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Techno-economic and environmental evaluation of biomass dryer

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Abstract

The pros and cons of various types of biomass dryers have been documented in this paper. Using dry biomass significantly reduces the cost of handling, transportation and pyrolysis. The main choices for drying biomass are rotary dryers, flash dryers, stationery bed dryers and fluidised bed dryers. The drying medium can be hot air, hot air mixed with steam, and/or superheated steam. A typical example for wood chip drying using a financial model is described, including the environmental performance. The energy requirements and greenhouse gas emissions have been estimated for drying biomass. From this study, it is evident that increasing temperature will decrease drying time and increase throughput but not necessarily decrease the drying cost. This is due to higher energy use and higher cost of capital inputs such as loading/unloading and heat plant. Thus, low drying temperature can be used if throughput is not a key issue for an operation. The global warming potential of the biomass drying process 9.2 kg CO_2-e/t of oven-dry biomass. This assumes that wood waste is used as fuel and drying is on a moving belt dryer. If this dry biomass is used in a power station as fuel for steam boiler, there is a significant reduction potential of CO_2 emission from a typical black coal-fired power plant due to fuel switching. This assumes that trees are planted to produce this biomass sustainably. Environmental impacts of any dryer type should be considered for selection in addition to its traditional techno-economic performance.

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Keywords: Biomass; drying; energy footprint; greenhouse gas; carbon footprint.

1. Introduction

Biomass drying is an inevitable part of overall value chain of bioenergy. With reference to reduction of CO_2 emission, the biomass has been considered as one of the most promising future energy sources [1]. Several million tonnes of biomass such as forestry harvesting residues, wood chips, sawdust, sugarcane bagasse, and agricultural residues from grain and fruit processing [2] are available from various regions of Australia. A potentially important product from this biomass is charcoal or biochar. In metallurgical industries, particularly in iron and steel making, the application of charcoal is very promising to reduce net CO_2 emissions. Whether the product from biomass is heat, electricity, transport fuel or bio-carbon, the preparation of wet feedstock for the handling, transport, and storage are the important steps throughout this utilisation chain. This has often been ignored as the use of dry biomass is assumed in most research studies. However, biomass typically has high moisture content (i.e. 50 to 100% dry-weight basis or 0.5 to 1 kg water per kg of oven-dry biomass). The typical energy density (i.e. calorific value) of biomass doubles (e.g. from 8 MJ/kg to 20 MJ/kg for wood) with reduction in moisture content. In order to increase the energy efficiency, improve the energy quality, and reduce emissions in the energy conversion, drying of biomass to the required moisture content is important in the development of the alternative energy systems. In a boiler, the energy efficiency can be increased by 5–15% with the increased combustion temperature and by using dried instead of wet biomass and the flue gas temperature can be reduced [3]. In gasification and pyrolysis, biomass needs to be dried to 10%, to reduce the water content in the energy products, be it the charcoal or biocrude.

Although a review on biomass drying was undertaken about a decade ago [4], research into drying and processing of biomass is burgeoning [5, 6, 7]. Research into gasification of wood for combined heat and power and modelling of biomass drying research is also underway [3, 8]. There is a need for techno-economic and environmental assessment of commercial

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drying and processing technology for biomass feedstock to support this research effort. In this paper, the techno-economics of drying technologies intended to prepare biomass for char making for use in iron and steel industry are assessed. Information about drying technologies for biomass (e.g. wood chips and sawdust) was collected from the open literature. A “gate to gate” life cycle assessment (LCA) results of wood chip drying have also been reported.

