SYSTEMS ANALYSIS OF INTEGRATED SOUTHERN PINE TORREFACTION
AND GRANULATION TECHNOLOGY

by

YIFEI WU

(Under the Direction of Sudhagar Mani)

ABSTRACT

A proof of concept integrated torrefaction and granulation technology was investigated to granulate southern pine using a lab-scale pan granulation unit. Southern pine chips were torrefied at 250, 275 and 300°C using a pilot scale torrefaction reactor. Torrefied materials were size reduced using a knife mill with 0.25 mm screen and were granulated with lignosulphonate and starch liquid binders. Granules produced from 300°C torrefied material with both the binders had acceptable granule properties with minimal binder usage. Techno-economic and life cycle assessments of integrated torrefaction and granulation of southern pine concluded that granulation of torrefied pine at 300°C had lower production cost and minimal environmental burdens compared to that of wood pellet production. Opportunities exist to further improve the proposed granulation technology prior to commercialization.

INDEX WORDS: Wet granulation, torrefaction, grinding energy, techno-economic analysis, life cycle assessment
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CHAPTER 1
INTRODUCTION

Fossil fuels such as coal, petroleum, and natural gas, play a dominant role in the current US energy market. Renewable and sustainable alternative fuels are sought to address possible energy crisis, serious environmental damage on our ecosystem through global warming, acid rain and toxic chemicals emission. Among various renewable fuel sources, biomass can play a critical role in developing sustainable fuel supply equivalent to fossil fuels. Biomass including agricultural crop residues, woody biomass, energy crops and other sources of organic materials are abundantly available for energy conversion, if they can be sustainably produced and supplied. A recent study by US Department of Energy (DOE) reported that more than 500 million tons of biomass is sustainably available for bioenergy applications annually and can be increased to one billion ton by 2030, if dedicated energy crops can be sustainably produced (DOE, 2012).

Economic and efficient conversion of biomass into fuels and chemicals depends not only on the cost of feedstock but also on the quality of feedstock delivered to a biorefinery. Biomass in its original form has low bulk density, low energy density due to moisture variations, uneven particle sizes and susceptible to moisture absorption during outdoor storage. Preprocessing and pretreatment of biomass is often proposed to eliminate above issues to improve fuel quality, but caused high feedstock cost. Torrefaction is a mild thermal pretreatment method used to heat biomass between 200-300 °C in oxygen-free environment. Torrefied biomass was proved to improve fuel
properties and grindability for efficient down stream conversion, but decreased the bulk density (Phanphanich & Mani, 2011). Densification is a process of increasing the bulk density by mechanically compressing and/or extruding biomass particles to produce densified pellets or cubes. Densification of forest biomass to produce wood pellets is currently commercialized and used for energy production (Mani, 2005). In 2010, wood pellets consumption by EU was about 10 million tonnes, and the demand is projected to increase as high as 219 million tonnes by 2020 (Beurskens et al., 2011). However, the current pelleting technology is energy and labor intensive and pose major challenges to densify low-lignin content (<15%) biomass species and torrefied biomass (Li et al., 2012; Stelte et al., 2013). Alternatively, densification by low pressure granulation technology can be used to densify either torrefied or low-lignin content biomass.

Granulation is a process of agglomerating fine particles by shear/vibrating forces with liquid binders. Granulation will not only increase the density of biomass, but also improve the bulk flow properties of a final product. Granulation of powders is affected by multitude of parameters such as particle size, binder type, binder amount/concentration and other machine parameters to generate highly desirable granules for transport, storage and further conversion. Earlier study by (Vikramaditya, 2013) on pine wood granulation reported that the required powder size for granulation (<0.5 mm) is usually smaller than that of pelletization (<1.0 mm). In this study, an integrated Torrefaction And Granulation (iTAG) process is proposed to experimentally evaluate the technical feasibility and economic and environmental benefits by systems modeling approach. Granulation of biomass technology is a novel process in early developmental stage. Commercial scale feasibility of this technology requires system level analysis on both existing pelleting and
proposed granulation technology. Systems analysis of iTAG can provide feasible guidance to optimize and improve integrated torrefaction and granulation technology and make it technologically and economically feasible and environmentally friendly.

The overall objective of this research was to develop an integrated torrefaction and granulation technology to generate high quality solid fuels at low cost with high environmental performance. The sub-objectives were:

- To experimentally investigate the grinding energy of torrefied biomass generated at different torrefaction conditions.
- To experimentally investigate the integrated torrefaction and granulation technology of southern pine using two distinct binders with three concentrations.
- To develop a techno-economic model to evaluate the energy use and cost of producing torrefied granules from southern pine.
- To conduct a life cycle assessment of torrefied pine granulation technology to evaluate net energy value and environmental impacts.
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CHAPTER 2
REVIEW OF LITERATURE

TORREFACTION OF BIOMASS

Introduction

Torrefaction is a process of heating biomass to between 200 and 300°C in the absence of oxygen at atmospheric pressure. Typically during torrefaction, 70% of the mass is retained as a solid product, containing 90% of the initial energy content; hence a significant energy densification can be achieved. That’s also because the product of reaction in the volatile part are rich in oxygen, namely H₂O, CO₂, and acetic acid (Bergman, 2005). Besides the higher energy density, torrefied biomass is less hydrophilic and easier to grind into powders (Phanphanich & Mani, 2011).

Factors affecting torrefaction

Generally, there are two factors that will affect torrefaction, namely temperature and residence time. Of the two, torrefaction temperature is the major factor. The weight loss obtained from isothermal Thermo gravimetric Analysis (TGA) experiments from 200°C reveal that hemicellulose is the most reactive component of general biomass to decompose (Prins et al., 2006). Cellulose may depolymerize at low temperatures, but volatilization of cellulose is negligible. However, a certain weight loss of cellulose was found above 267°C (Gaur & Reed, 1998).

Residence time represents the thermal treatment time of biomass at the required torrefaction temperature, which is also an important factor in torrefaction. Since biomass
must be heated through a lower temperature stage before reaching a desired temperature, Bergman et al. (2005) used reaction time to replace residence time. The length of reaction time was counted from temperature over 200°C to cooling start point at desired torrefaction temperature. However the concept of reaction temperature has not been widely used in other researchers’ works, maybe because of the inconvenience especially in continuous reactors.

**Heat for torrefaction**

The heat for torrefaction (Reed & Gaur, 1997), which was different from heat of torrefaction, was total energy provided to drive the whole torrefaction process. Heat for torrefaction included heating and drying energy consumption as well as heat of torrefaction. Bergman et al. (2005) concluded the largest heat duty was encountered during both drying and heating process, whereas the smallest heat duty was from torrefaction reaction itself, called heat of torrefaction. From the 1970s, much literature was published about calculating the heat of pyrolysis (Pyle & Zaror, 1984; Rath et al., 2003; Reed & Gaur, 1997; Stenseng et al., 2001). Garcia-Nuñez (2005) used a palm shell pyrolysis thermal model to predict char production and heat of pyrolysis in an indirectly heated continuous reactor.

However, the heat of torrefaction data were rarely reported in previous work. Some researchers calculated the mass and energy balance of feeding raw wood and product to estimate the heat of torrefaction. Prins (2005) reported both heat of torrefaction and willow mass loss at 250°C and 300°C. Because of the large uncertainties of heating value measurement, the imperfect mass balance method resulted in the large result variance. For the willow torrefaction at 250°C and 300°C, the heat of reaction value
was respectively 87(±449) J/g and 124(±400) J/g. Van der Stelt (2010)’s study included more important factors and reported exothermic heat of torrefaction values for beech wood of 130J/g and -230J/g at 240 and 280°C respectively after 30min residence time. Recently, Ohliger et al. (2012) for the first time determined the integral heat of reaction in a torrefaction reactor. In their study, the total heat consumption was measured in experiments and four different heat capacity calculation models were proposed. The heat of torrefaction value was in a range close to the border between endo- and exothermic reactions with a slight trend to more exothermic reactions for a higher mass loss. According to result of this study, residence time had a more significant influence than temperature: higher residence time resulted into a more endothermic heat of torrefaction.

**Torrefaction and Grindability**

Bergman et al. (2005) observed that the power consumption of a cutting mill reduced dramatically when processing biomass feedstock that was torrefied. The reduction varied from 70%-90% according to the torrefaction condition. Several other researchers also reported the dramatic increase of grindability after torrefaction. Their results were based on a different mill, a different kind of feedstock, and valuation system. Arias et al. (2008) conducted woody biomass (eucalyptus) torrefaction at 240°C, 260°C and 280°C. Those samples were ground by a cutting mill at identical situations, and the particle size distribution of grinds was evaluated by a size analyzer. As results shows, torrefied biomass at higher torrefaction temperature had the smaller product particle size distribution.

Bridgeman et al. (2010) used two energy crops (willow and Miscanthus) instead of wood in his study. Also, grindability was determined by the Hardgrove Grindability
Index (HGI) which was usually used for hard coal. Their work, for the first time, tried to represent grindability of biomass by a standard index that was widely accepted in commercial contract specifications. In the standard method for HGI (ASTM, 2011), 50g of samples are loaded in the Hardgrove Grindability Index Tester (Preiser Scientific Z90-9300-01, U.S.), while the fixed mass loading amount required all kinds of sample to have similar bulk densities. Obviously, biomass has much lower density than coal samples and its volume of 50g will be over Tester’s size capacity. To correct this inapplicability and compare biomass to coal sample in HGI, Joshi (1979) and Agus and Waters (1971) modified the HGI test by using the fixed volume (50 cm$^2$) for both coal and biomass samples instead of fixed mass (50g). Adopting this volumetric HGI test, their studies revealed that temperature was the major factor for grindability improvement in terms of HGI test, followed by residence time. The particle size during the torrefaction had negligible effect on the grindability. Results showed that it was unsuitable to represent raw biomass’s grindability by HGI, whereas severely torrefied energy crops behaved very much like coal in the test.

Repellin et al. (2010) and Phanphanich and Mani (2011) reported that torrefaction can reduce both grinding energy consumption and particle size distribution. In Repellin’s work, the torrefaction level was characterized as anhydrous weight loss (AWL). They ground spruce chips to a consistency using a rotary mill with 0.5 mm grid and recorded energy consumption by Watt meter in both unloaded and loaded condition, reporting the energy consumption without subtracting the unloaded energy consumption baseline. In this study, the authors proposed a grindability criterion (G) which was given by the ratio between grinding energy (E) and the volumetric fraction of particles small than 200 μm.
They found that the grindability criterion of spruce and beech was decreased to 8% when the AWL was around 28%. In Phanphanich and Mani’s study, a transducer was connected to a knife mill to measure the instantaneous power which was recorded by a computer recorded in real time every 2 seconds during the grinding experiment. The bottom sieve opening of 1.5mm was used in this study to get a grinding product with average particle size from 0.25 to 0.5 mm, which were suggested by Kaliyan and Vance Morey (2009) for producing high quality pellets. Both pine chips and coal samples were ground with the grinding energy consumption measured in the completely same situation. They completely ground a certain quantity biomass sample to obtain total energy consumption. In addition to the increased grindability of pine chips, they also report the improvement of fuel properties with the increase of temperature. However, the brittle nature of torrefied pinewood chips will also be the cause of fine generation during the transportation. Meanwhile, the removal of volatile matters will give rise to the lower bulk density of biomass.

DENSIFICATION OF BIOMASS

Introduction

Biomass in original form has serious difficulties in transportation, storage and conversion on a commercial scale. Densification was a critical process to increase the density of biomass as high as 10-fold from a loose form to the densified biomass (Tumuluru & Wright, 2010). Most densification technologies were primarily developed in other sectors, and then optimized for biomass industry. The first US patent issued for biomass densification was a steam hammer compaction of sawmill wastes by William Smith (Tumuluru & Wright, 2010).
Agglomeration and Densification

Agglomeration as a mechanical process engineering technology was defined by technical dictionary (Hamaker, 1937) as: “sticking or balling of (often very fine) powder particle due to short range physical forces”. There were three main discrete technology categories of agglomeration: Tumble/Growth Agglomeration, Pressure Agglomeration, and Agglomeration by Heat/Sintering (Pietsch, 2002). Each technology produces agglomerates with different structure properties which due to different dominant mechanisms.

The solid bond and interlock mechanism between particles was the fundamental force for biomass densification (Tumuluru et al., 2011). Thus densification and agglomeration were two interrelated areas in this context. We divide biomass densification technology into two categories based on its pressure condition.

Mechanical densification technology was also called pressure agglomeration. Mani et al. (2002) proposed three steps in the mechanical densification process. In the first step, particles rearrange and slide in to a more closely packed form and the porosity is reduced sharply. In the second step, the particles contact each other and undergo forced plastic and elastic deformation during which time the particle is bonded by electrostatic and Van der Waal’s forces. In the third step, the density of the pellet reaches the truth density of components when the stress will surpass the yield point of the particle material and result in mechanical interlocking. In addition, the high pressure applied on contact point between two particles, will reduce the melting point of the substance. Some solid bridging from the hardening of melted substances will also contribute to the densification effect.
In the second category, densification is conducted under a lower pressure, which is usually named Tumble/Growth Agglomeration. Detail of this technology will be described later when discussing granulation technology.

Cost and energy use

The cost of densification was directly related to energy use, equipment investment cost and maintenance cost. The maintenance requirement of piston press was highest, and granulator’s was very low (Table 2.1). The mechanical densification technology had relative lower production rate than the agglomeration process. From the energy use aspect, the pellet mill was the most energy saving mechanical densification equipment. The specific energy requirements for biomass densification depend on several process variables, such as feed material particle size, equipment type and the biochemical composition of biomass. In a mechanical densification process, both the compression and extrusion work were involved. Generally, the extrusion work was much greater than the compression work, because the extrusion needs to overcome a huge amount of friction during compression and pushing (Tumuluru et al., 2011). The total work was defined as 

\[ w = A \int_0^X P \, dx \]

in which A was the cross section area and P was the instantaneous applied pressure. The granulation process was based on a different mechanism, and the granulation energy consumption was very limited whereas post-granulation drying heat was the major energy consumer.

Current status of pelleting technology

In the biomass-to-energy industry, the pelleting technology was most widely used as densification method. In 2010, the EU annual demand for pellets was about 10 million tonnes and there are estimates that demand will grow to 219 million tonnes in 2020
Globally, the European Union was the biggest market for biofuel pellet in 2010. Such a huge consumption amount was stimulated by the 2009 Renewable Energy Directive (RED).

Traditionally, the biomass pellet was made from wood processing or logging residues, but currently the feedstock has increasingly expanded to chipped round wood. The United States of America, as one of the biggest producers of pellets, has developed export markets to supply European utilities. In 2010, approximately 750,000 tonnes of pellets were exported to Europe. The U.S. actually has some policies to encourage domestic use of solid biomass; unfortunately, none of them have created very significant domestic demand of wood pellet. Agricultural residue pellet have not been very successful in the wood pellet dominated market, due to high logistics cost, serious ash-related issues, and soil erosion hazard.

**Torrefaction and pelletization**

Previously, it used to a known fact that lignin was to be the main binding agent in pelletization. During torrefaction, the trivial lignin decomposition and significant total mass loss results in the increase of lignin percentage (Li et al., 2012a). Therefore, torrefied biomass pellets once had been believed to have higher bulk density than regular pellets (Bergman, 2005). However, recent studies have shown that turning torrefied biomass into pellets was a very challenging step (Larsson et al., 2013; Stelte et al., 2011), since the chemical changes during torrefaction had a negative effect on the pelletization process and pellet properties (Stelte et al., 2011). The pellets of torrefied spruce (Stelte et al., 2011), sawdust (Li et al., 2012a), and wheat straw (Stelte et al., 2013) were found to have lower density and durability in comparison to regular pellets. The pelletizing
pressure was a critical parameter in the pelletization process in terms of energy consumption. It also increased with the increase of torrefaction temperature (Stelte et al., 2011).

There were various explanations to the recently observed phenomena. Stelte et al. (2011) believed that hemicellulose decomposition and the hydrophobic nature of torrefied biomass would increase its glass transition temperature, because water was acting as a plasticizer. Also, hemicellulose degradation embrittled the wood structure and changed physical properties including friction coefficient and Poisson ratio that were directly related to pelleting pressure. Li et al. (2012a) thought that hydrogen bonding at the lignin and hemicellulose surface was the binding point in the pellet. Those low-melting or low-softening point components were removed during torrefaction.

**GRANULATION TECHNOLOGY**

**Definition and mechanism**

The tumble/growth process will be referred to as wet agglomeration (Ennis, 2010b), and has also been called low pressure agglomeration or granulation. As the name implies, wet agglomerates (or green agglomerates) are bonded by the effect of surface tension and capillary forces of the liquid binder (Pietsch, 2002). In wet agglomeration, small particles were colliding during irregular, stochastic motion in certain equipment while the binders and solvents were sprayed or added on it.

In modern view of granulation mechanism (Figure 2.1), the wet agglomeration process can be simply divided into two stages: seed formation and granule reaction. Seed formation was the nucleation process when small particles, with the help of binder or liquid, form a capillary state conglomerate that may act as a nucleus in the ball growth
process. In the granule reaction stage, the nucleus was the smallest granule unit and a bigger granule can be created by any aggregation between the nucleus and a small granule or between one or more small granules. Of course, a bigger granule can break into small granules or even into a nucleus during impact breakage. In addition to reaction between two granules, one granule can gain or lose solid (layering/attrition), liquid (drying/rewet), and air (consolidation).

**Role of binders**

In wet agglomeration, micrometer and sub-micrometer particles (approximately <5-10micron) will form granules by themselves, as a kind of dry agglomeration. Smaller particle size results in greater overall surface area, so Van der Waals’ forces are high enough to cause nucleation. Agglomeration of larger particles necessitates the addition of granulation liquid, in which the capillary adhesion force of the liquid bridge between particles provides tensile force of wet granule. Several different states of liquid saturation were first described by Newitt and Conway-Jones (1958) (Figure 2.2).

**Granulation equipment**

Broadly, based on the principles of wet agglomeration, any equipment-provided stochastic movement of the primary particles can be used as a granulator. Meanwhile, the fluidized-bed granulator, tumbling granulator and mixer granulator were the most widely used equipment (Ennis, 2010a). A fluidized-bed granulator mixes and supports the particles with heated gas provided from the bottom of equipment. It will provide the lowest density granules because of the low deformability process. The mixer granulator can be loosely divided into two categories: low shear particle mixer and high shear particle mixer. Each induces granulation through mechanical agitation. The mixer
granulator, especially the high shear particle mixer, produces medium to dense, irregular granules. Gravity and centrifugal force are used by the tumbling granulator to move and mix the particles. Tumbling granulators produce the most uniform and spherical granules with medium density. It is important to note that the tumbling granulator has the highest throughput of all granulation processes. In terms of biomass densification, the tumbling granulator was the preferred wet agglomeration equipment. Common designs include continuous, pan, cone, and drum granulators (Figure 2.3). The disadvantage of the drum granulator was the removal of fines and recycling step in the output compared to the pan and cone granulators where the largest agglomerates were always on the top and rolling out first. If strictly controlled, the pan and cone can produce uniformed granules without a step to remove fines.

**Granulation process factors**

A pan granulation operation process is illustrated in Figure 2.4. The most important biomass granulation factors we examined included the granule size distribution, bulk density, rate of production, and the amount of binder. Those were determined by only few parameters including: rpm of pan, granulation time, angle of inclination, pan depth, as well as feed and spray means and locations (Figure 2.5).

