

Forest waste to energy in the Himalayan region: technical and economic evaluation

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Abstract: The Himalayan subtropical pine forests spread all over the Himalayan region. Every year during the summer season, dry leaves (pine needles) fall from the trees and cover the forest area, destroying soil fertility and also cause forest fires. The energy recovery from waste biomass through gasification process is receiving renewed interest. In this present study, pine needle biomass gasification characterisation along with economics of energy generation are carried out. Results indicate that a maximum of 135 kJ/mol of energy is required for the complete gasification of pine needle biomass. The energy released per kg of pine needle gasification is found to be 15.66 MJ/kg. It produces producer gas of calorific value 5.07 MJ/Nm³. This producer gas is used in a 100% producer gas engine generator set for electricity generation. The levelised unit cost of electricity (LUCE) varies between 6.5 INR/kW to 14.84 INR/kW under the different financial and operating conditions.

Keywords: energy; biomass gasification; TGA; pine needle; kinetic investigation; regional bioenergy development; Himalayan region; forest fires; bio-energy; renewable energy.

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1 Introduction

The exhaustible nature of conventional fuels, as well as the growing concern about environmental protection and a demand for clean energy has created an interest in utilising waste biomass for energy generation (Nunes et al., 2016). As observed by Kim et al. (2020) biomass energy consumption has a potential to reduce net per capita CO₂ emission if used for a longer period of time. India produces annually 145.02 million tonnes of agricultural and 59.68 million tonnes of forestry surplus dry biomass. Surplus biomass, which is unsuitable for use as fodder industrial plants or as domestic use, is considered waste. The Indian Himalayan region is estimated to be 0.89 million hectares, and produces approximately 10 million tonnes of such forest biomass waste annually through pine trees (Bisht and Thakur, 2020). These trees scientifically known as *Pinus roxburghii*, in the summer season, the sharp, pine needles (leaves of pine trees) fall from the trees and spread all over the forest area, which destroys the fertile top layer and causes uncontrolled frequent forest fires in the region (Bisht and Thakur, 2017). Dry biomass is most suitable to utilise as a gasification feedstock for energy generation through thermochemical conversion process, and it consider as a potential replacement to liquid fossil fuels (Situmorang et al., 2020). Therefore, the present study concentrates on the significant potential to use pine needle biomass as a feedstock for gasification systems. The expansion of biomass utilisation would also help to meet climate change mitigation goals, energy security objectives, and sustainable development plans.

In the recent years, with a specific end goal to address biomass disposal issues, and to advance the utilisation of clean energy harvested from forest and agricultural biomass, researchers (Caballero et al., 2000; Lapuerta et al., 2008; Pérez et al., 2012; Yoon et al., 2012; Vera et al., 2013; Prasad et al., 2014; Cortazar et al., 2020; Filik, 2020; Yusuf and Inambao, 2020) have paid special attention to convert biomass waste, mainly wood waste, wood chips, rice husk, pine bark, olive oil, pongamia residue, bio-char, quinoa stalks and mbwazirume and nakyinyika peel into gaseous fuels using thermochemical conversion.

Biomass gasification proceeds via the pyrolysis process and it has an important effect on the gasification process. An inert atmosphere is required for pyrolysis reactions to occur and to avoid combustion reactions (Hook and Aleklett, 2010). It is a thermal decomposition process that includes complicated physical and chemical processes like mass and heat transfer and some relationship between them. These are dependent on many factors for example, biomass composition, its size, moisture content, resident time, heating rate, and temperature (Bisht and Thakur, 2019). Gasification technology can be a promising biomass waste management option that can convert biomass waste into producer gas and thus make it suitable for use in power generation (Karmakar and Datta, 2011). However, gasification is an extremely complex process and usually undergoes various processes like: drying, pyrolysis, oxidation and reduction. In the temperature range 200–600°C Pyrolysis occurs, which forms charcoal, tar and volatile gases (Buragohain et al., 2010). As indicated by White et al. (2011) for pyrolysis forecasting, functioning and design of gasification reactor, need a thorough knowledge of the kinetic parameters of pyrolysis. In order to interpret and explain the pyrolysis process, several researchers have studied the biomass thermogravimetry like: Biagini et al. (2008), Aboyade et al. (2011), Damartzis et al. (2011), Słopiecka et al. (2012), Gai et al. (2013), El-Sayed and Mostafa (2014), Ceylan and Topçu (2014), Chen et al. (2015), Kongkaew et al. (2015) and Huang et al. (2016) for rice husks, olive cake, and cacao shells; corn

cobs and sugarcane bagasse; cardoon; poplar wood; corn straw and rice husk; sugarcane bagasse and cotton stalks powders; hazelnut husk; pine wood sawdust, fern stem, wheat stalk, sugarcane bagasse and jute stick rice husk; and soybean straw, respectively.