2. Methodology

In the open literature, information available about various dryers has been reviewed. Data collected from the literature was used to construct a financial model. This financial model has been used to assess the techno-economics of various types of dryers. In addition, theoretical energy requirements have been estimated for biomass drying with assumed specifications given here. The energy data has been used to undertake life cycle assessment of the biomass drying process. For techno-economic evaluation, the main assumptions are shown in Table 1. Drying times and thermal energy usage have been predicted from a modified drying model based on heat and mass transfer principles [9]. Thermal and electrical energy prices have been used as found from industrial sources. Labour, insurance, capital maintenance, capital insurance are assumed from standard factors as used in other CSIRO techno-economic evaluation studies [10]. All the costs are in US currency unless stated otherwise. National Greenhouse Accounts (NGA) factors and methods have been used to estimate CO_2 equivalent emission [11].

Table 1: Main assumptions for techno-economic evaluation

Inputs	Values	Unit
Wood species	Radiata pine (*Pinus radiata*)	Unit
Woody biomass particle size	5	mm
Initial moisture content (oven-dry basis)	50	%
Final moisture content (oven-dry basis)	10	%
Air-flow around the material	0.2	m/s
Relative humidity	5	%
Drying temperature	50-200	°C
Dryer type	Conventional hot-air based industrial dryer	
Estimated dryer total cost including installation	6,600,000	US$ (Y 2010)

The main selected environmental impact categories for earlier LCA studies at CSIRO were gross energy requirement (GER) which is used to estimate global warming potential (GWP) or greenhouse gas emissions expressed as CO_2 equivalent or CO_2-e [12]. GWP was calculated and reported based on this estimated GER.

3. Results and discussion

3.1. General features of the drying process

Some distinguishing features of the drying unit operation are the variation in the material size and shape, variety of drying media used and the large range of drying times [13]. This is why, there are over 400 different types of dryers reported in the literature and over 100 distinct types of dryers are commonly available. The essential mechanisms involved with biomass drying are diffusion of bound moisture and bulk water mass transfer which depends on the applied temperature. The water vapour is carried away by forced or natural air flow in the dryer. Drying is a coupled heat and mass transfer process. This can either be enhanced or decreased depending the conditions employed surrounding the material to be dried. However, the radiant and conduction heat from the dryer wall can be significant in some situations. The selection of a dryer is rather complex since several choices can exist and the final decision depends on numerous criteria. It is also better to focus on the whole drying system (heating system, any pre or post-drying processes or treatment) rather than just the dryer itself. Computer-aided decision making software systems have been developed (e.g. DrySel software by ASPEN Tech Process Tools [14]) to choose appropriate dryers for a variety of products. However, product and feed-material specific dryer selection still needs some sound judgments. The main three requirements of a dryer are that the supply of heat (either with hot air or in mixture with steam), a carrier to remove the water evaporated from the material during drying, and the exposure of the wet surface to the drying medium by agitation or other means.

3.2. Dryers for biomass

There are several dryers currently available for biomass. These are grouped in various categories based on the handling of particles in terms of size, uniformity, the mode of heating, and the capital and operating costs. The biomass particle can be heterogeneous in terms of weight, shape and density. Forestry residues are a mixture of woody and foliage components of trees with a variety of shapes, sizes, density and complexity in nature for handling and processing. The first step can be the size reduction and sorting in at least three bins based on the density and shape.

3.3. Description of dryers

The descriptions of fluidised bed drying, rotary drum, flash dryer, fixed bed, solar and ambient air drying are given below. Textbooks cover many general aspects of fluidised bed drying [15]. Proper fluidised bed drying occurs after fluidising in dense fluid rather than in dilute fluid (which occurs with pneumatic flash drying). The important considerations are bed height and the velocity of air (e.g. operating superficial) at the chosen temperature as this dictates energy requirement. Fluidised bed drying can be batch or in continuous mode. Additional key variables are flow of the materials (kg/m^2h) and hold up (kg/m^2) in the furnace.

Rotary drum dryers are a common dryer type for larger woody biomass material such as wood chip for making particle board. The dryer consists of a cylindrical shell, inclined at a small degree to the horizontal (10-30% slope or 0.1 to 0.2 m/m) and rotating at about 1 to 10 rpm. The flue gas or hot gas is directly supplied to the drum which is rotated mechanically by an electric motor. The general temperature employed is around 200°C but should not be above 250°C.

