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An ASABE Meeting Presentation

Paper Number: 1009376

Torrefaction of Cellulosic Biomass Upgrading – Energy and Cost Model

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Written for presentation at the
2010 ASABE Annual International Meeting
Sponsored by ASABE
David L. Lawrence Convention Center
Pittsburgh, Pennsylvania
June 20 – June 23, 2010

Abstract. *The upgrading technology like torrefaction can convert biomass from a highly variable low density feedstock into a consistent high-energy-density commodity, which substantially reduce the production cost. The goal of this study was to quantify torrefaction as a transformative upgrading technology to break current cellulosic feedstock production cost barriers delivered to biorefinery. A robust and expanded torrefaction process simulation model having the capability to quantify biomass torrefaction energy and cost components was developed in Matlab Simulink. Simulation tests were carried out to analyze sensitivity of torrefied biomass energy and production cost scenarios in response to moisture content of corn stover using model key parameters. Torrefaction temperature at critical level is an important requirement for auto-thermal operation of torrefaction process, which can greatly reduce cost of energy requirement and also volatile waste stream. The process can generally be operated as auto-thermal at the temperature 240 ^{0}C and above depending upon moisture content of corn stover. For higher torrefaction temperatures of 240, 260, 280, and 300 ^{0}C, the rate of increase in cost is gradually linear up to 10, 30, 40, and 50 % moisture content respectively, where torrefaction energy requirement can be met by flue gas energy until this moisture content and above which the operation requires external energy supply (auto thermal operation). For a typical 30 % moisture content of corn stover the normalized net energy ratio is around 0.86 at 240 ^{0}C. Torrefaction upgrading should be* *considered over a minimum 4-month operational period in order to begin minimize production cost. The modeling approach demonstrated in this study may be extended to cost effective and quality enhancing pretreatment of a broad spectrum of other biomass feedstocks and thereby create opportunities in a variety of biorefineries ranging from cellulosic bio-coal to ethanol.*

Keywords. Biomass upgrading, torrefaction energy, production cost, cellulosic feedstock, biomass moisture, simulation model, torrefaction temperature

Introduction

The growing need for alternatives to conventional-based fuels has emerged as one of the nation's most urgent priorities to ensure a sustainable supply for the future. Reducing dependence on traditional fuel sources and lessening environmental impacts are important to the America's future economic growth and competitiveness. Biomass has become an attractive fuel recently because of its environmental benefits and the fact that it is made from renewable sources. Biomass derived from agricultural crop residues and energy crops can play an important role in the area of biofuel because of its sustainable, abundant source, and neutral or even negative CO_2 footprint. However, high moisture content, high bulk volume, and relatively low calorific value of raw biomass make it instable to store and expensive to transport. Other drawbacks of raw biomass are that greater loads are required to produce equivalent amount of energy (as coal) and difficulty in grinding into fine particles for co-firing with coal in thermal power stations.

The cost of biomass feedstock and processing accounts for 60 to 75% of the total cost of biofuel. Hence engineered solutions for feedstock production and supply logistics are very important for reducing the cost of biofuel. The upgrading technology like torrefaction that convert biomass from a highly-variable low density feedstock into a consistent high-energy-density commodity can serve as transformative technologies to break these current production barriers and substantially reduce the production cost. Torrefaction process can not only remove moisture from biomass but also enhance its energy density and other physico-chemical properties desirable for optimized logistics and storage stability. Torrefaction is basically used as a pre-treatment technology for upgrading biomass. Torrefaction is a process, which converts raw biomass into a high energy density with reduced energy requirement in grinding, which has a potential to address problems associated with physical properties of biomass feedstock.

Quality and consistency of stored biomass is highly variable. The torrefaction can be considered as one of the best methods to improve: grindability, calorific value, hydrophobicity, leechability, and the energy density of biomass properties (Bioenergy, 2000; Bergman et al, 2005; Prins, 2005). Increased biomass bulk density and flowability are the requirements for optimized logistics and storage infrastructure. It provides stability and hydrophobic nature of biomass for longer storage, which is essential for year round supply of feedstock to bio-refinery. It reduced elasticity of biomass, which helps in the densification. Reduced moisture content of biomass is the most desirable property with respect to process energy efficiency in thermal energy applications. Grinding into fine particles is a requirement for co-firing with coal in thermal power stations. Torrefaction can also improve grindability and combustible properties of biomass with high calorific fuel. This technology is considered to be a pre-treatment technology to make biomass more suitable for co-firing, transportability, and storability (Bergman et al, 2005, Bioenergy, 2000). These are most desirable factors responsible for determining quality of cellulosic feedstock.

Cost and energy analysis models can be considered as an effective tool in analyzing the economical and sustainable production of biomass based feedstock. No study has been conducted on simulation modeling approach using an expanded torrefaction process model to quantify production cost scenarios of torrefied biomass in response to key model parameters. The objectives of this study were to: (1) develop an expended torrefaction process simulation model to quantify torrefaction energy and cost components, and (2) analyze sensitivity of torrefaction energy and cost with respect to biomass moisture.

Materials and Methods

Concept of torrefaction

Torrefaction process can be referred under different synonyms viz., high temperature drying, roasting, pre pyrolysis, wood browning, mild thermal treatment, slow- and mild pyrolysis, and wood cooking (Bergman et al, 2005; Uslu et al, 2008). Traditionally, torrefaction is a thermal process operated at 200 ^{0}C to 300 ^{0}C carried out under atmospheric conditions and in absence of oxygen at typically less than 30 min. reaction time. Under these conditions, properties of biomass are improved through limited devolatization. (Bergman et al, 2005). A wide range of biomass feedstock can be upgraded with high-energy efficiency by means of torrefaction (Bergman et al, 2005). The torrefied biomass produced under different torrefaction condition (temperature and reaction time) leads to difference in material properties in terms of hydrophobicity, energy density, grindability, flowability characteristics.