In batch granulation study, Irshad et al. (2010) believed that angle of inclination had no significant effect on the granulation yield. However, in the continuous granulation process (Pietsch, 1991), the larger pan depth and smaller angle of inclination during granulation produced rounder and stronger granules. Generally, the granule size will increase by 23-52% if the angle of inclination is reduced 10°. Since the seed formation and ball growth always happen in lower layers, larger charges tend to lengthen the time
of granulation and overburden for each single granule. During the movement from the lowest layer to highest layer, only the strong granules will survive. Moreover, the wet granules produced from a pan granulator were relatively uniform and large in size with relatively higher moisture content (Figure 2.6)

Irshad et al. (2010) studied multiple operating parameters at laboratory scale for a pan granulator. By increasing the time of granulation, the granule bulk density and average size increased, which meant a better granule quality. The bulk density, granulation yield, and rate of production were increased to maximum at an optimized rpm of pan. In Pietsch (1991) work, rpm of pan was recommended as rpm of pan = 75% * 42.3 \frac{\sin\beta}{\sqrt{R}} where R was the pan diameter in meters and \beta was the angle of inclination in degrees).

**TECHNO-ECONOMIC ANALYSIS**

Biomass granulation was a new technology, so there was no record of economic analysis of this. Meanwhile, in last two decades, lots of tech-economic analysis research on pellet production had been done by academic, corporate, and government organizations around the world. Among the early reports in the 1990s, NEOS Corporation (NEOS, 1995) published a report describing many aspects of pellet manufacturing and markets which include cost analysis. Williams and Lynch (1995) gave a feasibility analysis of a wood pellet plant in Walden, Colorado, which includes not only the cost but financial return analysis. In Austria, Thek and Obernberger (2004) use both dry and wet wood shavings as raw material for producing wood pellets and the final cost was 120.98$/t. The pellet production cost from Mani et al. (2006) was as low as 50.57$/t and 46.8$/t from Hoque et al. (2006) for the low raw material price in North
America. Also proved in many other literatures, the cost of raw material takes an important part of the overall cost.

Since torrefaction technology had not become widely commercialized, very few related techno-economic analysis studies were reported. Shah et al. (2012) published the first complete techno-economic analysis of large scale torrefaction system. They developed a torrefaction system model of mass and energy balance in Simulink platform. For 30% moisture content feedstock, 240°C torrefaction temperature, the unit torrefaction process cost was estimated to be 17.25$/t in 25t/hr capacity facility. Recently, a torrefied pellet production cost study in the US has been reported (Pirraglia et al., 2013). They consider the raw material delivered price, labor, energy consumption and transportation cost. In a 100,000 metric tons/year facility, the pellet production cost was reported to be 261$/t and delivered price will be 282$/t.

**LIFE CYCLE ASSESSMENT**

Life cycle assessment (LCA) is a quantitative method to evaluate the environmental load of a product, process or activity throughout its life cycle (Roy et al., 2009). Researchers from academic, manufacturing and government sectors have widely evaluated the energy consumption, material usage, chemical emissions and waste treatment in a life cycle context. The life cycle assessment methodology has been defined by series of ISO international standards: ISO 14040–14044 (ISO, 2006; ISO, 1998; ISO, 2000a; ISO, 2000b). Also two standard examples were also published by ISO (ISO/TR, 2000; ISO/TR, 2003).
LCA of bioenergy system

In the biomass renewable energy area, life cycle environmental assessment has been a useful tool to analyze a new technology or alternative scenarios. The general purpose of LCA in bioenergy study can be (1) comparison of alternative products, processes (Kalinci et al., 2012) and systems (Fazio & Monti, 2011; González-García et al., 2012); (2) comparison life cycle environmental load between new bioenergy product and conventional fossil fuel (Renó et al., 2011; Tabata et al., 2011); and (3) identification of unit operations or technologies that are critical to significantly improve overall environmental performance (Iribarren et al., 2012; Yanfen et al., 2012).

Goal definition and scope

For every study, the goal definition is the first step in LCA study. It provides the guidance of system scope. The goal of the study states the intended application and audience, and the reason for conducting the study (ISO, 1998).

In defining the scope of study, the system boundary, functional unit selection, allocation criteria and reference system should be unambiguously described. An input and output flow diagram is usually used to illustrate the system boundary (Roy et al., 2009). “The functional unit was a measure of the performance of functional output of the product system” (ANSI/ISO, 1997). Functional unit can provide a reference to normalize the input and output data and make results comparable between different scenarios. There were 4 types of functional units in bioenergy system LCA study: input unit related, output unit related, unit of agricultural land and year. Among them, most studies adopted the output unit related reference unit (Cherubini & Strømman, 2011). Both allocation criteria and reference system choice were closely related with goal definition.
Process inventory

Life cycle inventory analysis (LCI) was about data collection, valuation, calculation, and aggregation. In conventional LCA, inventory data included energy usage, raw materials, emissions and some other categories. If these process data were not accessible, the input-output data from the EIO-LCA model will be used. In some studies, scholars use both inventory analysis methods to conduct Hybrid Life Cycle Assessment of bioenergy product. It is a controversial problem to calculate the environmental impact associated with manufacturing equipment. Among pellet LCA studies, Reed et al. (2012) did not include any pellet mill equipment or replacement parts into his study. In a wheat straw pellet LCA work (Li et al., 2012b), the equipment in drying, grinding and packaging used existing similar processes of “grass drying, wood residue chipping and food packing in Eco invent data system”. In Fantozzi and Buratti (2010)’s work, they only considered the main materials and disregarded assembly energy consumptions.

Impact assessment

In order to evaluate the potential environmental impact on natural resources and human health, Life Cycle Impact Assessment (LCIA) was conducted as part of LCA research. There were four steps of impact assessment: Classification, Characterization, Normalization, and Weighting. According to the ISO standard (ISO, 2000a), the first two steps were mandatory for a complete LCA study; otherwise, it was only a LCI work. The last two parts were optional elements, which were not always included with all standard impact assessment. Among bioenergy system LCA literature, few studies report the optional impact assessment results. Only about 20% of the literature published before 2010 considered other airborne emissions or other impact categories; while others only
consider fossil fuel depletion and global warming potential (GWP) (Cherubini & Strømman, 2011). Therefore, energy usage and global warming were the most popular factors in bioenergy system environmental evaluation.

**Interpretation**

Besides environmental impact, according to standards (ANSI/ISO, 1997; ISO, 2000b), life cycle interpretation was needed to analysis, understand and present the output of inventory and impact assessment step, in context of the defined goal and scope. Most LCA studies in the bioenergy field only interpret two critical qualitative interpretations: energy balance and GHG balance (Cherubini & Strømman, 2011). Obviously, anticipated fossil fuel depletion and trends of global warming were two major reasons to explore new renewable energy.

More particularly, life cycle energy balance quantifies the possible non-renewable energy savings of the bioenergy system from primary energy analysis. Arvidsson et al. (2012) summarized five types of energy: fossil energy, secondary energy, cumulative energy demand, net energy balance, and total extracted energy.

\[
E_{\text{fossil energy}} = E_{\text{coal}} + E_{\text{oil}} + E_{\text{natural gas}} + E_{\text{uranium}} \quad (2.1)
\]

\[
E_{\text{renewable energy}} = E_{\text{geothermal}} + E_{\text{wave}} + E_{\text{hydro}} + E_{\text{wind}} + E_{\text{sol}} + E_{\text{bio}} \quad (2.2)
\]

\[
E_{\text{secondary energy}} = \sum \eta_i E_{\text{fossil energy}} + \sum \eta_i E_{\text{renewable energy}} \quad (2.3)
\]

\[
E_{\text{cumulative energy demand}} = E_{\text{fossil energy}} + E_{\text{renewable energy}} \quad (2.4)
\]

\[
E_{\text{net energy balance}} = E_{\text{cumulative energy demand}} - E_{\text{product}} \quad (2.5)
\]

\[
E_{\text{total extracted energy}} = E_{\text{cumulative energy demand}} + E_{\text{raw material}} \quad (2.6)
\]
Besides, about 90% of studies interpreted GHG balance results from GHG emission, such as carbon dioxide, methane, and nitrous oxide.

Modeling software

For most of the LCA study, SimaPro 7 was selected because this software was built on Standard ISO which included the basic four steps in LCA research: goal and scope definition, inventory analysis, impact analysis, and interpretation. Namely, SimaPro integrated around 1000 inventory data from most major inventory databases including Eco invent, ETH-ESU, USA input output, and others. It also comes with a large number of standard impact assessment methods for impact analysis. Specifically, for uncertainty analysis, it was the only software integrated with a Monte Carlo analysis module and also has an excellent behavior on scenario and parameter comparison.
SUMMARY

Due to the low energy content and high volatile matter percentage of raw biomass, thermal pretreatment or torrefaction technology has been recently pursued as a novel energy densification technology to improve biomass fuel properties. While the energy density of biomass increased during torrefaction, the bulk density of biomass decreased significantly, causing increased transport cost. Due to the removal of low-melting/softening point components in torrefied biomass, the pelleting process, which is a commonly used densification technology, demands high energy input for compaction and external binders producing an expensive solid biofuel. Alternatively, torrefied biomass can be agglomerated into granules at relatively less energy input and cost. Recently, a raw pine wood and raw switchgrass powder granulation work was reported by Vikramaditya (2013); however, there is not any torrefied biomass power granulation work published currently, until now. Due to the physical and chemical property changes of torrefied biomass, the effects of torrefaction temperatures on granulation performance and granule properties also need to be identified. The parameters of granulation, such as binder selection, binder usage and granulation time, also need to be optimized. Because of no commercial scale application existing to date, there are still considerable uncertainties of plant scale production. Current published economic analysis and life cycle assessment work is mainly focused on plant scale pellet production. Therefore, an economic analysis and life cycle environmental assessment of the torrefied pine wood granule production system are required to evaluate the economic and environmental performance of this new technology scenario.
References


Table 2.1. Comparison of different densification technology (Tumuluru et al., 2011).

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Pellet mill</th>
<th>Piston press</th>
<th>Roller press</th>
<th>Cuber</th>
<th>Tabletizer</th>
<th>Screw press</th>
<th>Granulator</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed Particle size (mm)</td>
<td>&lt;3</td>
<td>6-12</td>
<td>&lt;4</td>
<td>12-16</td>
<td>&lt;20</td>
<td>2-6</td>
<td>0.05-0.25</td>
</tr>
<tr>
<td>Addition of binder</td>
<td>Not required</td>
<td>Not required</td>
<td>Required</td>
<td>Required</td>
<td>Not required</td>
<td>Not required</td>
<td>Required</td>
</tr>
<tr>
<td>Specific energy (kWh/t)</td>
<td>16.4-74.5</td>
<td>37.4-77</td>
<td>29.91-83.1</td>
<td>28-75</td>
<td>High energy</td>
<td>36.8-150</td>
<td>Very low</td>
</tr>
<tr>
<td>Throughput (t/hr)</td>
<td>5</td>
<td>2.5</td>
<td>5-10</td>
<td>5</td>
<td>0.5-1</td>
<td>0.5-1</td>
<td>Very high</td>
</tr>
<tr>
<td>Bulk density (kg/m³)</td>
<td>650-750</td>
<td>400-500</td>
<td>480-530</td>
<td>450-550</td>
<td>600-700</td>
<td>500-600</td>
<td>300-350</td>
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<tr>
<td>Maintenance</td>
<td>Medium</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
</tr>
</tbody>
</table>
Figure 2.1. Modern view of Granulation Mechanism.
Figure 2.2. Pan granulation states with Granulation Liquid Ratio increasing.
Figure 2.3. Schematic representation of common designs of tumble agglomeration. 
(a) pan, (b) cone, (c) drum (Pietsch, 1991)
Figure 2.4. Diagram Continuous Pan Granulation process.
Figure 2.5. Diagram of Relationship between all granulation parameters.
Figure 2.6. Relationship between Moisture, Time of granulation, Throughput, and Average granule size (Pietsch, 1991).
Figure 2.7. Components of Life cycle assessment (ISO, 2006)
CHAPTER 3

WET AGGLOMERATION OF TORREFIED PINE WOOD

PART 1: LIGNOSULPHONATE BINDER

Wu, Yifei and Mani, Sudhagar

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ABSTRACT

Thermal pretreatment or torrefaction technology has been recently pursued as a novel energy densification technology to improve biomass energy density and moisture control. While energy density of biomass was increased during torrefaction, the bulk density of biomass decreased significantly causing increased transport cost. Pelleting of torrefied biomass was often pursued to increase bulk density and flowability for efficient and economic handling and transport. Due to removal of low-melting/softening point components in torrefied biomass, the pelleting process often demands high energy input for compaction and external binders producing an expensive solid biofuel. Alternatively, torrefied biomass can be agglomerated into granules at relatively less energy input and cost. In this study, southern pine chips were torrefied using a pilot scale torrefaction reactor at different torrefaction conditions (Temperatures: 250, 275 and 300°C; Residence time: 20 min). The materials were then ground using a knife mill with 0.25 mm screen size and the power consumption was recorded during the process. Then pine wood powder was granulated in a pan granulator using 35% solid content lignosulphonate as binder with three binder amounts levels. Compared to control group, torrefaction can increase the grinding speed of pine chips by a factor of 5 and reduce energy consumption as much as 95%, which will make overall granulation process more energy favorable. Granulation of torrefied pine wood powder from high temperature condition (275°C and 300°C) required less binder and produced granules with better hardness, single granule density, and bulk density. Also torrefaction improved pine wood energy content and fuel property. Torrefied pine wood granulation was a potentially effective and economically favorable technology compared to conventional pelleting.
Keywords: Biomass, Binder, Lignosulphonate, Pine wood, Densification, Granulation, Torrefaction.
Nomenclature

C Carbon.

$D_{gw}$ The geometric mean diameter (mm).

H Hydrogen.

$HHV$ Higher heating value (MJ kg$^{-1}$).

MC Moisture content (%, wb).

$M_{\geq 1\text{mm}}$ Weight of granule sample which size larger than 1mm

N Nitrogen.

O Oxygen.

$P_1$ The pressure reading after pressurizing the reference volume (Pa).

$P_2$ The pressure reading in sample cell (Pa).

RH Relative humidity.

RPM Revolutions per minute.

RPW Raw pine wood.

$S_{gw}$ The geometric mean diameter standard deviation (mm).

$S_v$ The specific surface area (mm$^{-1}$)

$SHPT$ Sphericity (dimensionless).

$TPW$ Torrefied pine wood.

$V_C$ The volume of sample cell (m$^3$).

VM Volatile matter.

$V_R$ The reference volume (m$^3$).

W Sample weight.

$\rho_p$ Particle density.
1. INTRODUCTION

Biomass, as sustainable carbon carrier, is in unique position among all renewable energy sources to produce sustainable fuels, power and chemicals. Economical and efficient conversion of biomass into final products depends not only on the cost of feedstock but also the consistent and uniform quality of feedstock delivered to a biorefinery. Consistent and uniform composition of biomass feedstock is one of the major challenges that limit the growth of biofuel industries in US, as raw biomass had wide range of moisture content, particle size, bulk density and energy content compared to its fossil fuel counterparts (eg. coal) [1]. Torrefaction, as a mild thermal pretreatment method, can improve biomass energy density and hygroscopicity in 200~300°C oxygen-free environment. The torrefied lignocellulosic biomass will also have significantly better fuel properties and grindability [2].

As the energy density of biomass increases, the loss in mass causes low bulk density during torrefaction. Densification is another critical preprocessing step to improve the bulk density, flowability and bulk storage capability of large volume of biomass. The bulk density of torrefied biomass can be increased by either pelleting (pressure compaction) or low pressure agglomeration techniques. Torrefied biomass pellets once had been believed to be higher in bulk density than regular pellets [3]. However, recent studies have shown that turning torrefied biomass into pellets is still a very challenging step [4, 5], since their lower pellet quality, higher energy consumption and limited production capacity in comparison to regular pellets. Besides, pelletization itself, as a mechanical densification process, was very energy and labor intensive. In that context, a novel torrefied pine wood granulation technology was developed to replace existing
pelletization technology.

Granulation is a process of agglomerating fine particles by shear/vibrating forces with liquid binders. The main objective of this study was to determine the energy required to grind torrefied biomass generated at three different temperatures, to investigate the pan granulation of terrified biomass powders with lignosulfonate as a binder and to determine the physical and bulk flow properties of torrefied granules and compared with wood pellets.

2. MATERIALS AND METHODS

2.1. Materials and torrefaction treatment

Clean southern pine wood chips were obtained from a local pulp mill operation in Oglethorpe, Georgia. A rotary drum reactor, heated by natural gas (located in Whitehall Bioconversion Center; Athens, GA) was used to torrefy wood chips. Samples were torrefied at three different temperatures (250°C, 275°C and 300°C) with 20 min residence time. After torrefaction, the samples were cooled and mass yield was determined for each conditions. Torrefied pine wood chips were stored in black plastic bin for further analysis. For comparative analysis, bituminous coal was obtained from the University of Georgia’s Central Steam Plant in Athens, Georgia.

2.2. Grinding energy consumption and size reduction measurement

A laboratory heavy-duty knife mill (Retsch SM 2000, Germany) was used in the grinding experiments. In this study, the knife mill’s cutting blade rotor (1690 rpm, 60 Hz) was powered by a 1.5 kW electric motor. A multi-function transducer (CR Manetics Inc., MO) was assembled with a computer’s data logger. The transducer connected to the mill to measure the instantaneous power; meanwhile the computer real-time recorded every 2
seconds during the grinding experiment. The bottom screen opening 0.25mm was used in this study. All sample chips were ground and the grinding energy consumption was measured for each experiment. In this experiment, chips were continually fed to the knife mill and feed rate was stable; meanwhile, for a certain period time got the product and weighed it. It was worth mentioning that the lengths of every grinding test period were around 15 min and the feeding rate varied depending on the grinding speed of different type torrefied wood chips. Therefore, the feeding rate optimization was critical for collecting reasonable grinding energy data. If wood chips were fed too fast, the both instantaneous power level and output rate would be higher, however wood chips would stuck in the feeding hoop and discontinued the stable grinding process. On the other hand, if wood chips were fed slowly, knife mill worked below the maximum capacity. The instantaneous power consumption data with respect to time was recorded by computer. The total specific energy consumption for grinding was determined by integrating the area under the instantaneous power consumption curve (P-t) for every period time of grinding, divided by the mass feed rate \[6\]. Effective specific energy was estimated by subtracted no-load power requirements from total specific energy. Every test was repeated three times and performed under woodchip’s equilibrium moisture content.

Before grinding, all three dimensions (length, width, and thickness) of 50 wood chips from each treatment were measured using a digital caliper (Mitutoya, U.S.A.) with an accuracy of 0.01mm. The length was measured as the expansion parallel to the wood chip fiber; the width was recorded as the maximum expansion perpendicular to the wood fiber, while the thickness was the second longest expansion perpendicular to both length and width. Geometric mean and standard deviation of length, width, and thickness was
calculated based on ANSI/ASAE- S319.4 [7].

The analytical sieve shaker (Retsch AS 2000, Germany) was used in particle size distribution analysis. After grinding, powders were sieved with a series of sieves of mesh size 200, 160, 125, 100, 63 and 45μm for 15 min. The mass of each sample collected on each sieve was measured and recorded as a percentage of the original sample mass. The cumulative weight percentages were plotted against the corresponding sieve sizes. Geometric mean diameter was calculated based on standard ANSI/ASAE- S319.4 [7].