Flash drying is also called fluidising and drying in dilute fluid. The finer particles are flown through a very long steel tube (more than 100 m in length and 0.3 to 0.5 m in diameter). Drying load for high capacity modern dryers should be at least 20 tonnes of water evaporated per hour [16]. A stream of very hot air at high flow velocity (over 16 m/s) is passed through the tube. The air sucks the particles and exposes particles to the drying medium. This is usually done in a single or two stages. The typical residence time for each particle is only a few seconds (3-5 s) in the tube.

Bed drying is a biomass layer that is supported on a perforated belt which can either be stationery base or on a moving belt. Hot air is passed through the bed. The particles do not fluidise and thus do not require higher air flows. The depth of bed is generally recommended to be 0.4 to 0.6 m. Experimental drying tests reported [7] that the drying time would be around five hours for sawdust and ten hours for wood chips in fixed bed drying with moderate temperature (from 40 to 70°C) and low air velocity (0.2 to 1 m/s). The Bruks Klockner Wood Technology (equipment manufacturing company) based in Germany has released a commercial unit of bed dryer for sawdust, bark and woodchip [17]. The operating temperature is 80-110°C over the bed. An infeed auger spreads the material evenly across the dryer’s entire width. The hot air passes through the slowly advancing moving bed from below through the perforated bottom plates. The moist air is discharged outside by axial fans. The required estimated thermal power for a unit with 75 m^2 bed area is about 2.6 MW. The average outfeed capacity for such a unit is 2 tonnes dry product per hour if the moisture content is reduced from an initial 60% to 10% (wet-basis).

Over the last few decades, much research and development has been conducted into the use of solar drying [18]. Large rectangular trays with coarse mesh or perforated plate can be used for biomass drying with some other necessary modifications of the solar timber kiln.

Drying under the shed (barn drying) or in the open sun (in a heap) is common ambient air drying using atmospheric heat. The ground should be made level, preferably with an impervious lining or concrete paving with slight slope and with a good exposure to passing wind and good drainage. The heap needs to be mixed up together every now and then.

3.4. Techno-Economic evaluation of biomass drying

Drying times and thermal energy consumption were estimated using biomass drying models based on original wood drying models [9]. Figure 1 shows typical drying time and corresponding thermal energy requirement for a tonne of dry product at various temperatures. Figure 2 shows the throughput increase for an increase in temperature and resulting operating cost. The drying time is inversely proportional to temperature as expected provided other assumptions remain same. However, the estimated theoretical thermal energy requirement is expected to increase with higher drying temperature as shown in Fig. 1. Since the drying time is expected to reduce, throughput will increase as shown in Fig. 2.

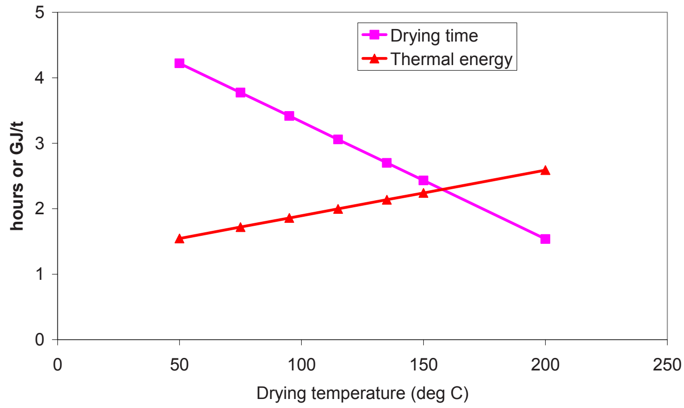

Fig. 1. Drying time and gross thermal energy requirement as function drying temperature.