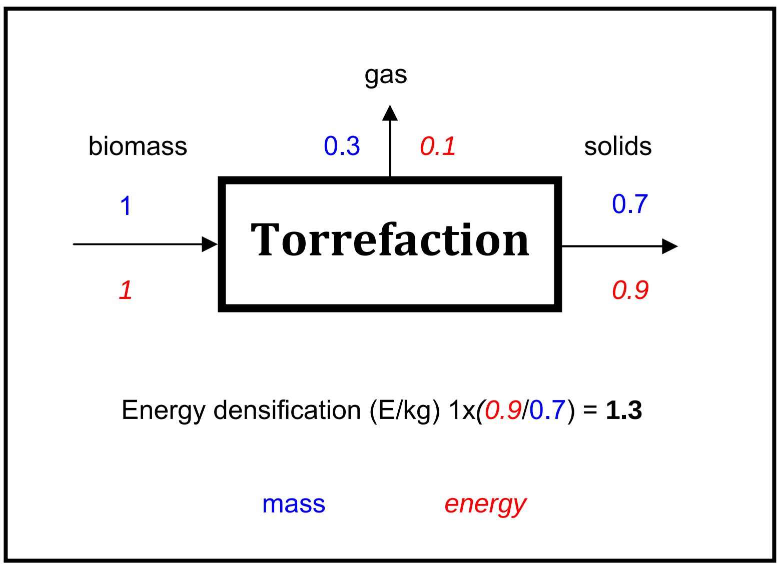

Fig.1. Energy densification in torrefaction (Bergman et al, 2005)

Typically, in the process of torrefaction, around 70 % of the mass containing the 90 % of the initial energy is retained as solid product. Around 30 % of the mass containing only 10 % of energy content of the biomass is converted into torrefaction gases. Hence, an energy densification by a factor of 1.3 on mass basis can be achieved (Uslu et al 2008; Bergman et al, 2005). During torrefaction, biomass loses relatively more oxygen and hydrogen compared to carbon. Subsequently, the calorific value of the product increases (Uslu et al, 2008).

Model concept

Net energy (HHV as fired) of raw wet feedstock

The first part of the model estimates energy required to dry the moisture and torrefy biomass based on theoretical concept of energy (HHV as fired) required for raw wet feedstock. The total energy required to torrefy the biomass can be considered as the sum of energy required to dry the moisture and then torrefy the dried biomass. Raw wet biomass can be considered as a mixture of mass of dry biomass and moisture. For instance, 1 kg wet biomass at 30 % moisture content is ideally consist of 0.7 kg of dry biomass and 0.3 kg of water. Its net energy content will be equal to energy content of dry biomass and energy required to dry the moisture. In the present case, net energy content of the raw wet biomass will be sum of energy content (HHV) of 0.7 kg of dry biomass and energy required to remove the 0.3 kg of water from the mixture.

The relationship for estimating energy content of raw dried biomass, $ED_{b(dry)}$ (MJ/kg) is represented by,

$ED_{b(dry)} = 0.3491(C) +1.1783(H) - 0.1034(O) - 0.0211(A) + 0.1005(S) - 0.0151(N)$ ---------Eqn. (1) (Anon 2010a)

The composition of carbon (C), hydrogen (H), oxygen (O), ash (A), sulfur (S), and nitrogen (N) of dried corn stover can be considered as 43.65, 5.56, 43.31, 5.58, 0.61, and 0.01 % respectively (Anon 2010a). The $ED_{b(dry)}$ of corn stover can be shown approximately as 17.00 MJ/kg.

Net energy from dry biomass in raw wet biomass, $E_{b(dry)net}$ (MJ) is represented by,

$E_{b(dry)net} = ED_{b(dry)} \times M_{b(dry)}$ ------------------------ Eqn. (2)

Where, $M_{b(dry)}$ is the mass of dry biomass in raw wet biomass mixture (kg). Hence, 12.078 MJ of energy is available in the 0.7 kg dry mass of corn stover. But there is also 0.3 kg of moisture present in the (mixture of dry biomass and moisture) raw wet biomass. This is the net energy available in the raw wet biomass of 1 kg with 30 % moisture content and which enters into the torrefaction process.

Energy required to dry and torrefy the feedstock

In the torrefaction process, the mixture of dry biomass and moisture undergoes in two stages. First, in the drying stage the moisture present in the mixture is completely removed. Second, the dried biomass is torrefied at desired temperature (for example 250 ^{0}C). Hence the total energy required to torrefy the biomass can be considered as the sum of energy required to dry the moisture and then torrefy the dried biomass.

Energy required to dry the moisture, Ed_{mc} (MJ/kg) is the sum of energy required to raise the temperature of moisture (to 100 ^{0}C), E_{mc} (MJ/kg), energy required to vaporize the moisture, ΔH_{vap} (MJ/kg), and energy required to raise the temperature of dry biomass (to 100 ^{0}C). That is,

$Ed_{mc} = ((E_{mc} + \Delta H_{vap} + Cp_b(100-T_i))/e_{ff})$ ------------------------ Eqn. (3)

Whereas, $E_{mc} = \Delta H/M = Cp_w (T_f - T_i)$ MJ/kg, specific heat of water, $Cp_w = 0.004181$ MJ/kg K (Incropera and David, 2001), initial temperature of raw wet biomass, $T_i = 25\ ^0C$, final temperature of raw wet biomass, $T_f = 100\ ^0C$, heat of vaporization of water/latent heat of water at boiling, $\Delta H_{vap} = 2.257$ MJ/kg (Incropera and David, 2001), specific heat of biomass = Cp_b = 0.002 MJ/kg K (Lauthouwers and Bellan, 2010; Janse et al, 2000), and the system efficiency of torrefaction unit, $e_{ff} = 0.65$.

Net energy required to dry the moisture, $Ed_{mc(net)}$ (MJ) can be represented as,

$Ed_{mc(net)} = Ed_{mc} \times M_{mctb(l)}$ ------------------------ Eqn. (4)

Where, $M_{mctb(l)}$ is the mass of moisture loss , (kg) and in this case it is 0.3.

It is obvious that ($Ed_{mc(net)}$) 1.348 MJ energy must be supplied to dry the moisture for the wet biomass having 12.078 MJ energy ($E_{b(dry)net}$). This is also equal to net energy of biomass after drying.

When analyzing biomass for thermo-chemical processing it is important to consider the energy content of the biomass in its ‘as-fired’ form. This allows for the downgrading of biomass energy to account for the energy loss required to vaporize the water contained within the biomass.

Typically energy contents are reported on a dry HHV basis, but this is not an accurate comparison when conducting a system level analysis of biomass feedstock energy and cost.

Net energy content of feedstock downgraded to moisture, $E_{b(moist)net}$ (MJ) can be represented as,

$E_{b(moist)net} = E_{b(dry)net} - Ed_{mc(net)}$ ------------------------ Eqn. (5)

The major portion of this energy requirement mainly depends upon the energy required to dry the moisture and hence amount of moisture present in the feedstock.

Energy required to torrefy the dried biomass $E_{tb(dry)}$ (MJ/kg) can be represented as,

$E_{tb(dry)} = \Delta H/M = Cp_b\ (T_t - T_i)/\ e_{ff}$ ------------------------ Eqn. (6)

Where, T_t is the temperature required to torrefy the biomass, = 250 ^{0}C, Cp_b is the specific heat of biomass = 0.002 MJ/kg K (Lauthouwers and Bellan, 2010; Janse et al, 2000), and e_{ff} is the system efficiency of torrefaction unit = 0.65.