2.3. Initial pine wood powder properties

The initial moisture content of raw and torrefied pine wood powder were obtained according to a standard protocol [8]. Not less than 10 kg each subsample was collected below the surface at nine points from powder sample stored in room temperature (23°C, RH: 59%). Reduce the mass of sample to about 50 g by coning and dividing reduction method. Dry sample in oven 103±1 °C for 6 hr and weight every 2 hr until the total weight change between weightings varies less than 0.2%. The moisture content data were reported in wet basis (equation (1)). Every test was repeated five times.

\[
MC\ (\text{wb percent}) = \frac{\text{loss in weight} \times 100}{\text{weight of wet sample}}
\] (1)

A standard ASTM E873-82 for densified particulate biomass would be used in this study to obtain bulk density [9]. For initial powder bulk density, a cylinder container with volume of 114.5mL and internal diameter of 52 mm was used. The container was filled by pouring powder on top of a container. It was dropped five times from a height of 50 mm on a hard surface and excess granules were leveled by a ruler before weighting. Every test was repeated 5 times.
Sample bulk density = \( \frac{\text{Sample bulk volume}}{\text{sample mass}} \) \hspace{1cm} (2)

The particle density of each initial powder was obtained by using a gas muti-pycnometer (MPV-D160-E, Quantachrome Corporation, FL, USA). When the helium gas was occupied the reference cell of volume \( (V_R) \), the pressured reading was noted as \( P_1 \). Then the gas was moved to another sample cell \( (V_c) \) with a certain amount \( (W) \) of powder sample, and the pressure changed to \( P_2 \). The particle density can be calculated by (equation(3)).

\[
\text{Particle density} \left( \rho_p \right) = \frac{W}{V_c - V_R \left[ \left( \frac{P_1}{P_2} \right) - 1 \right]} \hspace{1cm} (3)
\]

The pine wood powder was also analyzed for multiple fuel properties. The proximate and ultimate analysis covered the determination of ash, volatiles, fixed carbon and moisture content of samples. Proximate analysis were conducted in a Thermo Gravimetric Analyzer (Model TGA701, LECO Corporation, St. Joseph, MI) based on the procedure of standards for coal and coke \([10]\). Ultimate analysis was performed according to standard test method for coal and coke \([11]\). The C, H, N contents were measured using an elemental analyzer (LECO CHNS 932, LECO Corporation, St. Joseph, MI). Oxygen was calculated by the difference. Gross calorific value of grinds were determined by the adiabatic oxygen bomb calorimeter (IKA C 2000, IKA Works, Inc., NC) based on the ASTM D 5865-03, standard test method for coal and coke \([12]\). All calorific values were expressed in MJ/kg. All tests above were repeated at least three times.
2.4. Granulation experiment

Granulation experiments were conducted on a pan granulator (DP-14 Agglo-Miser, Mars Mineral, PA, USA) with diameter of 355.60 mm and depth of 304.80 mm (Figure 3.1). Pan angle was set to 45° and the pan speed was set to 30 RPM. Biomass powder was weighed on electronic balance to 200 g, accurate to ±0.02 g. In order to increase the spray accuracy, 35% solid content Lignosulphonate (Lignotech USA Inc., WI, USA) solution was used as binder. The binder was sprayed to biomass powder from an 80° angle flat spray nozzle (H1/4VV-8001, Spraying Systems Co., AL, USA) under the pressure 10 psi. The average spraying rate of the nozzle was 191.93g/min and the amount of binder can be controlled by the spraying time and expressed by binder to solid ratio. Binder to solid ratio represents the ratio of actual binder liquid usage weight to total granulation pinewood sample weight (Equation (4)). Granulated all fours pine wood powder samples for 30min and every test were carried out in duplicate.

\[
\text{Binder to solid ratio} = \frac{\text{Binder Liquid weight}}{\text{Pinewood sample weight}}
\]  

(4)

Then wet granule samples in the pan were collected and dried in oven (103°C ± 1 for 12 hours). Dry samples were sieved for 15 min with a sieve of mesh size 1mm on an analytical sieve shaker (Retsch AS 2000, Germany). The granules with over 1 mm size was generally acceptable [13]. The weight of sample above 1mm was measured and recorded as a granule yield in this study (Equation (5)).

\[
\text{Granule yield} = \frac{M_{>1\text{mm}}}{\text{Total dry sample weight}}
\]  

(5)

2.5. Binder Liquid property measurement

35% solid content lignosulphonate solution were analyzed in a rotational viscometer.
(DV-I Prime, BROOKFIELD, Middleboro, Massachusetts, USA), in order to determine liquid apparent viscosity. During the measurement, the liquid sample was kept at 25 °C in a temperature controlled water bath (TC-602, BROOKFIELD, Middleboro, Massachusetts, USA).

Surface tension measurements were performed with dynamic contact angle analyzer (DCA-322, Thermo Cahn Instruments, Madison, WI, USA). Platinum plate (19.62 mm × 10 mm × 0.11 mm) is also used for its high free surface energy based on Wilhelmy Plate method.

2.6. Granule properties

In order to determine granule bulk density, a cylindrical container with a volume of 792.69 mL and internal diameter of 10.10 cm was used as similar to the producer for measuring powder bulk density. Every test was repeated 5 times.

Granule shape and size distribution were measured by an image analyzer (HORIBA CAMSIZER, instruments, Inc. CA, USA). Two digital cameras in that analyzer captured image of granule, and analyzed size and size distribution by standard procedure [7]. To conduct this test, 200 g dry granule sample was loaded onto the hopper of the instrument, and then dropped across the measurement field. The size and shape of every single granule was recorded and analyzed by software. Finally, 1) geometric mean diameter (D_{gm}); 2) geometric mean diameter deviation (S_{gw}); 3) the sphericity (SHPT); 4) the specific surface area (S_v) were determined. The test was replicated for five times.

The hardness of the granules was measured according to standard [14] for compression test of rigid plastics. According to the standard procedure, granule was compressed between two parallel steel plates of Instron hardness tester (Insight 30, MTS
Systems Corporation, MN, USA). Hardness of granule was defined as the maximum compressive load before granule had failure. The test was replicated for twenty times.

Single granule density of each biomass granule sample can be measured by dividing the granule volume with corresponding weight. All three dimensions diameter of granules were measured using a digital caliper (Mitutoya, U.S.A.) and the geometric mean value was used to estimate the granule volume. Each single granule density test repeated twenty times.

2.7. Statistical analysis

Analyses were performed in the MINITAB 14 environment. Granulation sample and binder to solid ratio effects on granule properties were tested using two-way ANOVA. Multiple comparisons were conducted by Tukey’s test. All differences were considered significant at P≤0.05.

3. RESULTS AND DISCUSSIONS

3.1. Grinding energy consumption

Rate of grinding energy, grinding rate, wood chip size and grinds powder size are all given in Table 3.1. Specific grinding energy consumption of torrefied pine wood (TPW) was reduced as the torrefaction temperature was increased from 250 to 300°C. As torrefaction temperature increases, decrease of the grinding energy consumption could be up to 40%, 12% and 5% at 250, 275 and 300°C respectively, relative to raw pine wood chips (RPW). It was worth notices that, torrefaction did not only reduce the grinding energy consumption, but also significantly increased the knife mill grinding rate from 9.38 g/min to 48.95 g/min. Figure 3.2 showed that pine wood chips at higher torrefaction temperature could be ground into smaller particles than raw pine wood through the same
grinding screen. The particle size distribution curve was skewed into smaller size as torrefaction temperature increases. The similar result was also observed from other studies [2, 6, 15]. In the temperature range of torrefaction, the most reactive wood fraction was the hemicelluloses which would decompose above 225°C [16]. The increase of pine wood chips grindability might primarily due to fiber compound degradation and structure breakdown during the torrefaction reaction.

3.2. Initial pine wood powder properties

All data from ultimate, proximate and heat content analysis all revealed the improvement of fuel property during torrefaction (Table 3.2). Ultimate analysis results revealed an overall trend towards a decrease in hydrogen and oxygen content and increase in carbon content, as torrefaction temperature increases. The decrease of volatile matter was much more pronounced between 275 and 300°C, than at 250°C, as a result of aforementioned changes in chemical composition. Meanwhile, a consequence of the concentration effect of torrefaction was a decrease in the ash content of torrefied pine wood in comparison to raw pine wood. The improved carbon content and decreased hydrogen and oxygen content caused decreased H/C and O/C ratios, and higher energy content of biomass (Table 3.2).

The initial powder moisture content in room temperature was increased up to 6.48%, 4.27% and 4.03% at 250, 275 and 300 ºC respectively, compared to 9.77% of raw pine wood. This observation was consistent with reported hydrophobic nature of torrefied biomass in other studies [2, 3]. Hydrophobicity of torrefied biomass was due to the loss of hydroxyl (-OH) groups during torrefaction reaction. Thus, torrefied pine wood could be less likely to absorb moisture during long term storage or transportation.
No significant difference in particle density of torrefied pine wood powder was observed as compared to that of raw wood. Bulk density of torrefied biomass at 300°C (311 kg m$^{-3}$) was slightly higher than that of pine wood powder (298 kg · m$^{-3}$).

**3.3. Granulation experiment**

Lignosulphonate binder with 35% solid content used in granulation experiment had higher apparent viscosity 6.15 (0.03) ×10$^{-3}$ Pa s and liquid density 1.13 (0.00) kg/L, and lower surface tension 45.50 (0.30) dynes/cm than that of water. Table 3.3 depicted the granulation operation parameters in this study. At different torrefaction condition, the percent binder in dry granule varied from 25.15% to 40.82% responding to binder to solid ratio. Meanwhile wet granule moisture content also changes accordingly. Figure 3.4 illustrated that granule yields of each samples were significantly increased with increase in binder to liquid ratio thus indicating that more binder usage results in higher granule yield. In each Granulation process, the binder usage level more than 95% granule yield were considered as acceptable. As the torrefaction temperature increased, the binder usage requirement of torrefied wood sample was decreased. The granule yield of torrefied pine wood powder at 250 °C didn’t change significantly compared with that of raw wood powder. Granule yield was most sensitive to the binder usage variation, when torrefaction temperature was 300 °C. This negative correlation between binder usage and torrefaction temperature were probably due to the improved particle size and surface hydrophobicity of torrefied pine wood particle. In Schaefer, et al. (1992) [17]’s work of fine powder granulation, higher binder usage was reported in granulation of smaller particle size powder, as the consequence of the increase of surface area. However, Iveson, et al. (2001) [18] believed that wet powder would become harder to be granulated, when its particle
size was larger than a critical level. Pine wood powder was relative larger size and less sphericity than pharmaceutical powder which was widely studied by previous researcher. That might be the reason why more binder used in larger size raw pine wood powder. Besides, previous studies [19, 20] indicated that the hydrophobicity of various species of wood was significantly increased during torrefaction. This results were contrary to Rumpf (1962) [21]’s equation model which predicted decreased wet granule tensile strength as contact angle increases (more hydrophobic). However, on the one hand, this model was usually invalid for granule bound with viscous binders [18]; on the other hand, the granulation experimental studies for hydrophobicity effect were very rare up to now. The effect of particle surface hydrophobicity on granulation binder usage needed further investigation.

3.4. Granule properties

Table 3.5 summarized the two way ANOVA test result for granule size, single granule density, hardness and bulk density. Only the test on hardness showed that no significant difference (p<0.05) was observed between different sample bulk density data, and it was not true for other properties data. According to multiple comparison results (Table 3.4), torrefied pine wood granules at high binder usage level had higher granule size, hardness and density than that of granule at lower binder level. At high binder usage level, the effect of torrefaction temperature on bulk density of pine wood granule at was presented in Figure 3.5. Bulk density of torrefied granule decreased to 330.22 kg · m$^3$ until the torrefaction temperature of 250 °C; then, it was increased up to 387.06 kg · m$^3$ at 300 °C. The granule size and sphericity (Average SPHT: 0.87) of torrefied pine wood granules did not change pronounced compared to those of raw pine wood granules.
Therefore, it may be concluded that torrefied granules at 300 °C had best overall physical properties among all granule samples. The granule density and hardness had been reported to increase in many other studies [17, 22, 23] as powder particle size decreased. It was worth mentioning that hydrophobic nature of torrefaction sample might had slightly negative effect on granule physical property. As explained above [21], the consequence of the lower wettability surface of torrefied pine wood at 250°C resulted into lower interparticle static liquid bridge force which was component force of consolidation. More importantly, smaller particles size would increase the mechanical interlocking effect and decreased the intragranular porosity [22] through squeezing more liquid out during consolidation.

Figure 3.3 depicted the visual difference between torrefied granule and conventional wood pellet. Table 3.4 also compared physical properties of wood pellets with the torrefied pine wood granules at different temperatures and different binder usage level in this study. The hardness and bulk density of granule were nearly half of those of pellets. Because of the limit of truck and road capacity, over 350 kg/m³ bulk density [24] was good enough for prevent cube-out phenomena (low bulk density bio-feedstock which has over the dimension capacity of truck, have not reach the weight capacity yet). The minimum acceptable feed pellets hardness levels was 39.2 for 4-5 mm and 63.7 for 6-8mm [25-27]. Figure 3.3 showed a better flowability of granule than conventional wood pellets, which would be the advantage of solid handling in plant. There were enough reasons to believe that granules at 275 and 300 °C torrefaction temperature conditions have good qualities for long distance transport and storage.
4. CONCLUSIONS

Energy required for grinding of torrefied biomass was decreased by about 7 fold when torrefaction temperature was increased from 250 to 300 °C. Torrefied pine wood powders were successfully agglomerated into highly flowable granules suitable for long distance transport and storage. High temperature torrefaction conditions (275 and 300 °C) are recommended for pine granulation to reduce binder usage and generate higher density granules. Bulk density of pine wood granules was not as high as regular wood pellets, but their physical properties met regular logistics requirements. More opportunities may still exist to further reduce the granule binder percentage by selecting more effective binders.
References


Conshohocken, PA.


Table 3.1. The effective specific grinding energy, grinding rate and size reduction of pine chips at various torrefaction temperatures conditions.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Before grinding (chip size)</th>
<th>Powder particle size$^{a,b}$</th>
<th>Grinding rate (g/min)$^b$</th>
<th>Effective Specific Energy (kWh/t)$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Length (mm)</td>
<td>Width (mm)</td>
<td>Thickness (mm)</td>
<td>$D_{gm}$ (micron)</td>
</tr>
<tr>
<td>RPW</td>
<td>33.87</td>
<td>21.77</td>
<td>4.88</td>
<td>154.17 (13.32)</td>
</tr>
<tr>
<td>TPW-250</td>
<td>22.29</td>
<td>11.97</td>
<td>5.40</td>
<td>124.10 (9.46)</td>
</tr>
<tr>
<td>TPW-275</td>
<td>31.84</td>
<td>17.29</td>
<td>5.18</td>
<td>85.21 (3.31)</td>
</tr>
<tr>
<td>TPW-300</td>
<td>18.15</td>
<td>10.58</td>
<td>3.55</td>
<td>75.83 (3.72)</td>
</tr>
</tbody>
</table>

$^a$ Knife mill grinding using 0.25mm screen.

$^b$ Number enclosed in the parenthesis were standard deviations with n = 3.
### Table 3.2. Fuel and physical properties of torrefied wood powder.

<table>
<thead>
<tr>
<th>Property</th>
<th>RPW</th>
<th>TPW-250</th>
<th>TPW-275</th>
<th>TPW-300</th>
</tr>
</thead>
<tbody>
<tr>
<td>VM (%, db)</td>
<td>81.39 (0.36)</td>
<td>80.06 (0.21)</td>
<td>73.87 (0.34)</td>
<td>58.76 (0.20)</td>
</tr>
<tr>
<td>Ash (%, db)</td>
<td>0.11 (0.02)</td>
<td>0.23 (0.01)</td>
<td>0.29 (0.03)</td>
<td>0.44 (0.02)</td>
</tr>
<tr>
<td>C (%, db)</td>
<td>48.73 (0.13)</td>
<td>48.88 (0.58)</td>
<td>53.70 (0.07)</td>
<td>59.24 (2.35)</td>
</tr>
<tr>
<td>H (%, db)</td>
<td>6.14 (0.04)</td>
<td>6.08 (0.06)</td>
<td>5.80 (0.01)</td>
<td>5.00 (0.02)</td>
</tr>
<tr>
<td>N (%, db)</td>
<td>0.15 (0.02)</td>
<td>0.14 (0.01)</td>
<td>0.16 (0.01)</td>
<td>0.15 (0.00)</td>
</tr>
<tr>
<td>O (%, db)</td>
<td>44.99 (0.12)</td>
<td>44.89 (0.73)</td>
<td>40.34 (0.05)</td>
<td>35.60 (2.71)</td>
</tr>
<tr>
<td>HHV (MJ kg$^{-1}$)</td>
<td>19.48 (0.14)</td>
<td>20.08 (0.15)</td>
<td>21.87 (0.09)</td>
<td>25.32 (0.07)</td>
</tr>
<tr>
<td>Initial moisture content (% wb)</td>
<td>9.77 (0.10)</td>
<td>6.48 (0.03)</td>
<td>4.27 (0.04)</td>
<td>4.03 (0.03)</td>
</tr>
<tr>
<td>Bulk Density (kg m$^{-3}$)</td>
<td>297.94 (7.28)</td>
<td>307.67 (0.77)</td>
<td>277.95 (3.68)</td>
<td>310.82 (3.89)</td>
</tr>
<tr>
<td>Particle Density (kg m$^{-3}$)</td>
<td>1447.34 (34.24)</td>
<td>1471.09 (36.94)</td>
<td>1464.76 (31.57)</td>
<td>1456.61 (17.48)</td>
</tr>
</tbody>
</table>

*a* Number enclosed in the parenthesis were standard deviations with $n = 3$.

*b* Number enclosed in the parenthesis were standard deviations with $n = 5$. 

