Energy Conversion and Management 66 (2013) 153–164

Contents lists available at SciVerse ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Technical and economic assessment for the production of torrefied ligno-cellulosic biomass pellets in the US

Adrian Pirraglia *, Ronalds Gonzalez, Daniel Saloni, Joseph Denig

North Carolina State University, Department of Forest Biomaterials, College of Natural Resources, 1022F Biltmore Hall, Raleigh, NC 27695-8005, USA

ARTICLE INFO

Article history:
Received 16 May 2012
Received in revised form 20 September 2012
Accepted 21 September 2012
Available online 23 November 2012

Keywords:
Torrefaction
Bioenergy
Wood pellets
Densification
Biomass

ABSTRACT

Manufacturing and trade of wood pellets in the United States (US) has seen an exponential growth in the last few years, triggered by its potential utilization in applications typically dominated by fossil fuels, such as heat, power, and combined cycle generation. This combination holds the promise of delivering a high density, high heat value fuel, making it a better substitute for coal and other fossil fuels. This combined process exists only at pilot-plant levels. Scale-up of the technology and feasibility of such projects remain largely unexplored. This research developed a techno-economic model for the production of torrefied wood pellets, considering critical production parameters, and evaluating sensitivity to changes in CAPEX (Capital Expenditure), biomass delivered costs, labor, and energy consumption of a facility, evaluated through a case-study. Results indicated that biomass delivered costs and depreciation are the most significant factors influencing production with CAPEX being the most sensitive variable due to high investments in torrefaction reactors. The selection of different torrefaction technologies, and adequate binders, may represent a major improvement in the feasibility of a project by reducing capital costs drastically. Back-calculated price for torrefied wood pellets is $261/metric ton (100,000 metric tons/year facility), and delivered price may reach $282/metric ton, a similar cost compared to regular pellets. Preliminary analysis of carbon credits as additional income may considerably increase the likeability of the business, and further enhance profitability.

1. Introduction

The resurging interest in biofuels has produced a large amount of research and development in new technologies and reevaluation of old technologies. Among these technologies, torrefaction has been identified as one of the most promising pre-treatments [1] to improve the performance of biomass based fuels.

Traditional biofuels industries such as wood pellets have seen a renewed interest and an exponential market growth [2,3] in recent years. Most of this market growth is due to government mandates. Even with moderate projections (10% demand increase annually), 10–12% of all harvested wood in the world would be destined to end up as wood pellets by 2025 [4], and global markets are expected to double in 2014 (11.3 million metric tons in 2008 vs. 22 million metric tons by 2014 [5]). Part of the industry's success relies on using proven technology [6], making its expansion relatively easy, with only the occasional problems typical of growing industries. [7].

Torrefaction of ligno-cellulosic biomass has been extensively investigated in the literature [8–13]. It is described as a thermo-chemical process that degrades hydrophilic polysaccharides and hydroxyl radicals, producing an increase in the percentage of lignin on a dry weight basis, thereby reducing the hydroscopicity of the material and increasing energy density.

Wood pellets have also been broadly documented in previous literature. During pelletization the biomass is milled, dried and mechanically densified, enhancing its heating value and burning characteristics [3,7,14,15]. Previous research proved the feasibility of producing torrefied pellets from ligno-cellulosic biomass [6,16,17], demonstrating improved properties such as heating value, bulk density, and grindability vs. wood chips, pelletization, or torrefaction on its own.

A large part of the market growth of pelletized woody material has been intended to supplement or replace coal for power generation. Studies indicate that torrefied wood's energy content per kilogram are similar to that of coal, and 12–41% greater than that of wood pellets depending on the degree of torrefaction [18]. The disadvantage of wood vs. coal is its lower bulk density (641–721 kg/m^3 vs. 897–993 kg/m^3 for coal). The addition of pelletization to torrefaction would potentially create a bio-based fuel with similar energy density to coal, prompting the adoption of this product for replacing coal in heat and power facilities. Recent studies aim in the direction of making a combined torrefaction–pelletization process possible in a commercial scale [4,6]. The Energy

* Corresponding author. Tel.: +1 919 961 7730.
E-mail address: apirrag@ncsu.edu (A. Pirraglia).

0196-8904/$ - see front matter
http://dx.doi.org/10.1016/j.enconman.2012.09.024

Research Centre Netherlands (ECN [19]) developed a production process for torrefied pellets [6], while Andritz developed a brand-named process with similar unit operations and principles as the ECN process [20]. Both processes are said to provide pellets with better hydrophobic properties, higher density, and similar strength characteristics as non-torrefied pellets.

Mitchell et al. [21] evaluated the business case for torrefied wood pellets, describing that torrefied pellets may have twice the energy bulk density as wood pellets, with the potential of being highly competitive. Uslu et al. [22] confirmed that merging torrefaction and pelletization reduced transportation and handling costs. Van der Stelt et al. [1] found three potential applications for torrefied wood pellets; entrained flow gasification, small scale combustion using pellets, and co-firing in pulverized coal fired power stations. Gasification is still a technology under development for commercial applications, while co-firing in power plants is a concept that has been evaluated by the authors in a previous publication [23].