Net energy required to torrefy the dried biomass, $E_{tb(dry)net}$ (MJ) can be represented as,

$E_{tb(dry)net} = E_{tb(dry)} \times M_{b(dry)}$ ------------------------ Eqn. (7)

Total net energy required to torrefy the (raw wet) biomass, $E_{T(net)}$ (MJ) can be represented as,

$E_{T(net)} = Ed_{mc(net)} + E_{tb(dry)net}$ ------------------------ Eqn. (8)

$E_{T(net)}$ is the net energy required to torrefy the 1 kg of raw wet biomass with 30 % moisture content. The major portion of this energy requirement mainly depends upon the energy required to dry the moisture and hence amount of moisture present in the feedstock. Whereas the actual energy required to torrefy the dried biomass is relatively less compared to energy required to remove the moisture. This means the net energy required for torrefaction will be less for lower moisture content of biomass.

Torrefaction gas energy

The torrefaction system can be made more energy efficient and economical way of processing biomass so that the torrefied biomass cost as well as volatile waste stream can be reduced greatly. This could be possible if the energy content of volatile gas mixture cab be recovered at the possible extent and re-used in the process. The auto-thermal process will reduce the significant amount of energy requirement for torrefaction and also provides a useful means to reduce the waste stream.

For the overall mass balance of torrefied biomass (at 250 ^{0}C and 30 min torrefaction condition) and the corresponding yield of volatile products; the product yields of solid and volatiles are approximately fractioned into 85 and 15 parts of dry mass respectively (Prins et al, 2005). For example, a 15 % dry mass yield into flue gas consisting of 1/3rd of energy (Bergman et al, 2005). The heat content of gas mixture can be combusted to recover its energy content through combustor and then supplied to torrefaction and drying processes. The gas products are mainly formed from the decomposition of hemicellulose fraction as a result of dehydration and decarboxylation reactions (Prins et al, 2005). Water, acetic acid, formic acid, methanol, lactic acid, furfural, and acetone are the main condensable fractions. Carbon dioxide, carbon monoxide, hydrogen, and methane are the main non-condensable fractions of the volatile gas mixture (Prins et al, 2005). There may be other minute fractions of permanent gases and liquids. Among the different volatiles produced, water (condensable) and carbon dioxide (non-condensable) are the major fractions of the mixture and their amount depends on the torrefaction temperature (Bergman et al, 2006).

It is important to analyze combustible nature of gas mixture so as to recover its heat energy through combustor. Bergman et al, 2005 verified the adiabatic flame temperature and at this temperature a stable combustion process can be expected. For this, adiabatic flame temperature should be greater than temperature of auto ignition of components, which are most difficult to combust. To expect combustibility at least around 400 ^{0}C differences between adiabatic flame temperature raise and the ignition temperature of these components will be required. Experimental analysis of torrefaction gas reported by Bergman et al, 2005 showed that CO and phenol had highest ignition temperature of around 600 ^{0}C. Therefore adiabatic flame temperature of ± 1000 ^{0}C is required to expect full combustible gas. Increased torrefction temperature and reaction time contributes to increased yield or decreased concentration of reaction water yield. This increased the combustible products (except water and CO_2). The calorific value of the gas ranges from 5.3 to 16.3 MJ/Nm^3 with the presence of high water contents in the gas mixture. This can be reasonably well comparable with air blown biomass gasification (4 to 7 MJ/Nm^3) to syngas produced in indirectly heated gasification (15 to 20 MJ/Nm^3) (Bergman et al, 2005). Based on this analysis the torrefaction gas can be considered as combustible nature. Hence the heat content of gas mixture can be combusted to recover its energy content through combustor. However, further experimental studies may be required to enhance the confidence in justifying combustible nature of torreafction gas. In this study, actual energy required to torrefy the feedstock using torrefaction gas and external source of energy (CNG) were considered (Fig.2).

Heat energy of torrefied biomass

The sensible energy from torrefied biomass at the exit of the process can be recovered by heat exchanger. The torrefied material temperature at the exit of process can be considered as 250 ^{0}C (same as torrefaction temperature). The heat recovered from the torrefied material can be reused in the process and at the same time its temperature can be reduced (to room temperature). Net energy recovered from torrefied biomass, $E_{T(tb)net}$ (MJ) is given as,

$E_{T(tb)net} = (M_{tb}\ Cp_b\ (T_t - T_i)) \times ef_{(tb)}$ MJ ------------------------ Eqn. (9)

Where, Mass of torrefied biomass, M_{tb} (0.595 kg), specific heat capacity of torrefied biomass, Cp_b (0.002 MJ kg^{-1} K), torrefaction temperature, T_t (250 ^{0}C), normal room temperature, T_i (25 ^{0}C), and system heat recovery efficiency of heat exchanger, $e_{ff(tb)}$ (0.50).

At the exit of the torrefaction process, a completely torrefied biomass can be expected. Its energy content is equal to net energy of biomass plus 2/3rd of net energy of dry mass loss (Bergman et al, 2005; Uslu et al, 2008). The conceptualized torrefaction energy model showed that the solid (torrefied) mass at the exit of the process is 0.595 kg dry considering 15 % dry mass loss for the 250 ^{0}C torrefaction temperature for 1 kg corn stover with 30 % moisture content. An expended process of biomass torrefaction consists of pre-drying, torrefaction, product cooling and combustion of the torrefaction gas to generate heat for drying and torrefaction (Fig. 2). The mass and energy fractions at the various flow paths as well as energy losses due to efficiency factors of various sub-systems in the torrefaction process are also shown in the diagram.