---

60
Table 3.3. Granulation operation parameters and properties.

<table>
<thead>
<tr>
<th>Biomass</th>
<th>Binder to solid ratio (kg/kg biomass)</th>
<th>Average yield (%)</th>
<th>Percent Binder (% wt/wt)</th>
<th>Average wet granule moisture content (% wb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPW</td>
<td>Low 1.60</td>
<td>70.92</td>
<td>35.90</td>
<td>43.74</td>
</tr>
<tr>
<td></td>
<td>Medium 1.76</td>
<td>84.24</td>
<td>38.12</td>
<td>44.97</td>
</tr>
<tr>
<td></td>
<td>High 1.97</td>
<td>98.50</td>
<td>40.82</td>
<td>46.39</td>
</tr>
<tr>
<td>TPW-250</td>
<td>Low 1.60</td>
<td>77.82</td>
<td>35.90</td>
<td>42.47</td>
</tr>
<tr>
<td></td>
<td>Medium 1.76</td>
<td>91.85</td>
<td>38.12</td>
<td>43.78</td>
</tr>
<tr>
<td></td>
<td>High 1.92</td>
<td>99.10</td>
<td>40.20</td>
<td>44.94</td>
</tr>
<tr>
<td>TPW-275</td>
<td>Low 1.28</td>
<td>77.82</td>
<td>30.94</td>
<td>38.35</td>
</tr>
<tr>
<td></td>
<td>Medium 1.36</td>
<td>91.85</td>
<td>32.25</td>
<td>39.25</td>
</tr>
<tr>
<td></td>
<td>High 1.52</td>
<td>99.10</td>
<td>34.74</td>
<td>40.89</td>
</tr>
<tr>
<td>TPW-300</td>
<td>Low 0.96</td>
<td>63.74</td>
<td>25.15</td>
<td>33.88</td>
</tr>
<tr>
<td></td>
<td>Medium 1.12</td>
<td>76.27</td>
<td>28.17</td>
<td>36.22</td>
</tr>
<tr>
<td></td>
<td>High 1.20</td>
<td>98.79</td>
<td>29.58</td>
<td>37.27</td>
</tr>
<tr>
<td>Sample type</td>
<td>Binder usage level</td>
<td>Granule size (mm) (^{a,b})</td>
<td>Single granule density (kg/m(^3)) (^{a,c})</td>
<td>Hardness (N) (^{a,c})</td>
</tr>
<tr>
<td>-------------</td>
<td>-------------------</td>
<td>--------------------------</td>
<td>--------------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>RPW</td>
<td>Low</td>
<td>4.69 (0.16)a,A</td>
<td>484.03 (78.30) a,A</td>
<td>44.80 (19.86) a</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>4.47 (0.39)a,A,B</td>
<td>529.31 (65.15) a,A</td>
<td>34.94 (17.31) a</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>5.39 (0.24)a,A</td>
<td>580.35 (109.83) b,A</td>
<td>47.97 (17.10) a</td>
</tr>
<tr>
<td>TPW-250</td>
<td>Low</td>
<td>4.31 (0.25)a,A,C</td>
<td>511.41 (61.98) a,A</td>
<td>35.75 (14.85) a,b</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>4.72 (0.28)a,A</td>
<td>510.25 (66.06) a,A</td>
<td>36.06 (10.73) a</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>5.79 (0.42)b,A,B</td>
<td>487.81 (64.73) a,B</td>
<td>41.77 (21.56) b</td>
</tr>
<tr>
<td>TPW-275</td>
<td>Low</td>
<td>5.73 (0.88)a,B</td>
<td>513.60 (58.86) a,A</td>
<td>36.64 (14.95) b</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>3.41 (0.20)b,C</td>
<td>511.37 (69.87) a,A</td>
<td>28.67 (11.77) b</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>6.45 (0.68)a,B</td>
<td>531.49 (55.64) a,A,B</td>
<td>46.73 (19.22) b</td>
</tr>
<tr>
<td>TPW-300</td>
<td>Low</td>
<td>3.57 (0.09)a,C</td>
<td>533.38 (66.53) a,A</td>
<td>30.09 (16.03) a</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>3.53 (0.22)a,B,C</td>
<td>543.89 (44.52) a,A</td>
<td>26.48 (8.52) a</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>6.29 (0.68)b,A,B</td>
<td>620.90 (79.54) b,A</td>
<td>48.97 (17.58) b</td>
</tr>
</tbody>
</table>

\(^{a}\) Different uppercase letters within a column and binder usage level indicate significantly different values by sample type (p < 0.05);

Different lowercase letters within a column and type indicate significant different value by binder usage level (p < 0.05).

\(^{b}\) Number enclosed in the parenthesis were standard deviations with n = 5.

\(^{c}\) Number enclosed in the parenthesis were standard deviations with n = 20.
Table 3.5. ANOVA test results for the regression models of granule properties data.

<table>
<thead>
<tr>
<th>Source</th>
<th>Granule size (mm)</th>
<th>Single granule density (kg/m³)</th>
<th>Hardness (N)</th>
<th>Bulk density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>df(^a)</td>
<td>SS(^b)</td>
<td>df(^a)</td>
<td>SS(^b)</td>
</tr>
<tr>
<td>Biomass type</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>128833</td>
</tr>
<tr>
<td>Binder level</td>
<td>2</td>
<td>41</td>
<td>2</td>
<td>83820</td>
</tr>
<tr>
<td>Interaction</td>
<td>6</td>
<td>18</td>
<td>6</td>
<td>112351</td>
</tr>
<tr>
<td>Error</td>
<td>48</td>
<td>9</td>
<td>228</td>
<td>1121165</td>
</tr>
<tr>
<td>Total</td>
<td>59</td>
<td>72</td>
<td>239</td>
<td>1446169</td>
</tr>
</tbody>
</table>

\(^{ns}\) Not significant.
\(^a\) Degrees of freedom (df).
\(^b\) Sum of squares (SS).
Figure 3.1. Diagram of granulation process of laboratory pan granulator.
Figure 3.2. Particle size distribution of various torrefaction-temperatures of pine wood powder and granules.
Figure 3.3. The raw pine wood granules (a), torrefied pine wood granules at 250°C (b), 275°C (c), 300°C (d), and wood pellets (e).
Figure 3.4. The correlation between binder to solid ratio and granule yield for torrefied pine wood at various torrefaction conditions.
Figure 3.5. The bulk density of high binder usage level granule at various torrefaction temperatures.
CHAPTER 4

WET AGGLOMERATION OF TORREFIED PINE WOOD

PART 2: STARCH BINDER

Wu, Yifei and Mani, Sudhagar

To be submitted to the Biomass and Bioenergy
ABSTRACT

Economic and efficient conversion of biomass into fuels and chemicals depends not only on the cost of feedstock but also feedstock fuel and bulk flow properties. Pelleting was widely used as a densification technology to increase bulk density and flowability of bio-feedstock for efficient and economic handling and transport. Recently, torrefaction, a thermal pretreatment technology, has been proposed to integrate with pelleting technology to improve bio-feedstock energy density and moisture control. However, the torrefied biomass pellets show both the lower quality and the higher production energy, as a consequence of the removal of low-melting/softening point components. In this project, we have developed a proof of concept granulation process using 5% solid content starch as binder to densify the torrefied pine wood powder. The Randomized experiments with three replications included three factors: sample torrefaction temperature, binder usage level and granulation residence time. Increasing the granulation residence time of torrefied pine wood at 300 °C torrefaction conditions would pronouncedly improve granule yield and granule properties. Compared with lignosulphonate binder, bulk density and hardness starch granule was acceptable for logistic and feeding requirement, even as starch binder percentage of granule was as low as 5.77%. Thus, starch was a potentially effective and economically favorable biomass granulation binder compared with lignosulphonate.

Keywords: Biomass, Torrefaction, Densification, Granulation, Consolidation, single granule density, bulk density, hardness.
Nomenclature

$D_{gw}$  The geometric mean diameter (mm).

MC  Moisture content (% wb).

$M_{\geq 1 mm}$  Weight of granule sample which size larger than 1 mm

RH  Relative humidity.

RPM  Revolutions per minute.

RPW  Raw pine wood.

TPW  Torrefied pine wood.
1. INTRODUCTION

Non-renewable fossil fuels such as coal, oil, and natural gas, play a dominate role in the current world, but the anticipated energy crisis and serious environmental damage, like global warming, acid rain and toxic chemical emissions, urge the whole society to explore renewable energy sources. Biomass, as a sustainable carbon carrier, can be converted into available energy, biofuel and bio-products via various conversion processes.

Feedstock logistical cost has become one of the major limits of the growth of bioenergy utilization, because regular raw biomass has low energy density, low bulk density and is susceptible to moisture absorption compared with its fossil fuel counterparts (eg. coal). As a recent oxygen-free thermal pretreatment technology, torrefaction is promising for improving biomass fuel properties and grindability. As the energy density of biomass increases, the loss in mass causes low bulk density during torrefaction. Densification is another critical preprocessing step to improve the bulk density, flowability and bulk storage capability of large volumes of biomass. In that context, the integrated torrefaction and pelletization process was proposed by Bergman (2005) [1] to improve the bulk density of torrefied biomass by pelleting densification process. Though torrefied pellets once had been expected to be have higher bulk density [1], recent studies revealed that the current pelleting technologies required high energy input and produced lower quality torrefied pellets than conventional pellets [2, 3]. Pelletization itself, as a mechanical densification process, was very limited in capacity and labor intensive. In that context, a novel torrefied pine wood granulation technology was developed to effectively and economically densify wood powder. The granulation
process will be referred to as wet agglomeration [4] or low pressure agglomeration. As the name implies, wet agglomerates (granule) are bonded by the effect of surface tension and capillary forces of the liquid binder [5]. In pan granulation, small particles were colliding during irregular, stochastic motion in a pan granulator while the binders and solvents were sprayed or added on it.

The main objective of this study was to investigate torrefaction temperature, granulation residence time and binder usage effects on producing torrefied pine wood granulation. The optimal granulation residence time and binder amount were determined to generate high quality granules. Following last work [6], the starch binder was compared with lignosulphonate binder by evaluating granule percent binder, granule density, bulk density and hardness. The suitable torrefaction conditions and binder types were optimized to generate high quality granules with lower cost.

2. MATERIALS AND METHODS

2.1. Materials

Clean southern pine wood chips from a local pulp mill (Oglethorpe, Georgia, USA) were used as raw material. Wood chips were torrefied at three different temperatures (250°C, 275°C and 300°C) with 20 min residence time by a rotary drum torrefaction reactor, as described in previous paper [6]. Torrefied pine wood (TPW-250, TPW-275, and TPW-300), and raw pine wood (RPW) were ground with a laboratory heavy-duty knife mill (Retsch SM 2000, Germany). The ground pine wood powder fell through the bottom screen opening 0.25mm and was stored in black bin for experiment usage.

2.2. Granulation experiment

A pan granulator (DP-14 Agglo-Miser, Mars Mineral, PA, USA), described in
previous paper [6], was employed in present study. Pan angle was set to 45° and the pan speed was set to 30 RPM, as previous described. A basic experiment procedure was shown below:

a) Primary powder addition: the load of four different biomass powders (RPW, TPW-250, 275 and 300) was equally 200g (±0.02 g) in all experiments.

b) Binder preparation: The binder was prepared by mixing corn unmodified corn starch (PURE-DENT B700, GPC, IA, USA) into distilled water. Final binder is 5% solid content starch homogeneous suspension liquid.

c) Method of binder addition: binder was manually sprayed to primary powder in granulator by a trigger sprayer. The mass of binder spraying amount was metered by electronic balance and expressed as binder to solid ratio (Equation (1)), thus binder to solid ratio represented the binder usage level in each granulation process, For each samples, three different binder usage levels (low, medium and high) are applied.

\[
\text{Binder to solid ratio} = \frac{\text{Binder Liquid weight}}{\text{Pinewood sample weight}}
\]  

(1)

a) Sampling and drying: each granulation processes last for three different residence time (30, 60 and 90 min). Wet granule samples in the pan were collected and dried in oven (103°C ± 1) for 12 hours. The Randomized experiments with three replications included three factors: sample type, binder usage level and granulation residence time.

b) Sample analysis: The dry granule sample screening process was carried out with an analytical sieve shaker (Retsch AS 2000, Germany). After sieving for 15 min, the weight of dry granules above 1mm sieve was measured and
recorded as a percentage of the total dry sample weight, which was defined as granule yield in this study (Equation (2)).

\[
\text{Granule yield} = \frac{M_{\text{clump}}}{\text{Total dry sample weight}}
\]  

(2)

2.3. Binder Liquid property measurement

A rotational viscometer (DV-I Prime, BROOKFIELD, Middleboro, Massachusetts, USA) was used to measure the apparent viscosity of 5% solid content starch homogeneous suspension liquid. Constant temperature (25°C) of binder liquid samples was maintained by a thermostatic water bath (TC-602, BROOKFIELD, Middleboro, Massachusetts, USA). The starch binder liquid was also analyzed in a dynamic contact angle analyzer (DCA-322, Thermo Cahn Instruments, Madison, WI, USA) according to Wilhelmy plate method (Equation(3)).

\[
\gamma = \frac{F}{l \times \cos \theta}
\]  

(3)

Where \(\gamma\) was the surface tension, \(F\) was the measured surface tension force, \(l\) was the wetted perimeter and \(\theta\) was the contact angle. The standard solid probes were platinum plate, which gave a 0° contact angle, or \(\cos \theta = 1\), because of the extreme high surface energy of these two materials. In this study, a platinum plate (19.62 mm × 10 mm × 0.11 mm) was dipped into and slowly pulled out the liquid surface of starch binder that was maintained at 25°C. The real-time interaction force was measured by a sensitive microbalance and recorded to a connected desktop. In order to increase measurement accuracy, platinum plate was rinsed thoroughly with water and heated on nature gas burner till red before and after every measurement. Above tests were repeated 5 times.
2.4. Granule properties

In order to determine granule bulk density, a cylinder container with volume of 792.69 mL and internal diameter of 10.10 cm was used according to a standard ASTM E873-82 for densified particulate biomass [7]. The container was filled by pouring granule until granules were over flown. It was dropped five times from a height of 50 mm on a hard surface and excess granules were leveled with top edge of a container using a ruler before weighting. Every test was repeated 5 times.

\[
Sample\text{bulk density} = \frac{Sample\text{bulk volume}}{Sample\text{mass}}
\]  

(4)

Dry granule sample was analyzed an image analyzer (HORIBA CAMSIZER, instruments, Inc. CA, USA) for Granule shape and size distribution according to standard procedure [8]. Firstly, the dry granule samples were loaded onto the hopper of the instrument and fall to the measurement field for capturing by two cameras. The real-time image of falling granules was recorded and analyzed by software to determine the size and shape of every single granule. Finally, particle size distribution of each granule sample, as well as geometric mean diameter \((D_{gm})\) was given, and this test was replicated for 5 times.

Each granule samples was analyzed in Instron hardness tester (Insight 30, MTS Systems Corporation, MN, USA) for the hardness according to standard [9] for compression test of rigid plastics. As the standard procedure, granule was compressed between two parallel steel plates, and the maximum compressive load before granule had failure was defined as hardness of granule. Each single granule density test repeated thirty times.
Single granule density of each biomass granule sample was measured by dividing each single granule volume with its corresponding weight and repeated thirty times. The weight of single granule was weighted in an electronic balance which accurate to 0.001g. All three dimensions diameters of granules were manually measured by a digital caliper (Mitutoya, U.S.A.) and then, the geometric mean value was used to estimate the granule volume.

2.5. Statistical analysis

Statistical analyses were conducted using scientific software (MINITAB 14). Sample type and binder to solid ratio, and granulation residence time effects on granule properties were tested using three-way ANOVA. The following model was used:

\[
< \text{granule properties}> = \mu + gs \times lr \times rt + gs \times lr + gs \times rt + rt \times lr + \epsilon
\]

Where \( \mu \) was the general mean; \( \epsilon \) was the residual error; granulation sample (gs), liquid to solid ratio (lr) and residence time (rt) were treated as fixed effects. Samples with high binder usage were subjected to Tukey multiple comparisons test at 5% probability level.

3. RESULTS AND DISCUSSIONS

3.1. Granulation experimental runs

It is observed that pine wood granules from 5% solid content had the highest hardness, single granule density and bulk density. Therefore, 5% solid content starch homogeneous suspension liquid was selected as binder liquid in this study. In Vikramaditya (2013) [10]’s study, the three starch binder solid content value of 2.5%, 5%, 7.5% was compared with determine the best concentration for pine wood pan granulation. As shown in Table 4.1, the percent binder values of dry starch granules were ranged from
5.77 to 8.47, which is decreased by about 20% from that of lignosulphonate granules, as described in last paper [6]. This was mainly due to the low concentration of starch in the binder liquid.

According to binder property measurement, the apparent viscosity (1.35×10⁻³Pa s), liquid density value (1.02 kg/L) and surface tension value (65.06 dynes/cm) of starch binder solution was very close to those of water. The static surface tension force of aggregated primary wet granules was concerned as the dominant factor for granulation properties (Appendix A).

3.2. Granule yield

3.2.1. Effect of binder liquid usage

Pan granulator was generally designed to produce granules ranged from 1 to 20 mm, so the granule with larger than 1 mm was acceptable [11]. Figure 4.5 illustrated that the increase in binder to solid ratio would increase the granule yield of each torrefied pine wood powders, which was comparable with similar results reported in last paper [6]. It result also supported by Holm, et al. (1985) [12]’s work. They concluded that, during the granulation, the critical strain before failure generally increases with increasing binder content.

In pan granulator, the granule growth was a dynamic equilibrium with breakage and aggregation. In order to reduce the breakage rate, the tensile strength of granule must meet the minimum requirement to against inertia force and collision during the irregular, stochastic motion in pan granulation. According to tensile strength empirical equation given by Rumpf (1962) [13] (detail in Appendix A), higher liquid pore saturation level would increase the primary aggregated granule tensile strength (Equation (5)).
$$\sigma_i = SC \frac{1 - \varepsilon \gamma_{LV} \cos \theta}{\varepsilon / d_p}$$  

(5)

Where $S$ was the liquid pore saturation level, $\varepsilon$ was the intragranular porosity, $\gamma_{LV}$ was the liquid surface tension and $\theta$ was the liquid-solid contact angle. $d_p$ was the harmonic mean particle diameter.

3.2.2. Effect of torrefaction

In order to achieve high granule yield (95%), binder liquid to solid ratio value of torrefied pine wood increased slightly until the torrefaction temperature of 250 °C, compared with 1.85 of raw pine wood. Then, it was decreased down to 1.53 and 1.30 at torrefaction temperature of 275 and 300 °C respectively. According to the static tensile strength model (Equation (5)), particle size and surface hydrophobicity were the two major explanation on the binder usage difference between torrefied wood and raw wood granulation process.

First of all, according to the initial powder property reported in last paper [6], higher torrefaction temperature would decrease average particle size of torrefied pine wood powder, relative to raw pine wood. In a fine particle granulation [14], higher binder usage was reported in granulation of smaller particle size powder, as the consequence of the increase of surface area. However, Iveson, et al. (2001) [15] believed that wet powder with particle size over a critical level would become harder to be granulated. Since raw pine wood powder had coarser particle and less sphericity than normal food and pharmaceutical granulation powder (Figure 4.3), high liquid pore saturation level was required to meet the minimum requirement of tensile strength, according to Thus, the smaller torrefied pine wood powder size would more likely result in a decrease of wet
granule binder liquid usage.

Secondly, the torrefied wood had been reported a higher hydrophobicity surface than that of untreated wood [16, 17]. Increased hydrophobicity in torrefied pine wood powder would increase the contact angle of their surface.

According to the equation (5), the hydrophobicity of torrefied pine wood had negative effect on wet granule tensile strength.

In overall, the opposite direction effect of torrefied pine powder particle size and hydrophobicity properties on wet granule tensile strength confirm the downward trend of binder usage of torrefied pine granule at 250 °C and the upward trend at high torrefaction temperatures (275 and 300 °C).

3.2.3. Effect of residence time

The effect of granulation residence time on granule yield in low and high binder usage level was presented in Figure 4.4. The multiple comparisons resulted in Table 4.1 indicated that granule yield of torrefied wood at 250 °C and raw wood would not increase, when granulation residence time was over 30 min. Only at low binder usage level, torrefied pine wood at 275 °C had a significant trend towards an increase in granule yield from 52.05% to 77.02%, as residence time increases from 30 to 60 min. For torrefied pine wood at 300 °C, the granule yields at all binder usage level increased as residence time increases from 30 min to 90 min.