In view of the above context, the aim of the present work focuses on the study of pine needles as an alternative source of energy through pyrolysis and gasification. The plant economics also evaluated under different economic situations, i.e., subsidies, without subsidies, and revenue through gasifier waste. The pyrolysis kinetics of pine needle biomass analysed by thermogravimetry in the given temperature range under inert atmospheric conditions with four different heating rates, then the operating parameters of biomass gasification are calculated. These results have been compared with studies conducted by several researchers on various other biomass sources in order to confirm its suitability for energy generation through pyrolysis or gasification. To attain financial viability, LUCE should be less than the electricity selling price. It is expected that these results will provide additional information that would be useful for its future applications.

2 Material and methods

2.1 Composition of feedstock

The raw sample of pine needle has been prepared before its TGA test. The sample has been air-dries, crushed and finally sieved to obtained into final form which is shown in Figure 1. The proximate and ultimate analysis along with chemical compositions is presented in Table 1. The calorific value of pine needle biomass is calculated as 20.04 MJ/kg.

Figure 1 Pine needle, (a) raw sample (b) powdered sample (see online version for colours)

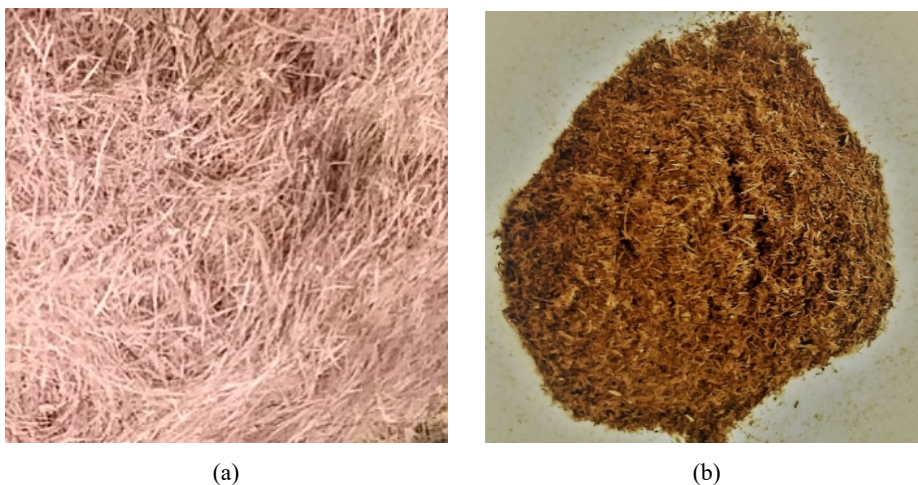


Table 1 Proximate, ultimate, and chemical analysis of pine needle

<i>Proximate analysis</i> (%wet basis)		<i>Ultimate analysis</i> (% dry basis)		<i>Chemical composition (%)</i> (Lal et al., 2013)	
Moisture content	09.80	Carbon	53.01	Holocellulose*	51.62
Fixed carbon	16.80	Hydrogen	06.00	Lignin	43.24
Volatile material	71.10	Nitrogen	00.59	Extractives	5.14
Ash content	02.30	Oxygen	40.40		

Note: *Cellulose + hemicellulose.

2.2 Experimental conditions for pyrolysis through thermogravimetric analysis

Thermogravimetric tests were executed utilising a thermogravimetric analyser EXSTAR TG/DTA 6300 and an Alumina pan. Nitrogen atmosphere has been used to attain the pyrolysis condition. The samples were heated in nitrogen atmosphere with varying rates of heating 10, 15, 20, and 30°C/min. For experimental purposes, 1.5 g of fine powder of pine needles was used. Ceramic sample holder was used to place the sample when heated from 25°C to 800°C. The furnace temperature and sample mass have been recorded during the heating.