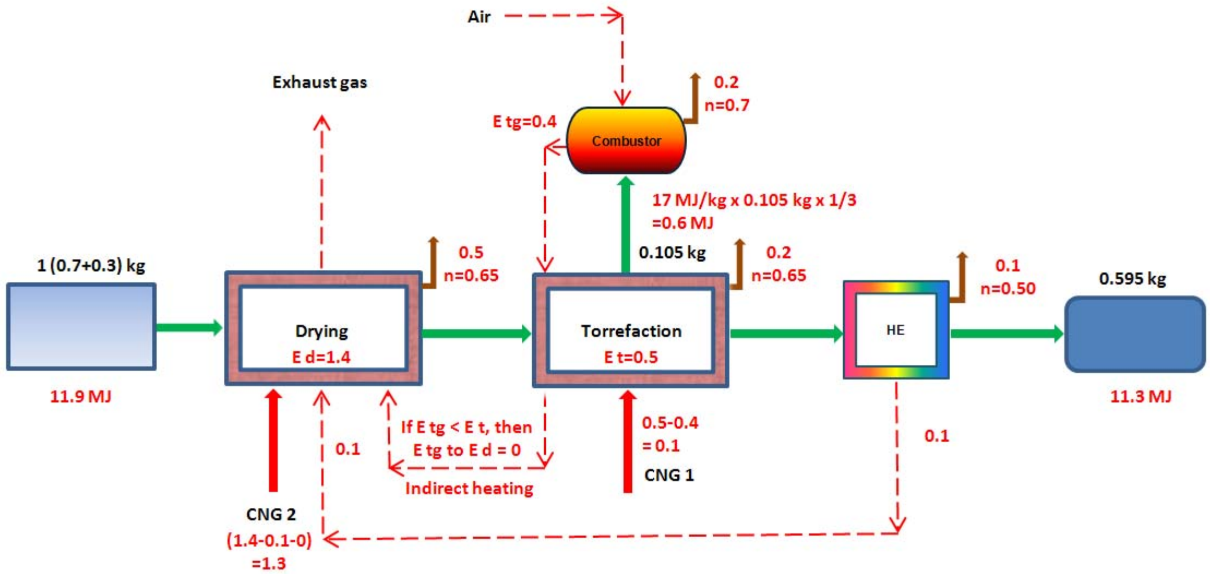

Fig.2. Schematic representation of an expanded process of biomass torrefaction

Cost Model for Biomass Torrefaction Process

The cost model is based on the various components of operating cost (including cost of feedstock and cost of energy to dry and torrefy) and capital cost of torrefaction process. In this, first the cost of feedstock per mass of wet biomass will be calculated. This will be actual cost of wet feedstock incurred by the processing plants. Secondly, the model estimates the cost of energy required to produce given mass of torrefied biomass. This cost of wet feedstock and the total cost of drying and torrefying energies will be the actual cost to produce mass of torrefied biomass.

Cost of feedstock & process energy – operating cost

Cost of feedstock per mass of torrefied biomass, Cf_{tb} ($/kg-dry) is represented as,

$Cf_{tb} = ((100 - MC_b)/100) \times (C_{b(dry)} \times 10^{-3}) \times (1/M_{tb})$ ------------------------ Eqn. (10)

Where, MC_b is the moisture content of biomass (%), $C_{b(dry)}$ is the cost of dry biomass, (considering 30 $/t-dry), and M_{tb} is the mass of torrefied biomass (0.595 kg-dry (tor)).

Cost of energy required for biomass drying, $CE_{b(dry)}$ ($/kg-dry(tor)) is represented as,

$CE_{b(dry)} = Ed_{mc(net)} \times CE_{CNG} \times 1/M_{tb}$ ------------------------ Eqn. (11)

Where, CE_{CNG} is the cost of CNG energy = 0.286 $/m^3. Because CE_{CNG} ($/1,000 ft^3) = 12 (Anon, 2010b) and CE_{CNG} ($/m^3) = 12/28 = 0.286. Gross heat of combustion of 1 normal cubic meter (at 0 ^{0}C and 101.325 kPa) of commercial quality of CNG = 39 MJ (Anon, 2010b).

Cost of energy required for biomass torrefying, $CE_{b(tor)}$ ($/kg-dry(tor)) is represented as,

$CE_{b(tor)} = E_{tb(dry)net} \times CE_{CNG} \times 1/M_{tb}$ ------------------------ Eqn. (12)

Other operating costs and total operating cost

Torrefaction plants capable of processing 750 tpd of dry chips are estimated to cost around $10 million (Sklar, 2009). Therefore for a capacity of 25 t/h, the cost of processing plant would be, ($10 M/(750 ton/day)) x (24 h/day) = $0.32 M/(1 ton/hr). That is $0.32 M x 25 ton/hr = $8 M. Since the proposed torrefaction plant design is intended for agricultural crop residues and energy crops and its capacity would be more than the above case. Hence, for the present case a capital cost of $7 M (for 25 tpd capacity) can reasonably be considered.

Cost of repair and maintenance, $C_{r\&m}$ ($/h) is given as,

$C_{r\&m} = (C_{ie} / U_{(ann)}) \times (C_{(r\&m)r} /100)$ ------------------------ Eqn. (13)

Where, initial cost of process equipment, C_{ie} ($7,000,000), $U_{(ann)}$ is the annual usage, (ex: 120 d x 24 h/d) = 2880 h/y, and $C_{(r\&m)r}$ is the rate of repair and maintenance with respect to equipment cost (10 %).

Cost of wages, C_w ($/h) is given as,

$C_w = N_{opr} \times C_{wage}$ ------------------------ Eqn. (14)

Where, N_{opr} is the number of operators required, (ex: 10) and C_{wage} is the operator wage rates, ($/h) (ex: 15)

Considering, energy cost for lighting, ventilating and other equipment, C_{mis} = 25 $/h

To produce 50 million gallons ethanol per year, it requires around 400 to 600 tons per day (640 to 960 bales 1250 lb each per day) of corn stover (Morey, 2010). For the maximum quantity (500 tons per day) of dry corn stover requirement the processing capacity of plant would be, 600 t/24 h = 25 t/h. Hence, the capacity of torrefaction process plant, $Cap_{(tor)plant}$ = 25 t-dry(tor)/h

Total cost of other operating costs per mass of torrefied biomass, $Cot_{(opr/tb)}$ ($/kg-dry(tor)) is given as,

$Cot_{(opr/tb)} = (C_{r\&m} + C_w + C_{mis})$ $/h x $(1/(Cap_{(tor)plant} \times 1000))$ ------------------------ Eqn. (15)

Total operating cost per mass of torrefied biomass, $Ct_{(opr/tb)}$ ($/kg-dry(tor)) is given as,

$Ct_{(opr/tb)} = Cot_{(opr/tb)} + CE_{nt} + Cf_{tb}$ ------------------------ Eqn. (16)

Capital (fixed) and total cost

Capital cost components were integrated into the cost model to estimate total cost of torrefied biomass. Capital costs includes, cost of depreciation, interest, insurance and taxes, and building. Total cost of torrefied biomass is the sum of operating costs and capital costs.