Increasing residence time was aimed at reducing their size and porosity, and squeeze liquid binder to surface to facilitate the further layering and aggregation that eventually increased granule yield. This effect was named as granule consolidation [18], which was defined as by equation (6).
\[ \frac{\varepsilon - \varepsilon_{\text{min}}}{\varepsilon_0 - \varepsilon_{\text{min}}} = \exp(-kt) \]  

(6)

Where \( \varepsilon_0 \) and \( \varepsilon_{\text{min}} \) was the initial porosity and minimum porosity reached by the tumbling granules. \( \varepsilon \) was the current average granule porosity after \( t \) period of time. \( k \) was the consolidation rate constant. Here the porosity is defined as the volume fraction which is occupied by both liquid and air phase in the granule. The Iveson and Litster (1998) [19] proposed a correlation between granule strength and consolidation rate (Equation (7)).

\[ k \propto e^{-Y/B} \]  

(7)

The dynamic strength (Y) was positive correlated with granule static tensile strength in this study, because the static surface tension effect was dominant. Thus, increased in static tensile strength would decrease the consolidation rate and increase the required residence time for complete consolidation. According to this model, longer residence time for consolidation of torrefied pine wood at 275 and 300 °C was well explained by their higher wet granule tensile strength, which proposed in last section.

3.3. Granule properties

The three-way ANOVA test result in Table 4.3 shown the significant difference (p<0.05) on all three factor for granule size, single granule density, hardness and bulk density. Last paper [6] had reported that the granules at high binder usage level had better granule properties than the granules at lower binder usage level. Since pan granulator was expected to have high granule yield and low granule recycle rate [11], the multiple comparison results of were only summarized at high binder usage level (Table 4.2).

3.3.1. Granule size

The granule size distribution at high binder usage and 90 min residence time was
revealed in Figure 4.1. According to the multiple comparisons, the granule size of torrefied pine wood granules did not change significantly compared with those of raw pine wood granules, at 60 and 90 residence time. This is comparable to the similar results reported in last paper[6]. Besides, a consequence of the slow consolidation rate of pine wood at 300 °C was its smaller granule size at 30 min residence time, compared with granule samples.

The behaviors of granule size at high binder usage level also could be perfectly explained by the granule yield changes at various residence times. At high binder usage level, only torrefied pine wood at 300 °C had significant consolidation effect until 90 min. The lasting consolidation effect would squeeze intra-granule liquid binder to the surface. Especially in the later period, availability of liquid binder on the granule surface determined whether a collision between two granules (aggregation) and between granule and primary powder (layering) resulted in permanent bond [15]. The aggregation and layering effects were the major reason that only granule at 300 °C torrefaction condition increased granule size as residence time increased.

3.3.2. Bulk density and Single granule density

The comparison of the bulk density of granule at high binder usage level was illustrated in Figure 4.6. Compared with the bulk density of raw pine granule (~270 kg · m⁻³), that of torrefied pine wood slightly decreed to around ~240 kg · m⁻³ until the torrefaction temperature of 250 °C, Then, it was increased up to 360 kg · m⁻³ at torrefaction temperature of 300 °C. The single granule density values follow the same trend during torrefaction temperature increasing (Table 4.1). The similar behavior was also observed in lignosulphonate granules. Since the particle density of each torrefied
wood powder had no significant difference from raw pine wood (in last paper [6]), the bulk density and single granule density value was mainly determined by the minimum porosity \( \epsilon_{\text{min}} \) of granules. The minimum porosity was strongly influenced by powder particle shape and size distribution [15]. Pine wood powder particle were slender and irregular (Figure 4.3), powder with wider size distribution was easier to be consolidated into low porosity granules. According to the torrefied pinewood particle size distribution (in last paper [6]), the peak of the raw pine wood powder and torrefied pine wood powder at 250 °C is between 200~300 micron, whereas peak of torrefied pine wood powders at 275 and 300 °C was moved to lower than 100 micron range. This was the reason that torrefied wood granules at 275 and 300 °C had significantly higher bulk density than raw pine wood. In this study, the dominant static surface tension force was conservative and component force of consolidation effect. The lower bulk density and higher porosity of torrefied granule at 250 °C than raw pine wood could be explained by its lower surface tension force, as a consequence of its hydrophobicity (Equation (5)).

On the other hand, increased torrefaction temperature increased the dynamic strength of granule and then reduced the rate of consolidation \( (k) \). The multiple comparisons results in Table 4.1 indicated that single granule density of torrefied wood at 250 °C and raw wood did not increase, when granulation residence time was over 30 min. The single granule density of torrefied granule at 275 increased from 415.4 to 443.8 kg \( \cdot m^{-3} \), as residence time increased from 30 to 60 min. For pine wood granule at 300 °C torrefaction condition, the single granule increased as residence time increased from 30 min to 90 min. The bulk density values of each torrefied pine wood granule followed the similar trend, as the residence time increased. It is important to note that the bulk
density of torrefied granule at 275 °C increased from 30 min residence time to 60 min, but
decreased from 305 to 284 kg · m⁻³ at 90 min residence time. It was explained by drop
of granule yield value and wet granule moisture content of torrefied granule at 275 °C at
90 min residence time (Figure 4.1). If the extent of granulation had been reached, the
dying effect would become more pronounced due to the long granulation time.

The bulk density of torrefied pine wood granule at 300 °C reached over half of the
value of wood pellet. According to truck and road capacity limitation [6, 20], the density
property of torrefied pine wood granule was good enough for prevent cube-out
phenomena

3.3.3. Hardness

As the temperature increases, the hardness of torrefied granules decreased from
about 19 N down to 10 N at 250 °C and up to about 15 and 22 N at 275 and 300 °C
respectively. As the residence time increased, hardness value of each torrefied granules
followed the same trend of single granule density. In Vikramaditya (2013) [10]’s pine
wood granulation study, the smaller particle size wood powder was observed to increase
the granule hardness due to better binder solution distribution on larger particle surface
area during pan granulation. The strength of dry granule is contributed by particle
interlocking bond and binder solid bridge [5]. The higher single granule density and
lower porosity would increases the interlocking and binder solid bridge strength [15].
Since the minimum hardness requirement for 4~5 mm feed pellets was 39.2 N [21-23],
the hardness of torrefied pine wood granule with starch binder was little lower than the
requirement of pellet.
4. CONCLUSIONS

Increasing the granulation residence time of torrefied pine wood at 300 °C torrefaction conditions was proved to pronouncedly improve granule yield and granule properties. The result indicated that it was a promising alternative way to conduct granulation with lower binder usage and with longer residence times. Compared with lignosulphonate, using starch binder reduced the granule binder percentage by 80%; meanwhile, bulk density of starch granules was sufficient for regular logistics and hardness values were close to pellet requirement. Therefore it could be concluded that starch was a potentially effective and economical favorable binder compared with lignosulphonate for torrefied pine wood granulation application. More opportunities may still existed to further optimize the starch binder usage and residence time.
References


### Table 4.1. Granulation operation parameters and properties.

<table>
<thead>
<tr>
<th>Biomass</th>
<th>Binder to solid ratio (kg/kg biomass)</th>
<th>Percent Binder (% wt/wt)</th>
<th>Average yield (%)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Average wet granule MC (% wb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Residence time (min)</td>
<td>30min</td>
<td>60min</td>
<td>90min</td>
</tr>
<tr>
<td>RPW</td>
<td>Low</td>
<td>1.65</td>
<td>7.62</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>1.75</td>
<td>8.05</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>1.85</td>
<td>8.47</td>
<td></td>
</tr>
<tr>
<td>TPW-250</td>
<td>Low</td>
<td>1.60</td>
<td>7.41</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>1.68</td>
<td>7.73</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>1.85</td>
<td>8.47</td>
<td></td>
</tr>
<tr>
<td>TPW-275</td>
<td>Low</td>
<td>1.43</td>
<td>6.67</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>1.48</td>
<td>6.89</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>1.53</td>
<td>7.08</td>
<td></td>
</tr>
<tr>
<td>TPW-300</td>
<td>Low</td>
<td>1.23</td>
<td>5.77</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>1.26</td>
<td>5.93</td>
<td></td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>1.30</td>
<td>6.10</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> Different lowercase letters within a column and type indicate significant different value by residence time (p < 0.05).
Table 4.2. Physical properties of torrefied granules compared with wood pellet.

<table>
<thead>
<tr>
<th>Sample type</th>
<th>Residence time (min)</th>
<th>Granule size (mm)</th>
<th>Single granule density (kg/m$^3$)</th>
<th>Hardness (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Low</td>
<td>Med</td>
</tr>
<tr>
<td>binder usage level</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RPW</td>
<td>30</td>
<td>5.21</td>
<td>3.31</td>
<td>5.39 (0.03)</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>5.31</td>
<td>3.82</td>
<td>5.45 (0.14)</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>5.20</td>
<td>4.77</td>
<td>6.12 (0.61)</td>
</tr>
<tr>
<td>Wood pellet</td>
<td>30</td>
<td>4.53</td>
<td>4.77</td>
<td>4.68 (0.50)</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>4.43</td>
<td>4.98</td>
<td>5.11 (0.62)</td>
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<tr>
<td></td>
<td>90</td>
<td>3.88</td>
<td>5.38</td>
<td>5.35 (0.25)</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>3.51</td>
<td>4.60</td>
<td>4.54 (0.50)</td>
</tr>
<tr>
<td>TPW-250</td>
<td>60</td>
<td>4.72</td>
<td>4.33</td>
<td>6.00 (1.11)</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>4.22</td>
<td>4.96</td>
<td>4.80 (0.10)</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>2.89</td>
<td>2.97</td>
<td>3.22 (0.45)</td>
</tr>
<tr>
<td>TPW-275</td>
<td>60</td>
<td>3.13</td>
<td>3.36</td>
<td>4.54 (0.71)</td>
</tr>
<tr>
<td></td>
<td>90</td>
<td>3.30</td>
<td>3.66</td>
<td>6.22 (0.75)</td>
</tr>
<tr>
<td>TPW-300</td>
<td>60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>90</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$ Different uppercase letters within a column and binder usage level indicate significantly different values by sample type (p < 0.05);

Different lowercase letters within a column and type indicate significant different value by residence time (p < 0.05).

$^b$ Number enclosed in the parenthesis were standard deviations with n = 3.

$^c$ Number enclosed in the parenthesis were standard deviations with n = 10.
Table 4.3. ANOVA test results for the regression models of granule properties data.

<table>
<thead>
<tr>
<th>Source</th>
<th>Granule size (mm) df&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Single granule density (kg/m&lt;sup&gt;3&lt;/sup&gt;) df&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Hardness (N) df&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Bulk density (kg/m&lt;sup&gt;3&lt;/sup&gt;) df&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample type (S)</td>
<td>3</td>
<td>25.5</td>
<td>3</td>
<td>712086</td>
</tr>
<tr>
<td>Binder level (B)</td>
<td>2</td>
<td>19.5</td>
<td>2</td>
<td>358593</td>
</tr>
<tr>
<td>Residence time (R)</td>
<td>2</td>
<td>8.9</td>
<td>2</td>
<td>302517</td>
</tr>
<tr>
<td>S*B</td>
<td>6</td>
<td>14.8</td>
<td>6</td>
<td>341637</td>
</tr>
<tr>
<td>S*R</td>
<td>6</td>
<td>5.2</td>
<td>6</td>
<td>136811</td>
</tr>
<tr>
<td>B*R</td>
<td>4</td>
<td>4.5</td>
<td>4</td>
<td>5414&lt;sup&gt;ns&lt;/sup&gt;</td>
</tr>
<tr>
<td>S<em>B</em>R</td>
<td>12</td>
<td>8.8</td>
<td>12</td>
<td>140787</td>
</tr>
<tr>
<td>Error</td>
<td>72</td>
<td>19.3</td>
<td>1044</td>
<td>1432494</td>
</tr>
<tr>
<td>Total</td>
<td>107</td>
<td>106.4</td>
<td>1079</td>
<td>3430337</td>
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</tbody>
</table>

<sup>ns</sup> Not significant.
<sup>a</sup> Degrees of freedom (df).
<sup>b</sup> Adjusted Sum of squares (Adj-SS).
Figure 4.1. Particle size distribution of various torrefaction-temperatures of granules (high binder usage level, 90min residence time).
Figure 4.2. Raw pine wood starch granules (a), and torrefied pine wood starch granules at 250 °C (b), 275 °C (c), 300 °C (d).
Figure 4.3. Electron Microscope (EM) images of raw pine wood powder (a), and torrefied pine wood powder at 250 °C (b), 275 °C (c), 300 °C (d).
Figure 4.4. Effect of granulation residence time on granule yield (>1mm) at low (a) and high (b) binder usage level for torrefied pine wood at various torrefaction conditions.
Figure 4.5. The correlation between binder to solid ratio and granule yield for torrefied pine wood at various torrefaction conditions (Granulation residence time: 90min).
Figure 4.6. The bulk density of high binder usage level granule at various torrefaction temperatures.
CHAPTER 5

TECHNO-ECONOMIC ANALYSIS OF MANUFACTURING TORREFIED PINE WOOD GRANULES IN THE SOUTHEASTERN UNITED STATES

Wu, Yifei and Mani, Sudhagar

To be submitted to the Biomass and Bioenergy
ABSTRACT

A novel torrefied pine wood granulation technology holds the promise to manufacture granules with high energy density. This study conducted a techno-economic analysis of integrated torrefaction and granulation technology to estimate energy usage, capital cost and production cost of torrefied granules from southern pine. Cost of producing conventional pellets from raw and torrefied wood was also compared. The capital and operating costs of a base case granulation plant having a production capacity of 5 t/h were estimated and projected up to 50 t/h plant capacity. The cost data demonstrated that raw material cost had the highest influence on the production cost (30%~52%) followed by personnel, binder cost, debarking and chipping costs. Total production costs in base scale were significantly higher than those of larger capacity plants due to a scale of economy. The total production cost of torrefied granules (as low as 7.56 $/GJ) was less than that of raw wood granules (8.95 $/GJ). Granulation technology was preferred as a densification technology for high temperature (300°C) torrefied biomass. Torrefied granules produced at 300°C had a highly economically competitive production cost (7.47 $/GJ) to that of conventional pellet (7.68 $/GJ) and almost same production cost of torrefied pellets produced at 300°C. Moreover, biomass granules may require reduced downstream processing, storage and metering costs compared to these of pellets. Opportunities exist to further reduce the cost of biomass granulation in the future by exploring non-water based, low-cost binders and formulating consistent composition granules for efficient downstream conversion.

Keywords: Torrefaction, Pelletization, Wet agglomeration, Cost analysis.
1. INTRODUCTION

The anticipated fossil fuel depletion and global warming crisis has aroused increasing interest in bioenergy pretreatment, processing and conversion technology research (McKendry, 2002a; McKendry, 2002b). Among many pretreatment technologies, torrefaction, as a promising thermal pretreatment process, can improve biomass fuel properties, energy density, hygroscopicity and even grindability. Torrefaction of various kinds of biomass has been extensively investigated in the literature (Bergman, 2005; Bergman et al., 2005; van der Stelt et al., 2011). Torrefaction is a process of heating biomass between 200 and 300°C in the absence of oxygen at atmospheric pressure. Typically during torrefaction, 70% of the mass is retained as a solid product, containing 90% of the initial energy content; hence a significant energy densification can be achieved. That may be because the volatile reaction products, namely H₂O, CO₂ and acetic acid, are rich in oxygen (Bergman, 2005).

Pelletization, as a mechanical densification processing technology, has been widely applied to increase the bulk density of biomass, because of the exponential increase in international demand. In 2010, the EU annual demand for pellets was about 10 million tonnes and demand was forecast to grow to 219 million tonnes in 2020. However, while pellet mills are commercialized and profitable in the southeastern United States, pelleting is also very labor and energy intensive compared to granulation, a low pressure wet agglomeration process. As the name implies, wet agglomerates (or green agglomerates) are bonded by the effect of surface tension and capillary forces of the liquid binder (Pietsch, 2002). Our group had developed a novel lignocellulosic biomass granulation technology to replace existing pelleting and a torrefied pine wood granulation
study in a bench-scale pan granulator had been done by the author (Wu & Mani, 2013a; Wu & Mani, 2013b). Torrefied pine wood powders wetted with binder solution aggregate into granules by tumbling in pan granulator.

Despite the extensive research on torrefaction and granulation, there is no commercial scale application existing to date. There are still considerable uncertainties concerning plant scale production costs, because aforementioned studies were focused on experimental aspects. Since technical characteristics of each process were only evaluated individually, a system level economic study is urgently required to make both torrefaction and granulation components perform functions together organically.

The primary objective of this work is to develop a spreadsheet based techno-economic analysis model to estimate the manufacturing cost of a torrefied granule in the Southeastern United States. The base case study for 5 t/h facility was utilized to evaluate its economic feasibility by comparing it with conventional pelletization, torrefaction pelletization, and conventional granulation scenarios. A second objective was analyzing the breakdown of unit manufacturing cost distribution in different facility capacities of 5, 10, 25, and 50 t/h, and identifying potential technical improvements by individual parameter sensitivity analysis to significantly improve the overall economic performance.

2. METHODS

2.1. Pellet plant description

The key parameters of two pellet plant scenarios (torrefied pellet production and conventional pellet production) were revealed in Table 5.1. Round wood was a primary feedstock to the plant. Bark from round wood was removed by a debarker and clean wood is chipped. Then clean pine chips were dried by rotary drum dryers or torrefied by
torrefaction reactors. The severity of torrefaction depended on both temperature and residence time, and temperature was reported as having a major effect on fuel properties (Phanphanich & Mani, 2011). In this study, three different temperatures were selected (250, 275 and 300°C), with 20 min residence time. Bark and purchased green hog fuel were combusted in a solid fuel burner and flue gases was used to heat the torrefaction reactor or rotary drum dryer. Then pretreated chips was ground by hammer mill with 3.18 mm (1/8 inch) screen into powder which was pelletized by pellet mill. After cooling and screening, the final product was stored in silo storage.

2.2. Granule plant description

A typical biomass granulation plant was illustrated in Figure 5.1. The plant receives round wood logs and processed until dry chips as similar to conventional pellet plants. Dry wood chips were ground with 0.79 mm (1/32 inch) opening screen in a hammer mill, since finer particle size wood powders was required for high granule quality. During wet agglomeration process, small particles were colliding during irregular, stochastic motion in certain equipment for 30 min; meanwhile, the binders and solvents were sprayed on them. In this study, granulation of pine wood powder using 5% industrial starch solution as binder was used for economic evaluation. The post-drying process was required for wet granules. The binder solution percentage, granule bulk density, and binder usage amount (binder to solid ratio) value were estimated from the author’s bench-scale experiments. The parameters of two granule plant scenarios (torrefied granule production and conventional granule production) were illustrated in Table 5.1.
2.3. Cost estimation

In all four scenarios, the plant operated 24 hours a day for 330 days annually. The production cost components included capital cost and operating cost. Generic cost data were collected from the literature review and equipment specification documents. The operating cost comprising feedstock cost, maintenance cost, employee cost, energy cost and other costs was summarized in Figure 5.2.

2.3.1. Capital cost

The annual capital cost $C_c(\$/y)$ was calculated by:

$$C_c = CRF \times (\text{installed cost} - \text{salvage value})$$

where CRF was the capital recovery factor. Installed cost included equipment purchase, delivery and installing cost. The installed costs of each equipment were given by Table 5.3. The salvage value was considered to be 20% of the initial installed cost.