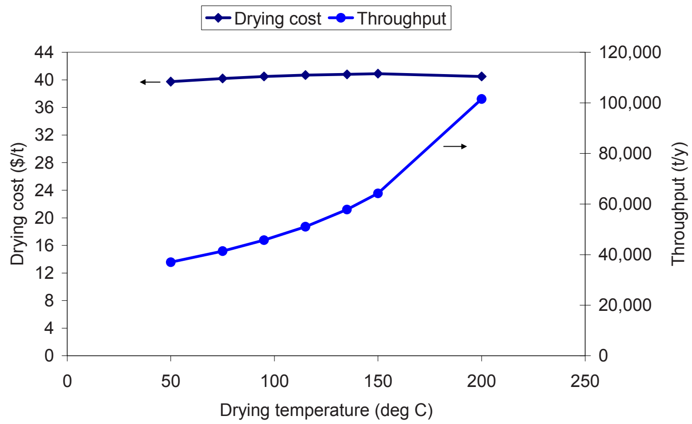

Fig. 2. Throughput and drying cost as a function drying temperature.

Although the throughput increase should decrease the cost per unit dry product, this is not straightforward for two main reasons. Firstly, increasing throughput will require increase in the capital items due to handling and processing of more materials. The capital cost for a new throughput can be estimated using equations found in the literature [19]. A power law equation (Eq 1) is commonly used to scale plant and equipment costs with changes in throughput or capacity.

$$\text{New plant cost} = (\text{New capacity/base capacity})^{0.65} \quad (1)$$

An exponent value of 0.60 – 0.65 is widely used for this purpose for most equipment [19]. Thus with the increase in throughput within a certain range, the capital cost is expected to increase with its maintenance and depreciation. This capital includes dryers and necessary feeding/unloading infrastructure including heat generation system (i.e. heat plant). Secondly, increasing temperature is associated with increase in energy consumption. Thus, the operating utility cost (i.e. for thermal energy) is expected to increase. However, since more materials are processed, there is no significant overall increase in drying costs. From this assessment, it is evident that increasing temperature will decrease drying time and increase throughput but not necessarily the drying cost. The operating cost was predicted to be around $40/t dry product from the financial model used in this paper.

A company based in Germany called Barr-Rosin under the Gesellschaft für Entstaubungsanlagen (GEA) Group of Companies has developed a commercial drying system for biomass such as sawdust and wood chips using superheated steam. The capital cost of this dryer unit is AU$15 M for a 20 tonne/h evaporation load reported in Barr-Rosin brochure 2009 [17]. The operating cost in Europe was estimated to be around AU$31/tonne of water evaporated. Independent calculations for this paper from the re-constructed financial model based on Barr-Rosin data found the operating cost was AU$35/t dry product or AU$54/t water evaporated. In terms of cheaper drying, ambient air and solar drying can be considered where throughput, control and dry product quality requirements are not so stringent. The likely cost of solar drying would be around AU$15/tonne of wet biomass as was quoted by an equipment supplier. This translates to about

AU$47/tonne of water evaporated (2010). Typical high temperature wood drying cost is around AU$50/t of wood (industry visit).

3.5. Energy and CO_2 emission from biomass drying

Drying thermal energy has been calculated based on 1.64 GJ/t of water removed from biomass at 95°C, as predicted by the drying model. About 0.68 t of water needs to be removed to produce a tonne of oven-dry biomass, if the initial moisture content is 68% (dry-basis). The thermal energy requirement was calculated to be 1.12 GJ/t oven-dry biomass. Drying thermal energy is assumed to be sourced from burning woody waste with 85% boiler efficiency. For obtaining 1.32 GJ thermal energy, 81 kg of wood waste is used as fuel. Wood has specific energy of 16.2 GJ/t. The emission factor for wood combustion is calculated to be 20.7 kg CO_2-e/t dry wood [11]. Thus emission from drying thermal energy using waste wood as a fuel is 1.69 kg CO_2-e/t of oven-dry biomass. Similarly, the factors can be estimated based on other fuels used for energy in drying.