Depreciation cost of equipment, C_{de} ($/h) is represented as,

$C_{de} = (C_{ie} - (C_{ie} \times 0.1)) / (L_{ue} \times U_{(ann)})$ ------------------------ Eqn. (17)

Where, useful life of process equipment, L_{ue} = 20 years

Cost of interest on capital C_i ($/h) is represented as,

$C_i = ((C_{ie} + (C_{ie} \times 0.1)) / (L_{ue} \times U_{(ann)})) \times (I_r / 100)$ ------------------------ Eqn. (18)

Where, rate of annual interest, I_r = 12 %

Cost of insurance and taxes $C_{i\&t}$ ($/h) is represented as,

$C_{i\&t} = (C_{ie} / U_{(ann)}) \times (C_{(i\&t)r} / 100)$ ------------------------ Eqn. (19)

Where, rate of insurance & taxes with respect to equipment cost, $C_{(i\&t)r}$ = 2 %

Cost of building to house processing equipment, C_{bld} ($/h) is represented as,

$= (C_{ie} / U_{(ann)}) \times (C_{(bld)r} / 100)$ ------------------------ Eqn. (20)

Where, rate of building with respect to equipment cost, $C_{(bld)r}$ = 1 %

Total capital cost per mass of torrefied biomass, $Ct_{(cpt/tb)}$ ($/kg-dry(tor)) is represented as,

$Ct_{(cpt/tb)} = (C_{de} + C_i + C_{i\&t} + C_{bld}) \times (1/(Cap_{(tor)plant} \times 1000))$ ------------------------ Eqn. (21)

Total cost of torrefied biomass, $Ct_{(tb)}$ ($/kg-dry(tor)) is represented as,

$Ct_{(tb)} = Ct_{(opr/tb)} + Ct_{(cpt/tb)}$ ------------------------ Eqn. (22)

Total cost per torrefied biomass energy, $CtE_{(tb)}$ ($/MJ) is represented as,

$CtE_{(tb)} = Ct_{(tb)} / ED_{(tb)}$ ------------------------ Eqn. (23)

Where, $Ct_{(tb)}$ is the energy density of torrefied biomass.

Based on the expanded torrefaction process configuration a systematic model was developed in the MATLAB Simulink. The identified critical input parameters, which govern the model key components of biomass torrefaction cost analysis, are: feedstock moisture content, torrefaction temperature, operational period of torrefaction plant, and capital cost of plant.

Results and Discussion

1. Minimum energy requirement

Fig. 3 shows the net energy required to complete torrefaction process for feedstock moisture content. The relationship curves between torrefaction temperature and feedstock moisture content are exponential. In the figure, an auto thermal line is shown. Auto thermal operation means, energy required to torrefy the biomass can be achieved without the aid of any external supply of energy. That is energy generated by combusting the flue gas can exactly meet the energy demand for the process. It can be seen that as the torrefaction temperature increases the net energy requirement falls below the auto thermal line at a given feedstock moisture. That is more production of flue (torrefaction) gas energy than the energy required for torrefaction process. Torrefaction temperature curves of 200 and 220 ^{0}C fall above the auto thermal line at all feedstock moisture. The process can be operated as auto thermal at the temperatures 240 ^{0}C and above depending upon moisture. For the feedstock moisture content of 10, 30, 40, and 50 %, the process can be operated at auto thermal point at torrefaction temperature of 240, 260, 280, and 300 ^{0}C respectively.

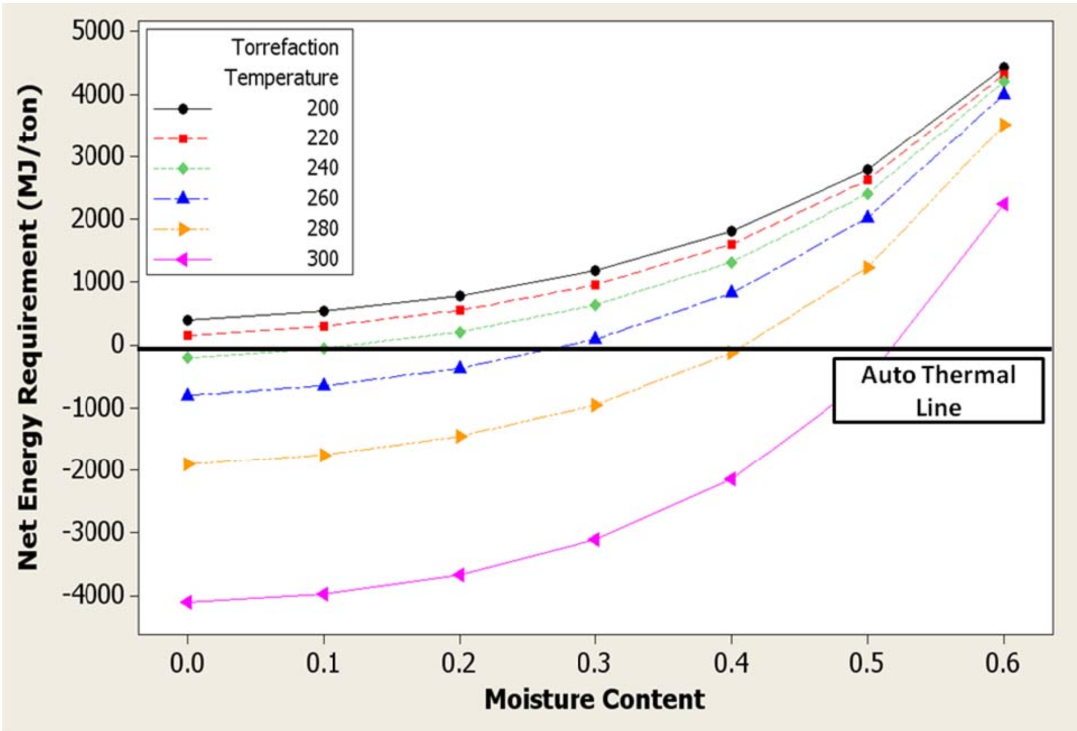

Fig.3. Net energy required to complete torrefaction process

2. Normalized net energy

Fig.4 represents the normalized net energy with respect to moisture content of biomass for various torrefaction temperatures. Normalized net energy is the ratio of energy content of torrefied biomass to the total energy required for the process. The energy ratio decreases with increase in torrefaction temperature. This may be because increased dry mass loss at higher temperature due to devolatalization and partial carbonization of hemicellulose. At a given torrefaction temperature the energy ratio decreases with increased moisture due to higher energy requirement for drying. For a typical 30% moisture content of corn stover the energy ratio is around 0.86 at temperature of 240 ^{0}C.