The capital recovery factor (CRF) was calculated by

$$\text{CRF} = \frac{i(1 + i)^n}{(1 + i)^n - 1}$$

where $i$ was the interest rate (decimal) and $n$ was the utilization time of investment in years. In this study, a nominal interest rate of 6% was used for CRF calculation (Mani et al., 2006).

The equipment cost was not linearly related to the capacity of the equipment, whereas following this formula:

$$\text{Cost of equipment } a = \text{cost of equipment } b \times \left(\frac{\text{capacity of equipment } a}{\text{capacity of equipment } b}\right)^\alpha$$

where $\alpha$ is scale factor. Generally the scale factors were less than 1, which means the larger the equipment capacity, the lower specific the capital cost. As a rule of thumb, 0.6
was used as the scale factor in the absence of other information; nevertheless, for most of the equipment that was an oversimplification. Since the scale factor can vary from more than 1.0 to less than 0.3, it was better predicted from similar unit’s reported value (Peters et al., 2003). In a study from Sultana et al. (2010), the scale factors of several main equipment were calculated from curve fitting of the cost data points from the literature for different capacities. However the economic data were collected from the literature published from 1995 to 2007 at different places around the world and used in curve fitting without consideration of the inflation factor.

This study takes inflation into consideration:

\[
\text{Cost in 2012} = \text{Original cost} \left( \frac{\text{Index value in 2012}}{\text{Index value at time original cost was obtained}} \right).
\]

Many different types of cost index were published regularly, and the Chemical Engineering plant cost index (2013) was used. It is worth mentioning that the cost index never takes technological advancement and local conditions into account. In this study, cost dates for pilot scale plants or those published in foreign countries a long time ago were used with caution.

2.3.2. Feedstock cost

Southern pine pulpwood was used as raw material in this model. As pulpwood, the diameter at breast height (DBH) of pine logs was 6~8 inches. The bark percentage of green log is 11.9% (Bergman & Bowe, 2009; Lambert et al., 2005) and the moisture content of green wood and bark was 50% (Bergman & Bowe, 2009). The raw material cost included standing timber purchase cost, logging and infield cost, transportation cost, and storage cost. In this study, the pine pulpwood South-wide annual average delivered price value reported by Timber Mart-South (2012) for 2012 was (30.06 $/green tonne).
2.3.3. Employee cost

There were two kinds of employees in plants: hourly wage employees and annually paid employees. At full capacity, the plant ran three shifts a day, five days a week. The hourly wage rate was assumed as $19/h. The numbers of hourly wages employees per shift were described in the Table 5.4. Dryer/torrefaction reactors, solid fuel burners, pellet mills, and debarking knuckleboom loaders required people to watch or operate the feeding system and make sure it is running smoothly. In the large capacity production plant, control technology for a fully automatic operation was installed and needed only one person to watch the control system for multiple production lines.

In all plant production rate scenarios, four salaried employees were paid $80,000 annually. They were the general supervisor, the finance manager, the marketer, and the receiving clerk/administrative assistant (Campbell, 2007).

2.3.4. Energy cost

The energy usages of each operating unit were given by Table 5.3. There are three major energy source: electrical energy, diesel energy and hog fuel thermal energy.

The cost of electricity was estimated from large business electricity price from the Georgia Power Company. For all industrial customers contracting for no less than 500kW, a monthly bill with a basic service charge of $20 and a demand charge of $9.01 per kW were paid every month, and kWh charges were paid based on actual usage. The overall electricity energy cost was about 4.50 cent/kWh and depended on the plant capacity.

The thermal energy consumption for drying and torrefaction was extraordinarily high. Natural gas was widely used as the major fuel in conventional pellet plant. Many researchers suggested that the use of biomass residue or pellets as fuel instead of natural
gas or coal (Hoque et al., 2006; Mani et al., 2006). The heat of drying, post-drying, and torrefaction was provided by bark and purchased hog fuel combustion in a solid fuel burner. In the North American scenario, the wet hog fuel purchase cost and bark resale price could be estimated as $10/t (Mani et al., 2006; Milota et al., 2004). The thermal energy system model, which included torrefaction reaction, rotary drum drier, conveyor post dryer and solid burner, was built on spreadsheet, using assumptions given by (Shah et al., 2012). The outputs from this model were used to analyze the mass balance and energy balance (Table 5.5). The energy balance was based on theoretical energy drying and torrefaction energy ($E_{req}$, GJ/t product), recovered energy ($E_{rec}$, GJ/t product) and energy loss ($E_{loss}$, GJ/t product).

\[
E_{net} = E_{in} - E_{rec}
\]

\[
E_{in} = E_{req} + E_{loss}
\]

\[
\eta = \frac{E_{req}}{E_{in}}
\]

where $\eta$ was the total torrefaction or drying system efficiency and $E_{net}$ was the net external energy required which was provided by hog fuel and bark residue. It was reasonable to estimate the energy content of dry bark and dry hog fuel as 20.55 MJ/kg (Corder, 1976; FAO, 2002). In this study, the system efficiency was assumed as 65%.

### 2.3.5. Maintenance cost

Maintenance cost was assumed to be 2% of the capital cost, whereas hammer mills and pellet mills had a higher maintenance cost, which was assumed to be 10% of the purchase cost (Mani et al., 2006).
2.4. Sensitivity Analysis

Since both torrefaction and granulation technology were not widely commercialized, the lack of plant scale production data also gave rise to elevated overall production cost uncertainty. Conducting sensitivity analysis in this techno-economic analysis did not only help to quantify the impact of uncertainty, but also helped to identify the cost reduction potential for future technology development. In this study, capital cost, operating cost, and the overall production cost of 300°C torrefied granules were compared in different plant capacities (5, 10, 25 and 50 t/h).

Also, a sensitivity study was performed for individual parameters that varied from the established base case over a reasonable range to evaluate how a single process parameter influenced the overall production cost of 300 °C torrefied granules. In this study, the grinding rate and grinding energy consumption varied within ±15% due to the lack of commercial scaled hammer mill fine grinding data for granulation usage. There is also no commercial scale torrefaction available; however, theoretical estimations of the torrefaction system investment cost had been made in previous studies. On a unit capacity basis, Shah et al. (2012) reported that the installed cost of a torrefaction system ranging from 0.1 to 0.3 million dollars per unit capacity (t/h) was reasonable. Besides the above parameters, hog fuel delivered price, binder delivered price, binder usage amount, personnel salary level, pine log delivered price, and torrefaction mass yield were all included in this sensitivity analysis.

3. RESULTS AND DISCUSSIONS

3.1. Energy consumption

The resulting production thermal and electrical energy consumptions of all scenarios
in base case (5 t/h) were shown in Figure 5.2. The thermal energy included hog fuel thermal energy and diesel energy. In conventional cases, granules had both a higher both thermal and electrical energy consumption than pellets. The extra wet granule post drying process and finer biomass powder input grinding resulted in more thermal energy and more electricity consumed in post-drying unit and hammer mill respectively (Figure 5.1). Granules produced from torrefied pine wood needed much less electrical energy (10 MJ/GJ products) than raw granules (49.85 MJ/GJ products), because torrefied pine wood had better grindability and its powder was easier to be granulated with lower binder requirements. Due to the replace of energy intensive pellet mill with granulator, the electrical energies of the high temperature (275 and 300°C) torrefied granule production were obviously less than that in that of any pellet production scenarios (23.54~38.18 MJ/GJ products). Regarding to thermal energy, the increase of torrefaction temperature would increase the thermal energy consumed in torrefaction reactor, because extra energy was required to dry more wood chips to compensate the dry mass loss in torrefaction reaction. The total trends of thermal energy consumption in torrefied pellet production kept increasing up to 377.2 MJ/GJ in 300 °C torrefaction temperature, whereas these in torrefied granule production were slightly downslope. That could be explained by the heat recovery from rotary drum dryer exhaust heat to conveyor post-drying process. In the 300 °C torrefied granule scenario, the thermal energy consumption (429.8MJ/GJ product) was lower than that in the conventional granule scenario (429.8MJ/GJ product), so 300 °C torrefaction treatment was energy favorable in granule production. Even compared with torrefied pellets, it still had chance be more economically favorable, because the electricity price was much higher than hog fuel.
3.2. **Base case production cost**

In torrefaction pelletization and torrefaction granulation scenarios, production costs of torrefied pine pellets or granules produced from three different torrefaction temperatures (250, 275 and 300 °C) were also revealed (Figure 5.3). The raw granule and low temperature torrefied granules had higher total production costs than all pellets production scenarios. There was a trend in the reduction of total granule production cost from $8.95/GJ down to the highest torrefaction temperature of 300 °C. Overall production costs of 300 °C torrefied pellets and granules were found out to be $7.54/GJ and $7.56/GJ respectively, which were all slightly lower to the conventional pellet cost $7.68/GJ. From an economic aspect, 300 °C was as the best torrefaction temperature in both pellet and granule production cases.

Raw material costs followed by personnel costs were the two largest cost components in all four scenarios (Figure 5.4). This was consistent with other pellet mill techno-economic studies (Mani et al., 2006; Thek & Obernberger, 2004). The overall production costs of conventional wood pellets ($96/t) in this study were much higher than waste wood pellet production cost, $51/t and $46.8/t, reported by Mani et al. (2006) and Hoque et al. (2006). However, it was much lower than the agri-pellet production costs, $122/t and $172/t, given by Sultana et al. (2010) and Nilsson et al. (2011) respectively, because of the high collection and handling costs of agriculture residue. In this study, the delivered price of raw material, $30/t, was lower than crop residue ($47.61/t) and higher than shaving and sawmill residue. In a reported work from Uasuf and Becker (2011), both the low wood waste cost and low wage rate in Northeast Argentina draw pellet costs down to as low as $34.90/t.
Binder cost and post-drying were also major cost components only in the granule plant. In the granule plant, pan graduation replaced pellet mill and the densification unit cost was reduced to negligible. In previously reported studies, grass biomass (Mupondwa et al., 2012) and the raw material with smaller particle size (Mani et al., 2006; Thek & Obernberger, 2004; Uasuf & Becker, 2011), such as sawdust and wood shavings had smaller grinding costs. Since pine pulpwood was used as raw material in this study, chipping, debarking and hammer mill fine grinding were all major cost components. In both the granule and pellet plant, torrefaction at 300℃ would largely increase pine chips grindability (Arias et al., 2008; Bridgeman et al., 2010; Phanphanich & Mani, 2011; Repellin et al., 2010) and significantly reduced the hammer mill grinding process costs. Also, from Figure 5.4, the cost of the torrefaction reaction unit was less than cost of conventional drying and costs of post-drying was only included in granule production.

3.3. Sensitivity analysis

A sensitivity analysis of plant production rate in each production scenarios was illustrated in Figure 5.5. In this figure, manufacturing costs (without raw material cost) at 5 to 50 t/h production rate were shown an obvious decreasing trend. The manufacturing cost in each production scenario decreased more than 20% from 5 t/h to 20 t/h. Figure 5.6 showed that the overall production costs were most sensitive to the pulp log delivered price and higher torrefaction mass yield. The grinding energy consumption and grinding rate of the large scale hammer mill had significant uncertainty, since they were closely related to machine brand and model. Fortunately, variability of both grinding parameters showed very limited effect on production costs. From the literature (Shah et al., 2012), it was reasonable to assume the large scale torrefaction system investment cost ranged from...
0.1 to 0.3M$/t/h, yet the overall costs only had less than $0.1/GJ difference within that range. Since personnel salary level, binder usage and binder price were all associated with major cost components in production (Figure 5.4), production costs was sensitive to their value variation.

4. CONCLUSIONS

A detailed techno-economic assessment model was developed to estimate manufacturing costs for producing torrefied pellets and granules cost of manufacturing wood granules was relatively expensive (9.24 $/GJ) compared to that of wood pellets (7.68 $/GJ). Granulation process had lower densification and personnel costs but higher grinding, post drying and binder usage costs compared to that of pelleting process; since the raw material cost was the largest cost contributor in any production scenario, the mass yield of high temperature torrefaction and raw pine wood price was also very important to the overall production costs. The personnel cost in base scale was significantly higher than in larger scale plants; as a result, the total production cost was significantly reduced by increasing the plant capacity. In granulation scenarios, high temperature torrefaction (300 °C) was preferred as pretreatment before granulation, because of its high grindability and low granulation binder requirements. According to the base case production cost comparison, the granulation of 300 °C torrefied biomass is highly economically competitive compared to that of conventional pelleting technology. Further opportunities was exist to reduce the cost of biomass binders and post drying by selecting low cost binders and optimized lower binder requirement for producing high density granules for efficient transport and storage.
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*Bioenergy*, **35**(9), 3748-3762.


Table 5.1. Key parameters in different scenarios. (Li et al., 2012)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Conventional pellet production</th>
<th>Conventional granule production</th>
<th>Torrefied pellet production</th>
<th>Torrefied granule production</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pellet mill</td>
<td>Pan granulator</td>
<td>Pellet mill</td>
<td>Pan granulator</td>
</tr>
<tr>
<td>Densification unit</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pretreatment unit</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Torrefaction temperature (°C)</td>
<td>N/A</td>
<td>N/A</td>
<td>250</td>
<td>275</td>
</tr>
<tr>
<td>Mass yield (%)</td>
<td>100.00</td>
<td>100.00</td>
<td>82.40</td>
<td>68.34</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>58.90</td>
<td>82.40</td>
</tr>
<tr>
<td>Product energy content (MJ/kg, db)</td>
<td>17.54</td>
<td>17.54</td>
<td>18.73</td>
<td>20.94</td>
</tr>
<tr>
<td>Product moisture content (% wb)</td>
<td>9.96</td>
<td>9.96</td>
<td>6.72</td>
<td>4.27</td>
</tr>
<tr>
<td>Product bulk density (kg/m²)</td>
<td>650.00</td>
<td>280.00</td>
<td>550.00</td>
<td>243.37</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>283.73</td>
<td>358.37</td>
</tr>
<tr>
<td>Grinding energy (kWh/t)</td>
<td>81.45</td>
<td>224.19</td>
<td>37.84</td>
<td>104.16</td>
</tr>
<tr>
<td>Relative grinding rate</td>
<td>1.00</td>
<td>0.36</td>
<td>0.82</td>
<td>0.73</td>
</tr>
<tr>
<td>Biner to biomass ratio</td>
<td>N/A</td>
<td>1.85</td>
<td>N/A</td>
<td>1.85</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
<td>1.53</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
<td>1.30</td>
</tr>
</tbody>
</table>
Table 5.2. Methodology for plant capital cost and operating cost estimation. (Brown et al., 2013; Peters et al., 2003)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total capital cost</strong></td>
<td>$TIC + IC$</td>
</tr>
<tr>
<td>Total installed cost (TIC)</td>
<td>$\sum \text{unit purchase cost} \times \text{multiplier}$</td>
</tr>
<tr>
<td>Indirect cost (IC)</td>
<td>$0.3 \times TIC$</td>
</tr>
<tr>
<td>Engineering</td>
<td>32%</td>
</tr>
<tr>
<td>Construction</td>
<td>34%</td>
</tr>
<tr>
<td>Legal and contractor fee</td>
<td>23%</td>
</tr>
<tr>
<td><strong>Total operating cost</strong></td>
<td>$FOC + VOC$</td>
</tr>
<tr>
<td>Fix operating cost (FOC)</td>
<td></td>
</tr>
<tr>
<td>Labor</td>
<td>$130% \times \text{Labor payment}$</td>
</tr>
<tr>
<td>Overhead</td>
<td>50% of labor cost</td>
</tr>
<tr>
<td>Maintenance</td>
<td>1.5~10% of unit installed cost</td>
</tr>
<tr>
<td>Insurance and taxes (I&amp;T)</td>
<td>2% of capital cost</td>
</tr>
<tr>
<td>Variable operating cost (VOC)</td>
<td></td>
</tr>
<tr>
<td>Energy cost</td>
<td>Diesel: 4$/gallon</td>
</tr>
<tr>
<td></td>
<td>Hog fuel (MC: 50%_wb): 20 $/t</td>
</tr>
<tr>
<td></td>
<td>Electricity: ~4.5cent/kWh (Georgia Power, GA)</td>
</tr>
<tr>
<td>Oil consumption</td>
<td>15% of fuel consumption, at price 0.53 $/L</td>
</tr>
<tr>
<td>Feedstock cost(^a)</td>
<td>30$/green tonne Pulp wood (The Georgia Forestry Commission: South-wide average)</td>
</tr>
<tr>
<td>Binder</td>
<td>306 $/dry tonne starch (USDA, 2012)</td>
</tr>
</tbody>
</table>

\(^a\) Included the co-product credit for wet biomass residues
Table 5.3. The installed cost and operating parameter assumptions. (PR: production rate; CE: combustion energy; AP: annual production; TIC: total installed cost)

<table>
<thead>
<tr>
<th>Unit equipment</th>
<th>Single equipment Installed cost (k$)</th>
<th>Max. Size (t/h)</th>
<th>utilization (yr)</th>
<th>Energy usage</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Debarker</td>
<td>37.81*(PR^0.7)</td>
<td>N/A</td>
<td>5</td>
<td>0.55 gallon diesel/t</td>
<td>(Polagye et al., 2007)</td>
</tr>
<tr>
<td>Chipper</td>
<td>36.90*(PR^0.7)</td>
<td>N/A</td>
<td>5</td>
<td>0.55 gallon diesel/t</td>
<td>(Polagye et al., 2007)</td>
</tr>
<tr>
<td>Knuckleboom loader</td>
<td>10.95*(PR^0.7)</td>
<td>N/A</td>
<td>10</td>
<td>0.07 gallon diesel/t</td>
<td>(Polagye et al., 2007)</td>
</tr>
<tr>
<td>Solid Burner</td>
<td>36.42*(CE^0.7)</td>
<td>N/A</td>
<td>10</td>
<td></td>
<td>(Polagye et al., 2007)</td>
</tr>
<tr>
<td>Torrefaction reactor</td>
<td>200*PR</td>
<td>N/A</td>
<td>30</td>
<td>6.74 kWh/t and hog fuel</td>
<td>(Pierik &amp; Curvers, 1995; Shah et al., 2012)</td>
</tr>
<tr>
<td>Dryer^a</td>
<td>224.63*(PR^0.6369)</td>
<td>13.44</td>
<td>15</td>
<td>6.74 kWh/t and hog fuel</td>
<td>(Pierik &amp; Curvers, 1995)</td>
</tr>
<tr>
<td>Hammer mill^a</td>
<td>32.796*(pellet PR^0.59)</td>
<td>14.5</td>
<td>10</td>
<td>11.86~224.19 kWh/t</td>
<td>(Zhao, 2011)</td>
</tr>
<tr>
<td>pan granulator</td>
<td>20.032*(PR^0.5664)</td>
<td>N/A</td>
<td>10</td>
<td>(10.931xpan capacity) kW</td>
<td>(Mujumdar, 2006)</td>
</tr>
<tr>
<td>conveyor post-dryer</td>
<td>35*PR (k$)</td>
<td>N/A</td>
<td>20</td>
<td>6.74 kWh/t and hog fuel</td>
<td></td>
</tr>
<tr>
<td>Pellet mill^a</td>
<td>162.6*(PR^0.6369)</td>
<td>6.72</td>
<td>10</td>
<td>(41*Dry loss%+ 29)*2.5 kWh/t</td>
<td>(Campbell, 2007; Li et al., 2012)</td>
</tr>
<tr>
<td>Pellet cooler^a</td>
<td>24.713*(PR^0.5797)</td>
<td>29</td>
<td>15</td>
<td>3.13 kWh/t</td>
<td>(Hoque et al., 2006)</td>
</tr>
<tr>
<td>Screener &amp; shaker^b</td>
<td>15.241*(PR^0.5781)</td>
<td>13.55</td>
<td>10</td>
<td>0.94 kWh/t</td>
<td>(Hoque et al., 2006)</td>
</tr>
<tr>
<td>Silo storage</td>
<td>34 $/m4 (30% AP)</td>
<td>N/A</td>
<td>20</td>
<td></td>
<td>(Chen, 2012)</td>
</tr>
<tr>
<td>Front-end loader</td>
<td>110 per unit</td>
<td>N/A</td>
<td>10</td>
<td>4.1 gallon diesel/h</td>
<td>(Campbell, 2007)</td>
</tr>
<tr>
<td>Miscellaneous equipment</td>
<td>80.54*(PR^0.6)</td>
<td>N/A</td>
<td>10</td>
<td>19.16 kWh/t</td>
<td>(Mani et al., 2006)</td>
</tr>
<tr>
<td>land</td>
<td>1.5 % of TIC</td>
<td>N/A</td>
<td>25</td>
<td></td>
<td>(Peters et al., 2003)</td>
</tr>
</tbody>
</table>

^a The installed cost of these units was estimated by curve fitting of published investment cost data. (Campbell, 2007; GEC, 2006; Hoque et al., 2006; Mani et al., 2006; NEOS, 1995; Polagye et al., 2007; Samson et al., 2000; Thek & Obernberger, 2004; Uasuf & Becker, 2011)
Table 5.4. The employee number assumption in different plant production rate scenarios.

