nomenclature

CI	capital investment
CI_{base}	the capital investment of the base unit size
CI_{max}	the capital investment of the maximum size
S	equipment size
S_{max}	maximum size
f	scale factor
N	the total required number of equipment items
$d_{hauling}$	biomass hauling distance
P	the annual biomass supply needed by the conversion depot
τ	road winding factor
M	biomass availability
M'	the unit biomass availability (one dry tonne of biomass per square kilometer per year)
F	biomass field conditions – the dispersion and accessibility of biomass
t_{days}	the on-site drying time required in days
BC_{gate}	the biomass cost at the conversion depot gate
$BC_{purchased}$	the biomass purchased cost in the field before on-site drying
r	daily interest rate
i	the month when biomass is hauled to the conversion depot (i = 1–12)
MC	the final biomass moisture content after on-site drying
MC_0	the initial biomass moisture
MC_{eq}	equilibrium moisture
Temp	the average temperature during the entire on-site drying period
RH	the average relative humidity during the entire on-site drying period
Precip	the average precipitation during the entire on-site drying period
TPC	total production cost
VC	variable cost
FC	fixed cost

becomes porous and fragile, resulting in low density and low durability. As handling and transporting such a material is challenging and costly, densification typically follows torrefaction to improve bulk physical properties [14,17].

The production of raw biomass pellets or torrefied biomass pellets, to take place in biomass processing depots, is subject to the competing effects of process scale, transportation distance, and moisture content. The minimum production cost for (1) densified only or (2) torrefied and densified fuels is a strong function of depot capacity and feedstock moisture content. It is important to note that the economic behavior of small-scale biomass processing depots differs from that of large fossil fuel refineries. Like fossil refineries, the capital cost per unit of product decreases with increasing scale, a concept known as 'economies of scale'. Unlike large refineries, a larger biomass collection area is needed for larger depots, which leads to longer transport distances and higher feedstock cost. Thus a trade-off between economies of scale and economies of transportation results in an optimal scale for biomass processing depots. Sultana et al. determined the optimal size of agricultural pellet depots to be 150,000 tonnes per year [18]. In addition to depot size, biomass moisture content affects the economics of biomass upgrading depots. Roise et al. developed a method to determine the optimum moisture content for a woody fuel production system by balancing the efficiencies of hauling and drying [19]. However, the effects of dry matter loss during on-site drying were not included in this study [19]. Sosa employed a linear programming model to optimize the moisture content of wood chips to determine the minimum delivered cost to end-users [20]. However, this was for raw biomass and not torrefied and densified solid fuels. A model that encapsulates the competing effects of economies of scale, economies of transportation, dry matter losses during storage and changing moisture content is needed to better understand the economics of torrefaction for making a renewable solid fuel.

Previous research has been conducted to estimate and compare the economics of conventional pellets and torrefied pellets [21,22]. However, these comparisons were performed assuming the same depot capacity and feedstock moisture content rather than on scales and moistures optimized for each type of product. A comparison of production costs for conventional and torrefied pellet systems is needed when each system is optimized for depot scale and moisture content.

In this study, depot size and biomass moisture were simultaneously optimized for the production of woody biofuels. For the first time, three technology scenarios, including conventional pellets (CP), moderately torrefied pellets (TP1), and severely torrefied pellets (TP2), were compared based on the optimum total production cost at the upgrading depot's exit gate. The effects of biomass field conditions and climate conditions were also studied to determine the behaviors of these three scenarios in different geographical regions. Costs are accrued from wood chip purchase to the upgrading depot's exit gate, while subsequent transportation and grinding at end-users are objects of future study. Minimizing the costs inherent in torrefaction energy systems is critical to be competitive with other renewable alternatives under the mandates in place in several States within the U.S.A.

2. Methods

2.1. Process description

Three different scenarios are considered for upgrading willow chips in this study, including: (1) the use biomass pellets from raw wood, referred to as conventional pellets (CP), (2) low temperature torrefaction and pelletization to upgrade biomass properties (TP1), and (3) high temperature torrefaction followed by pelletization (TP2). The scope of the three scenarios includes everything from purchasing wood chips from plantation owners through processing at the upgrading depot. The scope encompasses the process configurations for the CP and TP scenarios as depicted in Fig. 1(a) and (b) respectively.

2.1.1. On-site drying and hauling wood chips

Initially, wood chips are bought in the field at a price of $50 per dry tonne. Wood chips are dried in the field before hauling to reduce transport and drying costs. Pecenka et al. stated that 6–8 months of on-site drying can reduce moisture contents from 60 wt.% to 35 wt.%, depending on the weather conditions [23]. After on-site drying, wood chips are hauled to the upgrading depot by standard semi-trailers, which have cargo capacities of 25 tonne and 100 cubic meters.

2.1.2. Drying

Rotary dryers are employed to reduce the moisture content of biomass. For CP, the biomass moisture content must be reduced to an appropriate range. If the moisture content is too low (below 4%), pellets tend absorb water, elongate and become fragile in a