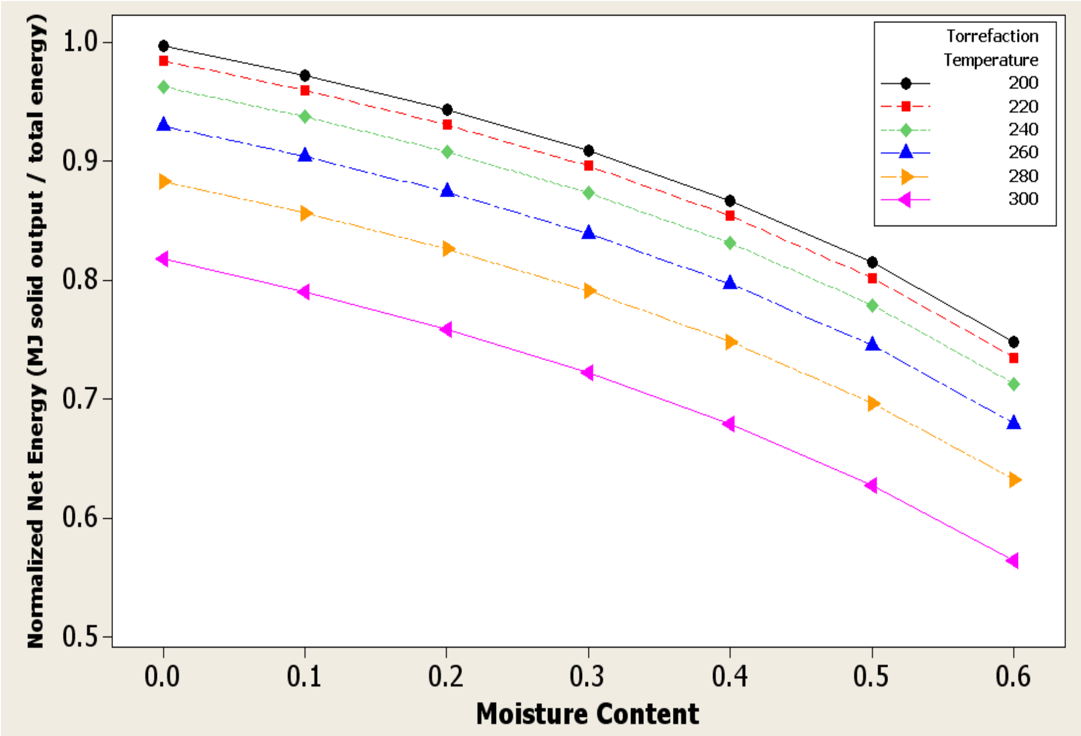

Fig.4. Fraction of net energy contained within torrefied biomass solid

3. Plant operation period

The torrefied biomass production cycles involves various feedstock operations starting from biomass harvest. After the harvest, the biomass should be transported from farm to torrefaction processing plant and then transported to biorefinery as the need arises. Hence production plant parameters especially at torrefaction process plant are considered as at most important for economical production of feedstock.

The fig.5 shows the relationship between cost of torrefied corn stover and moisture content of feedstock (at 0.3 $M-h/t plant cost and 240 ^{0}C torrefaction temperature) at various operational periods. It is clear that the torrefaction cost increased with moisture content due to increase in cost of energy associated with drying the moisture. This trend remains the same at all the levels of operational period. It can be seen that for given moisture content the rate of decrease in cost with increase in annual operational period. At 30 % feedstock moisture the increase in annual usage from 2 to 4 months decrease the cost from 40 to 24 $/t, where as it decrease from 20 to 17 $/t while operation from 3 to 4 months. The cost of torrefying dry (0 %) feedstock at 4 months operation period is nearly same (22 $/t) as that for 40 % moist feedstock at 6 months period. At 4 months of operation period, the cost decreases substantially. Further reduction in cost is also possible with increased operational period beyond 4 months, but the rate is small.

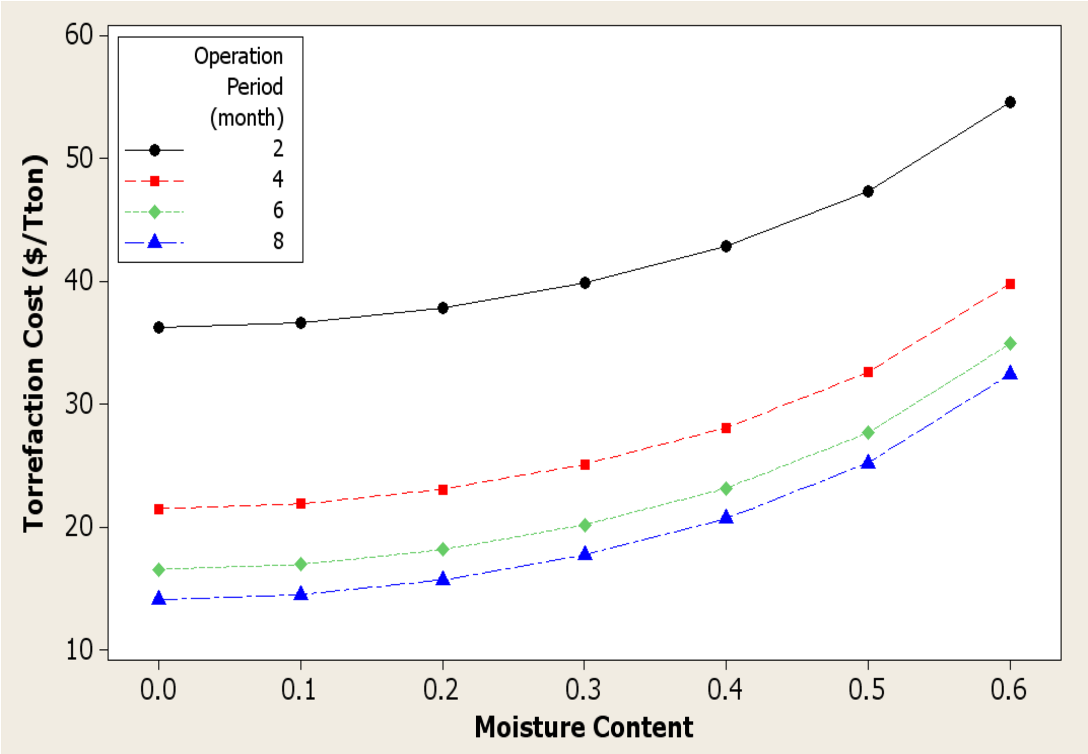

Fig.5. Comparison of torrefaction costs for 0.3 $M-h/t plant operating at 240 ^{0}C

4. Torrefaction temperature

The torrefaction cost curves at various temperature for 0.3 $M-h/t capital cost operating at 6 months is shown in fig.6. The cost curves for 200 and 220 ^{0}C temperatures follow the same path. The torrefaction cost for 240 ^{0}C is nearly the same as 220 and 200 ^{0}C up to 30 % moisture and beyond which there is slightly increase in the cost. At 30 % moisture content torrefaction cost is nearly same for all temperatures except for 280 and 300 ^{0}C. For higher torrefaction temperatures (240, 260, 280, and 300 ^{0}C) the rate of increase in cost is gradually linear up to a certain level of moisture content and beyond which the increase is non-linear. The linear trend is observed up to 10, 30, 40, and 50 % moistures for 240, 260, 280, and 300 ^{0}C temperatures respectively. This linear behaviour is due to the fact that torrefaction energy requirement can be met by torrefaction gas energy until this moisture content and above which the operation is above auto-thermal point and requires additional input energy from external energy supply.