<table>
<thead>
<tr>
<th>Plant Production Rate (t/h)</th>
<th>Pelleting plant</th>
<th>Granulation plant</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Salaried employees</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supervisor</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Finance manager</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Marketer</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Receiving clerk/Admin. asst.</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Labor per shift</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Knuckleboom loader</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Front-end loader</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Dryer/torrefaction unit</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Pellet mill</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Others/ Center control</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>
Table 5.5. The thermal energy balance of drying, torrefaction and post drying system in each scenario.

<table>
<thead>
<tr>
<th></th>
<th>Pellet production</th>
<th></th>
<th></th>
<th>Granule production</th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>RPW</td>
<td>TPW-250</td>
<td>TPW-275</td>
<td>TPW-300</td>
<td>RPW</td>
<td>TPW-250</td>
<td>TPW-275</td>
</tr>
<tr>
<td>Energy required (GJ/t product)</td>
<td>2.21</td>
<td>3.38</td>
<td>4.25</td>
<td>5.04</td>
<td>5.79</td>
<td>6.98</td>
<td>7.25</td>
</tr>
<tr>
<td>Energy loss (GJ/t product)</td>
<td>1.19</td>
<td>1.82</td>
<td>2.29</td>
<td>2.71</td>
<td>2.03</td>
<td>2.64</td>
<td>2.96</td>
</tr>
<tr>
<td>Energy in (GJ/t product)</td>
<td>3.40</td>
<td>5.19</td>
<td>6.54</td>
<td>7.76</td>
<td>7.82</td>
<td>9.62</td>
<td>10.22</td>
</tr>
<tr>
<td>Energy recoverd (GJ/t product)</td>
<td>1.10</td>
<td>3.77</td>
<td>6.01</td>
<td>7.02</td>
<td>1.94</td>
<td>4.90</td>
<td>7.46</td>
</tr>
<tr>
<td>Energy net input (GJ/t product)</td>
<td>2.30</td>
<td>1.42</td>
<td>0.53</td>
<td>0.74</td>
<td>5.88</td>
<td>4.72</td>
<td>2.76</td>
</tr>
<tr>
<td>Bark produced (kg/ t product)</td>
<td>287.83</td>
<td>361.88</td>
<td>447.80</td>
<td>520.87</td>
<td>264.32</td>
<td>332.56</td>
<td>418.85</td>
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<tr>
<td>Bark consumed (kg/ t product)</td>
<td>287.83</td>
<td>184.73</td>
<td>69.10</td>
<td>95.52</td>
<td>264.32</td>
<td>332.56</td>
<td>357.60</td>
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<tr>
<td>Hog fuel consumed (kg/ t product)</td>
<td>10.82</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>498.95</td>
<td>280.36</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Figure 5.1. Schematic process of torrefied and conventional pellet production scenarios (a); torrefied and conventional granule production scenarios.
Figure 5.2. The production thermal energy (a) and electricity energy (b) consumption of granules and pellets in different torrefaction conditions for base case (5t/h). (RG: raw pine wood granules; TG: torrefied pine wood granules; RP: raw pine wood pellets; TP: torrefied pine wood pellets.)
Figure 5.3. The overall production cost of granules and pellets in different torrefaction conditions for base case (5t/h).
Figure 5.4. The raw material, binder, personnel, and unit operations production cost comparison between four scenarios for base case (5t/h).
Figure 5.5. Pellet and granule manufacturing cost vs. production rate.
Figure 5.6. Conventional granule (a) and 300°C torrefied pine wood granule (b) production cost sensitivity analysis.
CHAPTER 6

LIFE CYCLE ASSESSMENT OF TORREFIED PINE WOOD GRANULES
PRODUCTION IN THE SOUTHEASTERN UNITED STATES

Wu, Yifei and Mani, Sudhagar

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ABSTRACT

Torrefaction is a thermal pretreatment of biomass to improve energy density and hygroscopicity. Densification processes such as pelletization and granulation increase the bulk density of biomass in the form of pellets or granules. The objective of this study was to conduct cradle-to-gate inventory analysis and environmental impact assessments of producing torrefied pellets and granules from pine in the Southeast region. The system boundary was comprised of pine tree plantation, logging, transportation, and manufacturing of pellets and granules with a functional unit of one GJ of pellets/granules. Four manufacturing scenarios considered were: conventional pelletization, torrefied pelletization, conventional granulation, and torrefied granulation. Detailed mass and energy balances for each manufacturing scenario was conducted and used for life cycle inventories and impact assessments. The environmental impact of each unit process was also reported. Compared with conventional pellets, 300°C torrefied granules production needed less fossil energy (168.71 MJ/GJ) and had better environmental impact on global warming (12.02 kg CO2 eq), acidification (6.85 mol H+ eq) and respiratory effects (2.32E-02 kg PM10 eq). Meanwhile, starch binder usage was the major reason for negative performance in some other environmental impacts, such as ozone depletion, eutrophication, water intake, and non-carcinogenics. Opportunities likely exist to reduce environmental impact of torrefied biomass granulation in the future by exploring binders with less environmental burden that produce lower moisture content granules for efficient downstream conversion.

Keywords: Torrefaction, Pelletization, Wet agglomeration, Fossil energy, air emission, LCIA,
1. INTRODUCTION

Biomass is an alternative energy resource to produce multitude of fossil fuel counterparts (bioethanol, green diesel, biopellets, biogas) including chemicals and bioproducts. Torrefaction, a thermal pretreatment method, can improve the energy density and hygroscopicity for efficient downstream conversion for biomass. Torrefaction is a process of heating biomass between 200-300°C in absence of oxygen that produces a brown solid fuel containing 80-90% of energy with 60-70% loss of mass compared to that of original biomass (Phanphanich & Mani, 2011). As the energy density of biomass increases, the loss in mass causes low bulk density biomass during torrefaction. Biomass pelletization can produce a dense, dry and easily handled solid fuel for power plant co-firing and residential heating. In 2010, the European Union annual demand for pellet was about 10 million tonnes. The demand is projected to rise to 219 million tonnes in 2020 (Beurskens et al., 2011). Though biomass pretreatment technologies will improve fuel properties and reduce logistical cost, it is still questionable whether incurring additional emissions and energy usage of pellet production can be balanced by those savings from efficient transport, storage and combustion. Life cycle assessment (LCA) was a quantitative method to evaluate the environmental load of a product, process or activity throughout its life cycle (Roy et al., 2009). LCA can be used to compare production scenarios and optimize values of parameters to improve the environmental impact of potential bio-feedstock products. Li et al. (2012b) conducted a life cycle assessment of wheat straw pellet production in the Canadian Prairies. The drying and pelleting process was shown as major environmental burden contributors. Reed et al. (2012) conducted a complete life cycle assessment study on pellet production for
hardwood flooring residues in the Southeastern United States. They showed that the electricity use during pelletization and production of wood residue contributed most of the total environmental impacts. Another wood pellet study (Komata et al., 2010) in Hokkaido, Japan, showed that the production process had the highest \( CO_2 \) emissions; thus the improvement of pelletization production process was very important. Also recent studies (Larsson et al., 2013; Stelte et al., 2011) have reported that torrefied biomass is not suitable for pelletization: torrefied biomass pelletization either required more densification energy or produced lower quality pellets. We developed a novel lignocellulosic biomass granulation technology to replace existing pelleting, and integrated it with torrefaction technology to produce torrefied granules (Wu & Mani, 2013a; Wu & Mani, 2013b). Torrefied pine wood powders were wetted with binder solution and aggregated into granules by tumbling in a pan granulator. Our earlier study demonstrated that granulation was more suitable to produce torrefied biomass and had higher unit capacity and lower electricity consumption than that of pelletization technology. The main objectives of this study were to conduct cradle to gate life cycle inventory assessment and to evaluate and compare the environmental impact assessments of producing densified solid biofuels from pine in the southeastern US.

In this study, pine wood from the Southeastern United States was selected as the biomass to estimate the environmental impact of the pretreatment and densification system. There were four production scenarios in this study: conventional pelletization, torrefaction pelletization, conventional granulation and torrefaction granulation. The life cycle inventory of 1 GJ of pellet/granule product from four scenarios was developed in SimaPro software. The impact of the forestry system (including plantation and harvesting)
and the pretreatment and densification system were investigated. This study systematically evaluated fossil energy usage, air emissions and environmental impact associated with the entire life cycle of torrefied pinewood pellet/granule production.

2. METHODS

2.1. Goal and scope

The goal of this study was to document the cradle-to-gate life cycle inventory and environmental impact assessment of torrefied pine wood pellets and granules production in the southeastern United States. The function unit in all scenarios was defined as 1GJ pellet/granule product. The life cycle assessment was conducted following ISO international standards: ISO 14040~14044 (ISO, 2006; ISO, 1998; ISO, 2000a; ISO, 2000b).

2.2. Scenarios

Two pretreatment technologies were studied: drying and torrefaction, and two densification technologies: pelletization and granulation. To compare the environmental influence of different pretreatment and different densification methods, four different production scenarios were developed in this study: conventional pelletization, torrefied pelletization, conventional granulation and torrefied granulation (Table 6.1). Torrefaction was conducted at three different temperatures (250, 275 & 300 °C) to produce either pellets or granules.

2.3. Pellet production system boundary

The pellet production system comprised of four stages: plantation, harvesting, preprocessing and pelletization. The system boundary was illustrated in Figure 6.1. The plantation stage included the nursery process to produce seedlings, site preparation, and
planting. The fertilization usage in the nursery process and operation in the site preparation process was different in different plantation intensity, which was low density, medium density and high density respectively. Three levels of southern pine plantation intensity (low, medium and high) were considered as defined by Johnson et al. (2005). It was assumed that pine logs were obtained from 37% low intensity, 58% medium intensity and 5% high intensity lands. Only burning was performed to prepare the low intensity site; meanwhile the medium intensity preparation was consist of both burning and shearing. Debris in the forestry was removed by dozer. In high intensity site preparation, shearing and pilling were utilized. In this study, the plantations in all kinds of site were used mechanical plantation method. The planting density was 726 trees per acre and the rotation length was 25 years. Tree harvesting stage had five steps: felling, skidding, delimbing, loading and transportation. Trees were felled and bunched by feller-bunchers and moved by grapple skidders to the landing area where tops and limbs were removed. The logs (>6 inch DBH) were transported from the harvesting area to the plant by truck and the average distance was assumed as 100 km. Diesel fuel and lubricant oil consumption were calculated from literature (Johnson et al., 2005).

After pine wood logs were delivered into plant, the preprocessing stage started with debarking and chipping. In different scenarios, green wood chips (50% wb) should be either dried in rotary drum dryer or torrefied in torrefaction reactor. Bark and purchased hog fuel were combusted in solid fuel burner and then flue gas was used to heat torrefaction reactor or rotary drum dryer. The dried or torrefied wood chips were ground using a commercial scale hammer mill into required size powder. In pelletization stage, pellet mill compress wood powder and extrude pellets using machinery which was driven
by an electric motor which ranged from 40 to 500 HP (Campbell, 2007). After cooling and screening, final product would be stored in silo storage.

### 2.4. Granule production system boundary

The granule production system comprised of four stages: plantation, harvesting, preprocessing and granulation. It shared the similar plantation and harvesting, and preprocessing stages with pellet production system. It was worth mentioning that granulation required pine wood powder with smaller particle size (250~150 micron) than pelletization. A hammer mill screen opening of 1/32 inch was required for granulation powder preparation, while only 1/8 inch screen is enough for preparing pellet mill powder. In the granulation stage, pine wood powder particles were colliding during irregular, stochastic motion in pan granulator; meanwhile 5% solid content binder solution of industrial grade starch was sprayed on it. The binder solution percentage, granule bulk density and binder usage amount (binder to biomass ratio) values were estimated from the author’s bench-scale experiments. The electricity consumption was estimated from the manufacturer’s reported maximum motor power and efficiency from bench scale pan granulator (Zhao, 2011). The flow of wet granules from pan granulator was screened and fine particles would be recycled to granulator. At the end of granulation stage, the post-drying process was required to dry wet granules to low moisture content that was suitable for storage and transportation. A large scale conveyor dryer was used for post-drying in this study.

### 2.5. Hybrid life-cycle inventory analysis

A hybrid Life Cycle Inventory (LCI) model was constructed using both conventional process-based LCI and economic input output (EIO) LCI method. The inventory analysis
was carried out in LCL software platform (SimaPro 7.0) and the input data were shown in Table 6.1. The emission species investigated in the study were generic CO$_2$, fossil CO$_2$, biogenic CO$_2$, fossil CO, biogenic CO, generic CH$_4$, fossil CH$_4$, Particulates, NO$_X$, SO$_2$, SO$_X$, volatile organic compounds, NH$_3$.

Process-based LCI data included energy usage, raw materials, emissions and some other categories. Generic data were collected from literature reviews, equipment specification documents and first principle calculations (Table 5.3). Most unit processes in this study were recorded in strictly process-based LCI. In plantation and harvesting process, the process-based LCI of forestry machineries considered only the main materials and discarding assembly energy consumptions (Fantozzi & Buratti, 2010).

The input-output data from the EIO-LCI model could be used when process data were not accessible. In this case, environmental impact associated with production and routine maintenance of plant manufacturing machineries was evaluated in EIO-LCI sectors: “Farm machinery and equipment manufacturing” and “Commercial and industrial machinery and equipment repair and maintenance” respectively. The cost input for these EIO-LCI models was the producer cost in 2002, which was calculated from corresponding purchaser cost. The producer cost to purchaser price ratios was obtained from 2002 Benchmark Input-Output Account which was developed by U.S. Bureau of Economic Affairs. The ratios were 0.76 and 1.00 in manufacturing sector and maintenance sector respectively. The original purchaser costs of machinery were collected from various literature published from 1995 to 2007, and the annual repair and maintenance costs were estimated at 2~10% of installed cost of associated machinery. Price inflation effects were normalized by using the Chemical Engineering plant cost
index.

\[ \text{Purchaser cost in 2002} = \text{Original purchaser cost} \times \left( \frac{\text{Index value in 2002}}{\text{Index value (published year)}} \right) \]

2.6. Impact assessment

In order to evaluate the potential environmental impact on natural resource and human health, Life Cycle Impact Assessment (LCIA) was conducted as part of this LCA research. According to ISO standard (ISO, 2000a), Classification and Characterization steps were mandatory for a complete LCA study, and Normalization, and Weighting was optional elements. Two American based Impact Assessment Methods were used in this research. The Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) was developed by the U.S. Environmental Protection Agency (EPA), and Building for Environmental and Economic Sustainability (BEES) was developed by the National Institute of Standards and Technology (NIST). All midpoint impact categories in TRACI method and water intake in BEES method were discussed in this study. Besides, the non-renewable fossil energy usage, a characteristic factor of Cumulative Energy Demand (CED) method, was evaluated for each production scenarios.

2.7. Sensitivity analysis

The sensitivity analysis for three production scenarios, the conventional pelleting, the conventional granulation and the 300°C torrefaction granulation, were carried out in order to evaluate the effect of the main factor on the total fossil energy consumption and global warming impact (Figure 6.5). Due to the lack of commercial scale grinding and pelleting data for torrefied biomass, electricity energy consumption had large uncertainty in published works (Larsson et al., 2013; Li et al., 2012a; Pirraglia et al., 2013; Stelte et al., 2011; Stelte et al., 2013). With regarding to the granulation binder usage for each
torrefied wood powder, this study adopted the bench-scale experimental results from author’s study. Forestry production and transportation distance were also based on reasonable assumption. This sensitivity analysis adapted ±15% variance in these factors described above.

3. RESULTS AND DISCUSSIONS

3.1. Fossil Energy consumption

Pine wood granules or pellets were a potential source of renewable bioenergy, but there was certain amount of non-renewable fossil fuel required in production process. Conventional fossil fuel, such as coal, crude oil, and natural gas are consumed mostly in machinery electricity and diesel usage. The fossil energy consumption was calculated in SimaPro using Cumulative Energy Demand (CED) method (insert reference here). Figure 6.2 depicted the relationship between total potential energy in biomass final product and the associated cradle-to-gate fossil usage during pine tree plantation, harvesting and manufacturing pellets or granules. To produce 1 GJ conventional pellets, 12.04, 50.67 and 151.22 MJ fossil fuel were required in plantation, harvesting and in plant manufacturing respectively. Reed et al. (2012) reported the fossil fuel for wood residue pellet manufacturing was 132.94 MJ. Since green pine pulpwood was used as the raw material in this scenario, the extra debarking and chipping unit process, and more hammer mill grinding energy consumption would be the reason for the fossil fuel usage difference in manufacturing. Compared with different scenarios in Figure 6.2, the raw pine wood granulation requires most fossil fuel among all and that of 300°C torrefaction granulation reduces to 168.71MJ. Hammer mill fine grinding and pan granulation process in raw granule production scenario was the major fossil fuel consumer. 300°C torrefaction
pretreatment significantly reduced these two energy consumption value from 131.10 and 57.16 MJ/GJ to 14.20 and 30.73 MJ/GJ respectively, meanwhile increase fossil energy requirements in plantation and harvesting from 57.60 to 77.50 MJ/GJ due to the dry mass loss in torrefaction. In all pelletization scenarios, pellet mill unit was also a major fossil energy consumer, which could be avoided in all granulation scenarios.