Despite the vast research efforts of integrating torrefaction and pelletization to produce a pelletized fuel, only one aspect has been considered in a limited scope up to date: its technical and economic evaluation for full scale production in the US. Uncertainty exists in large scale production costs, durability, and the necessity of external binding agents.

The objective of this research is to develop a technical and economic assessment that allows evaluating the feasibility of torrefied wood pellets production in the United States; a case study for a 100,000 metric tons/year facility is utilized to describe and evaluate the results of such model. A second objective of the research is the identification of potential binders for torrefied pellets production, and the determination of its influence on the economics and technical characteristics in a torrefaction–pelletization project.

2. Methods

The present model was developed with a similar concept as previous work performed by the authors [3,23–28]. The analysis of a completely integrated torrefaction–pelletization process involves the identification and assessment of variables in three areas: (1) Mass balance which accounts for biomass weight and energy consumption, (2) the type of fuel used in the production process and the associated energy costs, and (3) a financial section, integrating the main variables (biomass delivered costs, capital expenditure, depreciation, labor, operating, and miscellaneous) into indicators that allow evaluating profitability of torrefied wood pellets production (Internal Rates of Return (IRR), Net Present Value (NPV), and sensitivity analysis).

The model allows user-friendly inputs of costs and production related variables to evaluate scenarios and different production conditions. Table 1 summarizes the user-modified variables in the model.

Torrefaction level represents a critical variable for determining the product properties and quality, and is defined by the residence time and temperature of operation inside the reactor [13,29]. These two parameters determine the changes in the levels of cellulose, hemicellulose, and lignin, as well as the amount of VOC's (Volatile Organic Compounds) available for combustion. A wide range of torrefaction temperatures and residence times have been reported in the literature, varying between 1 and 40 min, and from 200–400 °C. Experimental information from a torrefaction machine (screw-type reactor) in operation at North Carolina State University, and previously described by the authors [13], allowed to establish three torrefaction levels in the model. These levels influence the final moisture content, binder requirements, and High Heating Value (HHV) of the product. Light torrefaction was established at 3 min residence time, and 280 °C with a resultant HHV of 19.7 MJ/kg (8458 Btus/lb.); medium torrefaction is defined as 4 min residence time at 350 °C with a resultant HHV of 21.1 MJ/kg (9060 Btus/lb.), and dark torrefaction is defined as 6 min residence time at 400 °C with a resultant HHV of 22.1 MJ/kg (9502 Btus/lb.).

In order to estimate the profitability of torrefied wood pellets production, the process design and unit operations have to be properly identified. Fig. 1 presents the schematics of a proposed process for torrefied pellets production, from delivered biomass to final storage of torrefied pellets at the facility's gate, assuming that biomass is debarked by wheeled forestry debarkers (cost of debarking included in biomass delivery as debarked roundwood).

2.1. Process description

The process flow in Fig. 1 is modified from previous investigations on torrefaction–pelletization as pretreatment, with the addition of a mixing or conditioning process, for the inclusion of a binding agent to aid in pellets formation and durability, as well as a hammermilling process for further particle size reduction. This is allocated after particle cooling in the torrefaction unit. The model considers biomass received in an open-space storage area, and product is considered to be stored in a naturally ventilated warehouse area.

A torrefaction unit is capable of producing 80–100% of the necessary heat to pre-dry the biomass entering the reactor and during torrefaction [13,30], by combusting the VOC's released, removing the majority of moisture present in the biomass at the time of processing. In this model torrefaction is assumed to be an autothermal operation; a process that takes place without the addition of external heat except for initial ignition. The model proposed accounts for a thorough analysis of the torrefaction unit, calculating a detailed mass and energy balance. One of the most important energy balance factors is represented in the torrefaction unit, in which water is evaporated, a pilot flame of propane is kept, and the energy density of the biomass is increased. Ten percent of the original energy is lost in the process. Fig. 2 shows a schematic of the energy balance.

Biomass entering the unit is considered at 45% moisture content; an average 10.5 MJ/kg heating value for wood is considered (wet weight basis), and VOC's extracted from the biomass are recirculated and burned in a combustion chamber along with the propane. This type of mass balance is the minimum required for the autothermal operation of the unit. Fig. 3 shows the detail (mass circulation) of the torrefaction unit.

Previous studies indicate that torrefaction is performed in five main stages: initial heating, pre-drying, post-drying, torrefaction, and solids cooling [1]. The stage of pre-drying is performed between 100 °C and 200 °C, eliminating the need for a separate drying unit in the process. In addition, due to high operation temperatures, biomass exiting the reactor requires cooling of the material prior to pelletization. The task is accomplished by utilizing a counterflow cooler after torrefaction. It operates by the circulation of fresh air through the product. It discharges the product only once the required temperature set by the operator has been reached.

Three different types of feed mechanisms for the torrefier can be selected in the model: screw reactor, rotating drum, and moving-bed. Based on the recommendations of Bergman [6] four separate production lines with same conditions are utilized in the model. The hammermilling process is allocated after torrefaction in order to minimize power consumption [31]. Conditioning or binder addition to the biomass is performed due to the non-fibrous properties of the torrefied material in order to improve quality on the pelletization process [13].