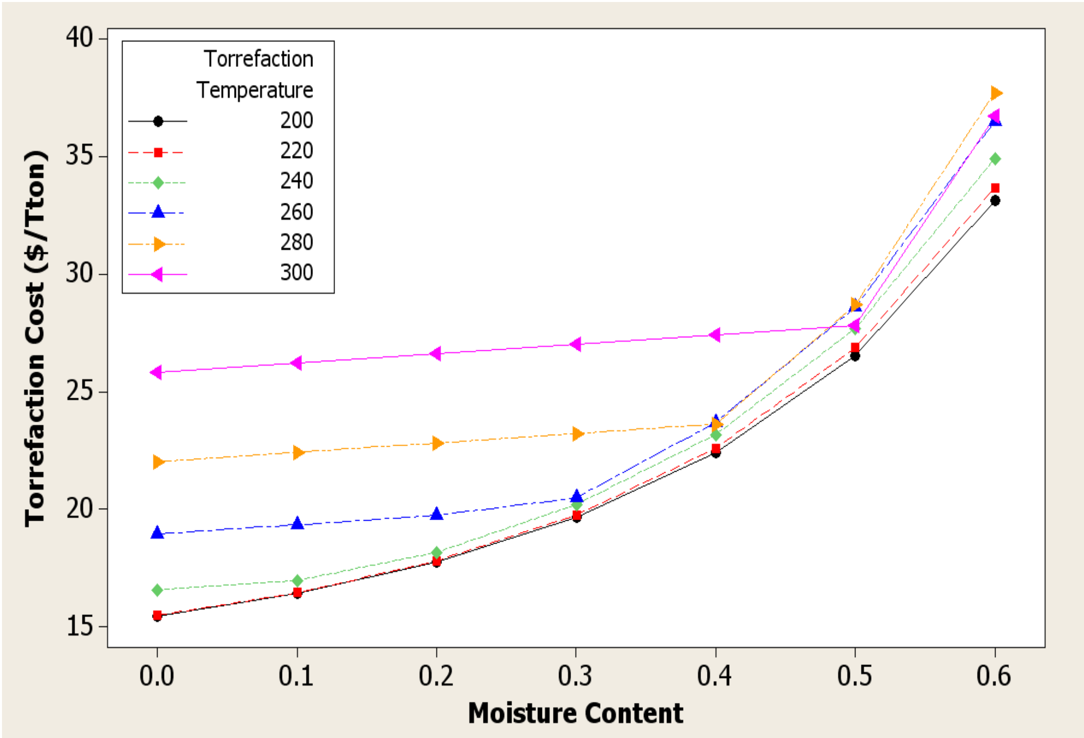

Fig.6. Torrefaction costs for 0.3 $M-h/t plant operating 6 months

5. Energy and DML costs

It is important to understand at what temperature the biomass should be torrefied, so that the energy cost and dry mass loss costs can be minimized. During the torrefaction process, energy spent and dry mass loss (DML) of biomass is proportional to temperature and feedstock moisture. The sub-cost incurred due to torrefaction energy and loss in dry matter of biomass with respect to torrefaction temperature is shown in fig 7. At the higher torrefaction temperature the energy cost is almost nil up to certain moisture. This is because excess production of flue gas energy than the required torrefaction energy during the pre-treatment process. The energy cost is nearly zero at the moisture content of 10, 30, 40, and 50 % for the corresponding temperature of 240, 260, 280, and 300 ^{0}C respectively. Further increase in moisture increase the energy cost due to energy requirement above the auto-thermal point (Fig. 3). Temperatures 200 and 240 ^{0}C operates above auto thermal point and generally energy costs are higher.

The relationship between sub-cost of torrefied corn stover and moisture content of feedstock is shown in fig. 7. From the figure it is clear that the DML (dry mass loss) cost increased with moisture content due to reduced amount of dry mass loss (at lower DM for given per cent mass loss). This trend remains the same at all the levels of temperature but rate of increase in DML cost with temperature is higher due to higher mass loss. At 30 % moisture the increase in temperature from 200 to 240 ^{0}C increase the DML cost from 1.50 to 4.00 $/t (torr), where as it increase from 6.25 to 13.25 $/t (torr) while operating between 260 to 300 ^{0}C. The DML cost of torrefying dry (0 % moisture) feedstock at 240 ^{0}C is nearly same (3.00 $/t (torr)) as that for 40 % moist feedstock at 220 ^{0}C temperature.