3.2. Air emission analysis

Table 6.2 showed the inventory output of major air emission when produce 1 GJ final pellet/granule products in all scenarios. Carbon dioxide, as a major greenhouse gas contributed the most to global warming, generated more from biogenic sources than from fossil sources. Biogenic carbon dioxide emission of granulation scenarios was more than two times of pelletization scenarios emission. The breakdown analysis emission in 300°C torrefaction granulation scenario was revealed in Figure 6.3. From this figure, biogenic carbon dioxide and carbon monoxide were generated from hog fuel or bark combustion in solid burner. Granulation scenarios required more thermal energy in post drying process, so more hog fuel was consumed accompanied with CO₂ emission. The carbon monoxide from biogenic source was much less than that from fossil source. The fossil CO₂ and CO were the mainly from plantation, harvesting and hammer mill grinding. The emission of another common greenhouse gases, methane, could be reduced by torrefaction from 24.79 to 19.98g in pelletization scenarios and from 30.68g to 13.95g in granulation scenarios. Nitrogen dioxide, sulfur dioxide and sulfur oxide emission were directly related with acidification effect. These three emission values of raw pine wood granulation scenario were higher than pelleting scenarios; whereas these emissions form torrefied granule production were decreasing as torrefaction temperature increases up to
300 °C.

### 3.3. Impact analysis

Life cycle global warming potential (GWP) was computed in term of CO$_2$ as the equivalent substance. The results in Table 6.3 shown that 1GJ pellet production generated 14.72kg CO$_{2eq}$ by comparison, Mani et al. (2005) and Magelli et al. (2009) reported 13.56 to 25.43kg CO$_{2eq}$ from 1 GJ pellet (assuming the energy content of pellet to be 17.54MJ/kg). GWP value changes between different scenarios followed the same trends of carbon dioxide emission and methane in Table 6.2. The raw pinewood granulation had the highest GWP value (24.10kg CO$_{2eq}$) and GPW value of 300°C torrefaction granulation (12.02 kg CO$_{2eq}$) was lower than these of all pelleting scenarios. From results in Figure 6.4, GPW of plantation &harvesting, post drying, torrefaction, and starch binder usage in pan granulation were major components of the total GPW. Because acidification and respiratory effects were closely related with some acidifying substance emission like, SO$_2$ and NO$_x$, environmental impacts in both categories followed the same trends of these chemical emissions. The acidification (6.82 mol H$^+$eq) and respiratory effects (2.30E-2 kgPM10 eq) of 300°C torrefied granule production were lower than these of conventional pellets production (8.41 mol H+ eq and 3.47E-2 kg PM10 eq).

From Figure 6.4, the starch binder usage in pan granulator unit operation contributed more 50% total values of the ozone deletion, eutrophication, non-carcinogenics and water intake characteristics in 300°C torrefaction granulation. That was the reason that granulation scenarios (Table 6.3) had significant higher value of those factors than pelletization scenarios. In smog, carcinogenics and ecotoxicity characteristics, pine tree plantation and harvesting were the major contributors, so mass loss in torrefaction might aggravate those two environmental impacts.
3.4. Sensitivity analysis

Results were shown in Figure 6.5, where the output ranges of fossil energy usage and global warming obtained using ±15% variances in five important factors. Since the raw granule production consumed a large amount of grinding energy, the fossil energy consumption and global warming were sensitive to the grinding energy usage level. They were not sensitive to grinding energy usage level in 300°C torrefied granule production. For all three scenarios, 15% variance in forestry production brought a change of approximate 10 MJ in fossil energy usage and at least 0.5 kg CO2 eq in global warming. Besides, the final results in granulation scenarios were proven to be sensitive to binder usage. Transportation distance variance didn’t significantly change the final results.

4. CONCLUSIONS

A cradle to gate life cycle assessment model for producing torrefied pellets and granules were developed and environmental impacts for both pellets and granules were compared. Among different torrefaction temperature conditions, production of 300°C torrefied granule has the lowest fossil energy consumption, air emission and environmental impact. Compared with conventional pellets, 300°C torrefied granules production have lower fossil energy consumption, because the electricity energy intensive pellet mill was replaced by pan granulator and lower grindability of torrefied wood reduced hammer mill electricity energy consumption. In environmental impact level, the 300°C torrefied granule has better performance than conventional pellet in global warming, smog, acidification and respiratory effects. Starch usage is major reason for some shortcoming in environmental impact, such as ozone depletion, eutrophication, water intake, and non-carcinogenics. Generally torrefaction granulation technology for
torrefied biomass can be highly competitive to pelleting technology, and opportunities exist to reduce the environmental impact of binder usage by selecting industry waste binders with less environmental impact.
REFERENCES


Table 6.1. Input data of mass balance and energy consumption per GJ pellet/granule production within the system boundary. (RP: raw pine wood pellets; TP: raw pine wood pellets; TG: torrefied pine wood granules; TG: torrefied pine wood granules)

<table>
<thead>
<tr>
<th>Processes</th>
<th>Inputs</th>
<th>Units</th>
<th>pelleting</th>
<th>granulation</th>
</tr>
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<tr>
<td></td>
<td></td>
<td></td>
<td>RP</td>
<td>TP-250</td>
</tr>
<tr>
<td>Plantation</td>
<td>Water</td>
<td>l</td>
<td>234.15</td>
<td>289.11</td>
</tr>
<tr>
<td></td>
<td>Nitrogen</td>
<td>g</td>
<td>165.30</td>
<td>204.09</td>
</tr>
<tr>
<td></td>
<td>Phosphate</td>
<td>g</td>
<td>28.37</td>
<td>35.02</td>
</tr>
<tr>
<td></td>
<td>Potassium</td>
<td>g</td>
<td>7.11E-5</td>
<td>8.78E-5</td>
</tr>
<tr>
<td></td>
<td>Electricity</td>
<td>kWh</td>
<td>2.16E-5</td>
<td>2.67E-5</td>
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<tr>
<td></td>
<td>Gasoline</td>
<td>l</td>
<td>1.03E-5</td>
<td>1.27E-5</td>
</tr>
<tr>
<td></td>
<td>Diesel</td>
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<td>CO2</td>
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<td>0.27</td>
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<td>Lubricant</td>
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<td></td>
<td>Skidder</td>
<td>g</td>
<td>30.33</td>
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</tr>
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<td>12.29</td>
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<td>Loader</td>
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<td>46.80</td>
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<td>Transportation</td>
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<td>g</td>
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<td>Solid fuel</td>
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<td>5.58E-4</td>
<td>-8.73E-3</td>
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<tr>
<td></td>
<td>maintenance</td>
<td>$</td>
<td>3.20E-2</td>
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<td>Densification</td>
<td>Electricity</td>
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<td>0</td>
</tr>
<tr>
<td></td>
<td>Starch</td>
<td>t</td>
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</table>
Table 6.2. Emissions to air per GJ pellet/granule production from four scenarios.

<table>
<thead>
<tr>
<th>Substance</th>
<th>Unit</th>
<th>Conventional pelletization</th>
<th>Torrefaction pelletization</th>
<th>Conventional granulation</th>
<th>Torrefaction granulation</th>
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<tr>
<td></td>
<td></td>
<td>250°C 275°C 300°C</td>
<td>250°C 275°C 300°C</td>
<td>250°C 275°C 300°C</td>
<td>250°C 275°C 300°C</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>kg</td>
<td>0.22 0.24 0.23</td>
<td>0.21 0.23 0.19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon dioxide, biogenic</td>
<td>kg</td>
<td>18.00 10.52 4.29</td>
<td>45.90 30.87 11.47</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon dioxide, fossil</td>
<td>kg</td>
<td>13.66 12.17 11.27</td>
<td>20.64 13.72 12.24 10.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon monoxide, biogenic</td>
<td>g</td>
<td>7.17 4.18 1.68</td>
<td>18.39 12.39 7.25 4.60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbon monoxide, fossil</td>
<td>g</td>
<td>46.79 48.87 52.56</td>
<td>56.25 49.72 54.48 52.10</td>
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<td></td>
</tr>
<tr>
<td>Methane</td>
<td>g</td>
<td>24.79 21.97</td>
<td>30.68 18.57 16.57 13.95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Methane, fossil</td>
<td>g</td>
<td>2.59 2.67 2.73</td>
<td>9.75 8.23 7.50 6.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Particulates</td>
<td>g</td>
<td>20.60 15.38 11.05</td>
<td>41.49 28.04 19.68 14.35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrogen oxides</td>
<td>g</td>
<td>118.35 114.08 112.34</td>
<td>165.77 130.81 126.19 113.57</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulfur dioxide</td>
<td>g</td>
<td>63.27 52.23 43.40</td>
<td>86.13 45.78 35.33 26.35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sulfur oxides</td>
<td>g</td>
<td>7.01 6.87 7.05</td>
<td>8.31 6.47 6.73 6.29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VOC</td>
<td>g</td>
<td>2.81 2.90 3.07</td>
<td>3.17 2.73 3.00 2.85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ammonia</td>
<td>g</td>
<td>0.45 0.34 0.23</td>
<td>13.34 11.36 9.47 7.02</td>
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<td></td>
</tr>
</tbody>
</table>
Table 6.3. Impact assessment per GJ pellet/granule production from four different scenarios.

<table>
<thead>
<tr>
<th>Impact category</th>
<th>Unit</th>
<th>Conventional pellet</th>
<th>300°C torrefied pellet</th>
<th>Conventional granule</th>
<th>300°C torrefied granule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ozone depletion</td>
<td>kg CFC-11 eq</td>
<td>2.17E-07</td>
<td>2.23E-07</td>
<td>7.77E-07</td>
<td>4.81E-07</td>
</tr>
<tr>
<td>Global warming</td>
<td>kg CO₂ eq</td>
<td>14.72</td>
<td>12.14</td>
<td>24.10</td>
<td>12.02</td>
</tr>
<tr>
<td>Smog</td>
<td>kg O₃ eq</td>
<td>2.97</td>
<td>2.79</td>
<td>4.16</td>
<td>2.81</td>
</tr>
<tr>
<td>Acidification</td>
<td>mol H⁺ eq</td>
<td>8.41</td>
<td>7.09</td>
<td>12.81</td>
<td>6.85</td>
</tr>
<tr>
<td>Eutrophication</td>
<td>kg N eq</td>
<td>1.25E-02</td>
<td>1.42E-02</td>
<td>1.01E-01</td>
<td>6.02E-02</td>
</tr>
<tr>
<td>Carcinogens</td>
<td>CTUh</td>
<td>3.69E-07</td>
<td>4.41E-07</td>
<td>7.32E-07</td>
<td>6.06E-07</td>
</tr>
<tr>
<td>Non carcinogenic</td>
<td>CTUh</td>
<td>3.98E-06</td>
<td>2.17E-06</td>
<td>1.52E-05</td>
<td>6.85E-06</td>
</tr>
<tr>
<td>Respiratory effects</td>
<td>kg PM10 eq</td>
<td>3.47E-02</td>
<td>1.81E-02</td>
<td>6.94E-02</td>
<td>2.32E-02</td>
</tr>
<tr>
<td>Ecotoxicity</td>
<td>CTUe</td>
<td>22.83</td>
<td>23.25</td>
<td>44.43</td>
<td>30.96</td>
</tr>
<tr>
<td>Water intake (BEES)</td>
<td>litter</td>
<td>1853.00</td>
<td>2401.12</td>
<td>10044.12</td>
<td>6748.20</td>
</tr>
</tbody>
</table>

Methods: TRACI method and BEES method: Water intake
Figure 6.1. Schematic process of pellet and granule production system.
Figure 6.2. Breakdown fossil energy consumption per GJ pellet/granule production for major processes from all scenarios. (RG: raw pine wood granules; TG: torrefied pine wood granules; RP: raw pine wood pellets; TP: torrefied pine wood pellets)
Figure 6.3. Contribution to air emissions of each unites process in 300°C torrefaction granulation scenarios.
Methods: TRACI method and BEES method: Water intake

Figure 6.4. Environmental impact of unit operation of producing 300°C torrefied granules.
Figure 6.5. Conventional pelleting, conventional granulation and 300°C torrefaction granulation production sensitivity analysis of fossil energy consumption (MJ/GJ product) [(a), (b) and (c)] and global warming (kg CO2 eq/GJ product) [(d), (e) and (f)].
CHAPTER 7
CONCLUSIONS

Advanced preprocessing of biomass is required to not only increase energy density, but also improve bulk flow and handling properties of biomass. In this study, southern pine wood chips were torrefied or thermally treated at 250, 275 & 300 °C to increase energy density and to improve other fuel properties. The torrefied pine wood chips had lower grinding energy consumption, higher grinding speed and finer product particle size. Raw and torrefied pine wood powder was successfully densified by granulation, using 35% lignosulphonate solution as liquid binder. In saturated granulation condition, the starch granule required binder percentage 8.5%~6.1% and lignosulphonate granule had binder percentage 40.81~29.57%. High temperature torrefaction conditions (275 and 300 °C) were recommended for pine granulation to reduce binder usage and generate higher density granules. Pine wood granules were not as densified as regular wood pellet, but their physical properties had already met regular logistics requirements.

Starch at 5% (wt/wt) concentration was tested to granulate torrefied powders at three different residence times and three binder usage levels. Increasing the granulation residence time of torrefied pine wood at 300 °C torrefaction conditions proved to significantly improve granule yield and granule properties. Compared to lignosulphonate, starch binder reduced the granule binder percentage by 80%; meanwhile, bulk density and hardness of torrefied granules were sufficient for regular logistics.
Techno-economic analysis of large-scale torrefied granule production study concluded that granules production had lower densification and personnel costs as compared to that of pellet production. Compared with conventional pellets, raw pine wood granules had higher production cost on energy basis; whereas the granulation with 300 °C torrefied biomass had slightly lower production cost, due to low binder requirements and reduced grinding and post drying energy costs.

A cradle-to-gate life cycle assessment of torrefied pine wood granule production in the Southeast region of US was conducted to evaluate energy and environmental impacts. It was observed that 300°C torrefied granules production scenario had lower fossil energy consumption, air emission and environmental impacts than that of conventional pellet. Starch usage had a major influence on higher ozone depletion, eutrophication, water intake, and Non-carcinogenic impact values compared to that of pellets.

Future work can be focused on optimizing granulation parameters and finding low cost binders for improved granule properties. Pilot scale testing of granulation technology may be critical to evaluate commercial potential of this technology to evaluate economic and environmental benefits. Integration of pretreatment techniques with granulation and tailor-made biomass formulation for specific conversion application should be studied further to reduce overall biofuels production cost. It is expected that a fully developed commercial granulation technology can be relatively cheap compared to that of pelleting technology.
Appendix A

Mechanics of wet granulation

Generally, the tensile strength was contributed by the resultant force of static surface tension force, dynamic viscous forces and inter-particle friction force. These three forces are complex inter-related and rely on formulation property and granulation condition. The static surface tension is the only conservative forces among them and it always general the normal force to pull particles together. Viscous and friction force resist both compacting and breaking between particles which are dissipative forces[2].

1. **Static surface tension force**

   The static surface tension force has three components: the surface tension force acting on the surface of liquid bridge, the capillary suction pressure difference between atmosphere and liquid bridge inside, and the buoyancy force of submersion parts of spheres in the liquid bridge (Figure A1). However, study shows that the buoyance force is negligible for small size particle (<1mm)[3].

   The rest two forces have been extensively studied by previous workers. The major debates in analytically solution of capillary pressure term and surface tension form is about the position of liquid bridge in which should the forces been evaluated. Hotta, et al. (1974) [4]’s work support that the surface tension and capillary terms should be evaluated at the contact line of one of the sphere, which is called “boundary” method. However, Lian, et al. (1993) [5] found that another method called “gorge” method gave a better
estimation. In gorge method both force are evaluated at the mid-point of liquid bridge which has the smallest diameter.

Figure A1. Schematic of a pendular liquid bridge between two non-equal sized spheres.

\[ F_{\text{boundary}} = \pi \Delta P_{\text{cap}} a_1^2 \sin^2 \beta_1 + 2\pi a_1 \sin \beta_1 \sin (\beta_1 + \theta) \]  

(1)

\[ F_{\text{gorge}} = \pi \Delta P_{\text{cap}} r_2^2 + 2\pi r_2 \gamma \]  

(2)

A widely quoted model is based on Rumpf (1962) [1]’s classic work to predicting the tensile static strength of a wet granule. The tensile strength is given by:

\[ \sigma_t = SC \frac{1 - \varepsilon \gamma_{LV} \cos \theta}{\varepsilon d_p} \]  

(3)

Where C=6 is the material constant for sphere, S is the liquid pore saturation level, \( \varepsilon \) is the intragranular porosity, \( \gamma_{LV} \) is the liquid surface tension and \( \theta \) is the liquid-solid contact angle. \( d_p \) is the harmonic mean particle diameter, and for powder particle calculation, the surface mean particle size, \( x_{32} \) is the best appropriate value[6]. Eqs.(3) did
a good job on predicting granule strength’s proportional trend with liquid surface tension, saturation, particle size as well as the negative correlation with porosity[2]; however, the theory is usually incorrect quantitatively for the effect of crack growth along pore structures. Besides the ultimate tensile strength, the critical strain before failure also generally increases with increasing binder content [7].

2. Dynamic viscous forces

The dynamic viscous force between two sphere surfaces can be approximated by equation(4) and also verified by experiments [8, 9].

\[
F_v = \frac{3\pi \mu r^2}{2h} \frac{dh}{dt}
\]  

(4)

Practically, the dynamic viscous force for sufficiently small separation distance is derived by Goldman, et al. (1967) [10]:

\[
F_v = 6\pi \mu vr \left[ \frac{8}{15} \ln \left( \frac{r}{2h} \right) + 0.9588 \right]
\]  

(5)

Where \( r \) the harmonic mean particle radius, \( v \) is the relative velocity of the two spheres, \( \mu \) is the viscosity value and \( 2h \) is the gap distance between two spheres. Unlike equation(4), the equation (5) has not fully verified by experiments.

3. Inter-particle friction force

The friction force can be activated by normal force generated by liquid bridge. A simple model of inter-particle friction force inside granule had proposed in terms of the Coulombic relationship[6]:

\[
\tau_f = \mu_f \sigma_n + c
\]  

(6)
Where \( \tau_f \) and \( \sigma_n \), respectively, are the macroscopic shear stress and normal stress at failure. \( c \), the cohesively represent the shear strength which is not related with normal load. \( \mu_f \) is the coefficient of internal friction. Increasing binder content will reduce \( \mu_f \) as the lubrication effect.

4. The domination relationship

The relative importance between dynamic viscous force and static surface tension force was relying on the viscosity value of binder solution and surface tension. For water bridge[11, 12], the capillary force is more important, but for normal industrially binder solution bridge, the viscous force is dominate over capillary force by several orders of magnitude [8, 9]. The capillary number, \( Ca = \mu \dot{\varepsilon} d_p / \gamma_{LV} \) is used to make decision where \( \dot{\varepsilon} \) is the strain rate. If \( Ca < 10^{-3} \), viscous force is negligible, but became dominant for \( Ca > 1 \)[9]. In Iveson, Beathe and Page (2002) [6]’s work, based on average bulk strain rate of pellet, \( Ca = 10^{-4} \) is the transition between static dominated and viscous-dominated granule mechanical property. In granulation modeling context, this \( Ca \) criteria value is more meaningful than Ennis, Li, Gabriel I and Robert (1990) [9]’s from single liquid bridge.

The friction force was not generally considered as major contributor of granule strength property, so increasing liquid content will strengthen the granule by dominating liquid bridge effect. However, Kristensen, et al. (1985) [13] found that the very fine powder’s friction force can dominate the granule strength in their study. In that case, increasing liquid content will decrease the granule friction by acting as lubricant and then reduce the granule strength.
References