Dryer electrical energy has been estimated based on the assumption that two motors at 10 kW power are required for a rotary drum dryer with 4 t/h drying capacity (industry visit). The electrical energy is calculated to be 5 kWh/t of raw biomass. This is equal to 4.5 kg CO_2-e/t of biomass with black-coal based electricity emission factor. According to NGA factor, black-coal based electricity has 0.9 kg CO_2-e/kWh electricity. This is equal to 7.6 kg CO_2-e/t oven-dry biomass since 1.68 tonnes of biomass are processed to produce 1 tonne oven-dry biomass. Thus total CO_2 emission from drying using both thermal and electrical energy is 9.3 kg/t of oven-dry biomass. The specific GHG emission for dry product can be used to estimate the GHG emission per year of a typical drying plant. The GHG footprint of a typical drying plant with 500,000 t/y capacity can vary for various fuel types. The estimated emission from the dryer is 4,643 t CO_2-e/year for wood-waste based fuel. These emissions are 4,788 t for bagasse, 7226 t for charcoal, 36,617 t for natural gas and 62,060 t CO_2-e/y for black coal based fuel source.

A hypothetical scenario can be assessed here. If this plant produces dry wood chip for electrical power generation, there is a potential reduction of CO_2 emission from a power plant compared with a coal-fired power plant of the same capacity. This is based on the assumption that wood is produced sustainably using plantation rotation in perpetuity. The above mentioned drying plant can supply dry fuel for a 80 MWe power plant per year. The CO_2 emission reduction potential is highest if biomass based fuel is used rather fossil carbon such as black coal for the source of thermal energy for the dryer. This assessment shows that there is a potential emission reduction of about 0.6 Mt of CO_2 compared with that from a typical coal-fired power plant of this size. With the introduction of carbon tax, this is about AU$13.8 M tax savings for the power plant assuming a $23/t CO_2-e. The carbon footprint for biomass drying is 0.8% of the total emission from this power plant. If this dry wood is used for this power station, there is a significant reduction potential of CO_2 emission from this black coal-fired power plant.

3.6. Other environmental aspects of biomass drying

The main issues in biomass drying would be energy efficiency, environmental impacts, risk of fire, and costs. Because biomass is combustible, with an auto-ignition temperature of 260–288°C, the risk of fire needs particular attention. The environmental impact with biomass drying is another issue that needs to be considered carefully. The emission of resins and other organic acids can cause ‘‘blue haze’’, a common phenomenon due to the condensation of the chemical components of biomass. Unregulated and uncontrolled emissions of nitrogen oxide (NOx), formaldehyde (HCHO), and particulate matters can also damage the local environment. Generally drying temperature for woody biomass is recommended below 150°C to avoid emission of the wood chemical components. Short drying period of up to 200°C can be considered, however, above 250°C wood chemical components will breakdown, degrade and will be likely to emit blue haze.

4. Conclusions

Using dry biomass to produce energy for dryers has significant advantages as the handling, transportation and pyrolysis process reduces the cost. Three main choices for drying biomass are rotary dryers, flash dryers and fluidised bed dryers. The drying medium can be pure hot air, hot air with steam, and pure superheated steam. From this study, it is evident that increasing temperature will decrease drying time and increase throughput but not necessarily decrease the drying cost due to higher energy use and part of capital inputs such as loading/unloading and heat plant. Thus low drying temperature can be used if throughput is not a key issue for an operation. The total global warming potential of biomass drying process as expressed in CO_2 equivalent units is 9.3 kg/t of oven-dry biomass using dry wood waste as fuel for a rotary drum dryer. If this dry wood is used for a power station, there is a significant reduction potential of CO_2 emission compared with that from a typical black coal-fired power plant. This assumes that trees are planted to produce this biomass sustainably. Environmental impacts of any dryer type should be considered for selection. This is to determine energy requirement and efficiency and the net gain of energy in the biomass after drying. The other important factor is the temperatures, since at much higher temperature (above 300°C) the emissions to the air are likely to be under scrutiny by the regulatory authorities.

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