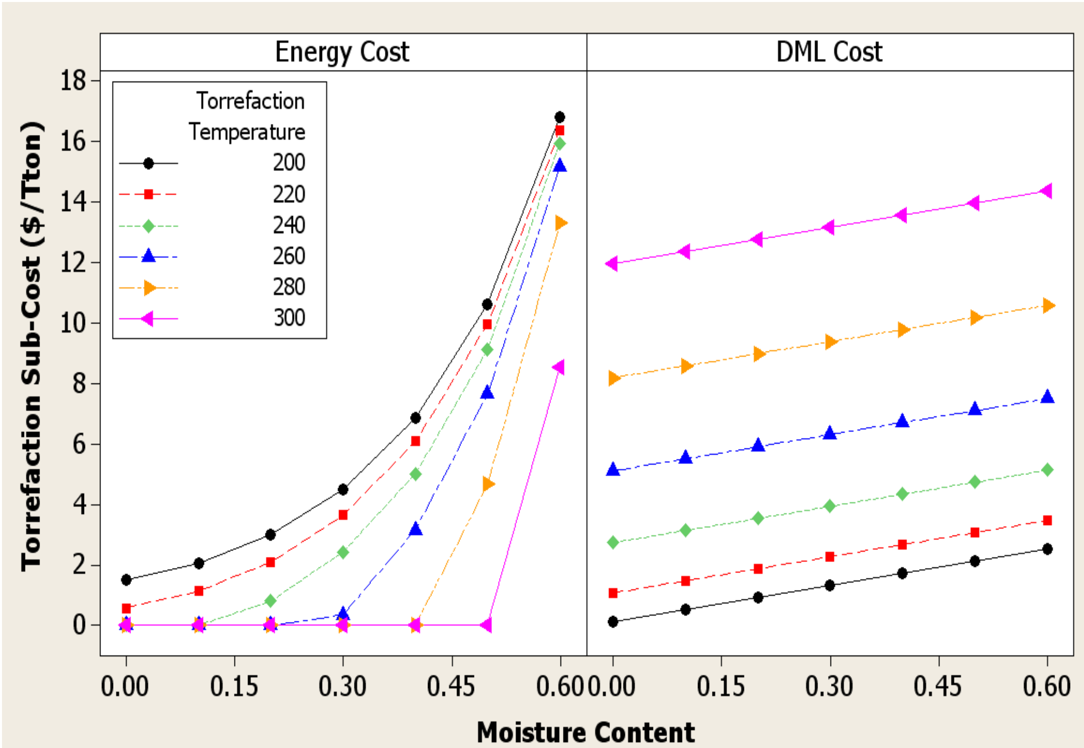

Fig.7. Comparison of energy and dry matter loss costs for torrefaction

6. Capital cost

It is very important to analyze how capital cost of torrefaction plant impact on the production cost. The torrefaction cost reduction through improved plant design was analyzed at 240 ^{0}C torrefaction temperature and 6 months plant operating period (Fig.8). As expected the cost of torrefied biomass increased with increasing plant capital cost and is higher for higher moisture content. The lowest total cost of 10 $/t (torr) can be expected at 0 % (dry) feedstock moisture for 0.1 $M-h/t capital cost. It is clear that the rate of increase in cost with moisture is gradually higher at higher moisture at all levels of capital cost. The rate of change in torrefaction cost increased with moisture and is greater for lowest capital cost (0.1 $M-h/t). The rate of change in cost with moisture will reduce at the highest (0.3 $M-h/t) capital cost when compared to that for the lowest capital cost. It is interesting to observe that the cost (14 $/t (torr)) at 10 % moisture with 0.3 $M-h/t is nearly the same at 30 % with 0.2 $M-h/t and at 40 % with 0.1 $M-h/t capital cost.

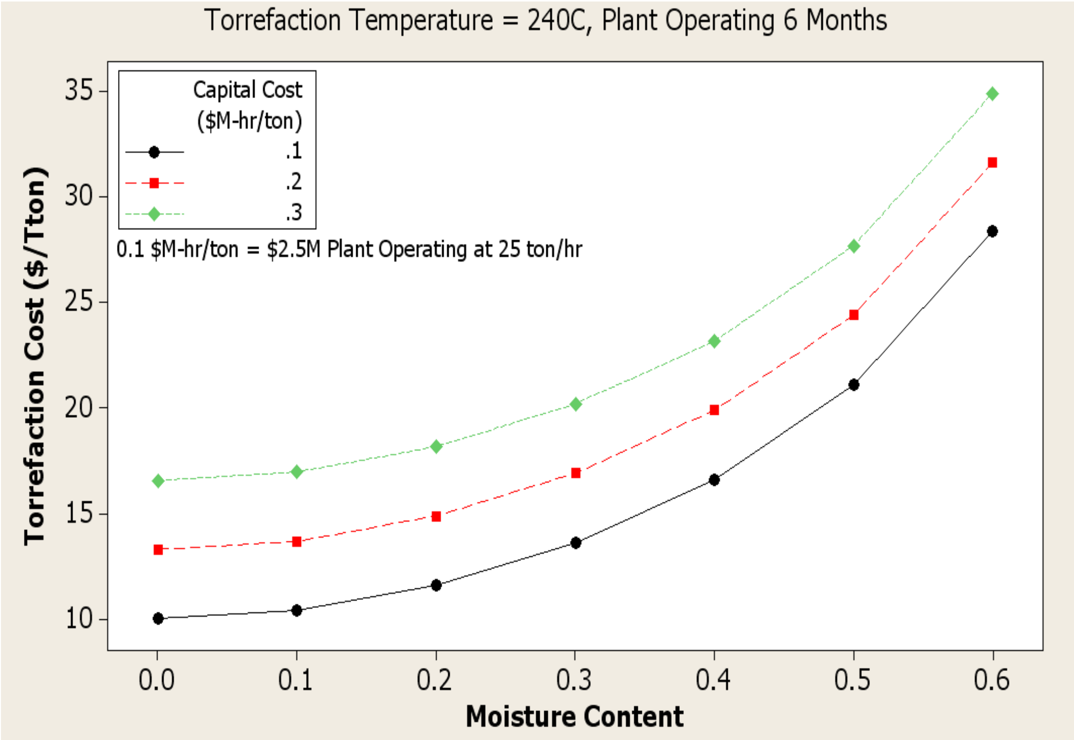

Fig.8. Torrefaction cost reduction through improved plant design

Conclusions

Based on the expanded torrefaction process configuration, a simulation model was developed in Matlab Simulink to quantify torrefaction energy and cost components for highly variable biomass feedstock. In the energy model various energy estimates including energy required to dry the biomass moisture and torrefy dried biomass, energy recovered from flue gas and torrefied solid material were considered. In the cost model various cost estimates associated with torrefaction energy, feedstock cost, total operating and capital cost components of torrefaction plant were considered in order to quantify total production cost of torrefied biomass. Model simulation tests were carried out to analyze response of critical key parameters including torrefaction temperature, operational period of torrefaction plant, and capital cost of plant, which influences total production cost of torrefied corn stover. The results of model analysis revealed the following conclusions:

1. When moisture removal from biomass feedstock is essential, torrefaction can not only provide a value added opportunity to enhance the feedstock and also reduce moisture.

2. A torrefaction temperature at an auto thermal line indicates that energy required to torrefy the wet biomass can exactly meet the energy generated by the flue gas. Depending upon the moisture content of biomass a critical temperature can be selected for the lowest energy cost. Hence auto-thermal operations should be a design requirement for torrefaction systems.

3. For typical biomass moisture of 10 - 30 %, torrefaction temperature of 240 - 260 ^{0}C should be considered in order to begin minimizes torrefaction energy cost and dry matter loss (DML) cost.

4. Torrefaction upgrading should occur over a minimum 4 months window in order to begin minimize costs. Further reduction in cost may be possible with increased operational period beyond this duration and also by staging multiple feedstock harvest windows.

5. Torrefaction is capital cost intensive and total cost is highly sensitive to capital cost. Opportunities exist to improve plant designs in this area.

6. Further, this study help integrate in to various systems of biomass upgrading procedure including storage, torrefaction, grinding, palletization, and storage to analyze optimal production cost scenarios. This cost can be compared with cost of traditional procedure biomass pretreatment including the systems storage, drying, grinding, palletization, and processing.

Acknowledgements

This material is based on work supported by the Bioeconomy Institute, Iowa State University.

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