Thermogravimetry can be performed under constant temperature or with varying temperature conditions. The data obtained from thermogravimetry analysis used for evaluating the kinetic parameters through different techniques. These techniques are classified as model-fitting and model-free techniques (Simon, 2004; Khawam and Flanagan, 2005; Sbirrazzuoli et al., 2009). Different methods for analysing thermogravimetry data are listed in Table 2. The disadvantage of constant temperature or isothermal conditions is that there is a small mass-loss before reaching the desired temperature, which causes error in the prediction of the pyrolysis reaction mechanism in the solid state. Therefore, varying temperature or non-isothermal conditions have turned into a broad scientific method in recent decades due to their high precision compared to isothermal methods (Gai et al., 2013). Model fitting methods fit the individual models to the available data and the model with the best 'fit' is used to calculate the kinetic parameters. This method makes certain assumptions about the reaction order and reaction models. Then again, model-free methods do not require these assumptions and can give kinetic parameters as an act of mass conversion (Vyazovkin, 2013).

Table 2 Different methods for analysing thermogravimetry data.

<i>Model fitting</i>		<i>Model free</i>	
<i>Isothermal</i>	<i>Non-isothermal</i>	<i>Isothermal</i>	<i>Non-isothermal</i>
Conventional	Differential	Standard	Kissinger
	Freeman-Carroll	Friedman	Flynn-Wall and Ozawa (FWO)
	Coats-Redfern	AIC	Kissinger-Akahira-Sonuse (KAS)
			Vyazovkin and AIC

To avoid errors related to isothermal conditions and model-fitting method, another method named model-free method for non-isothermal conditions to determine kinetic parameters has been widely used (Biagini et al., 2008; Aboyade et al., 2011; Çepeliogullar and Pütün, 2013; Gai et al., 2013; Jain et al., 2016) through the Kissinger (Slopiecka et al., 2012), FWO (Ounas et al., 2011) and KAS (Damartzis et al., 2011; Kantarelis et al., 2011) approaches. The FWO and KAS methods are also known as iso-conversional approaches, since the activation energy calculated by this method is a function of the degree of conversion. The terms ‘model-free’ and ‘isoconversional’ are sometimes used incorrectly; however, it should be noted that the Kissinger method, while a model-free method, is still not isoconversional.

2.2.1 Kinetic theory

Below reaction strategy represents the basic pyrolysis process of biomass:

$$\text{Biomass} = \text{moisture} + \text{volatile matter} + \text{Char}$$

The thermal decomposition can be expressed as:

$$\frac{d\alpha}{dt} = kf(\alpha) \quad (1)$$

α can be defined as:

$$\alpha = \frac{w_i - w_t}{w_i - w_f} \quad (2)$$

The value of k from Arrhenius equation as:

$$k = Ae^{-\frac{E}{RT}} \quad (3)$$

From equations (3) and (1)

$$\frac{d\alpha}{dt} = Ae^{-\frac{E}{RT}} f(\alpha) \quad (4)$$

Because the temperature is dependent on time and it is increasing with β , β can be defined as:

$$\beta = \frac{dT}{dt} = \frac{d\alpha}{dt} \times \frac{dT}{d\alpha} \quad (5)$$

Combining equations (4) and (5)

$$g(\alpha) = \int_0^T \frac{A}{\beta} e^{-\frac{E}{RT}} dT = \frac{AE}{\beta R} \int_x^x u^{-2} e^{-u} du = \frac{AE}{\beta R} p(x) \quad (6)$$

where $x = E/RT$ and $p(x)$ has no exact solution. Therefore, equation (6) must be solved by approximations method.

$f(\alpha)$ defined below using the uniform kinetics of reaction:

$$f(\alpha) = (1 - \alpha)^n \quad (7)$$

Equations (7) and (4) give:

$$\frac{d\alpha}{dt} = Ae^{-\frac{E}{RT}}(1-\alpha)^n \quad (8)$$

Heating rate defined below using the non-isothermal condition in TGA

$$\frac{d\alpha}{dT} = \frac{d\alpha}{dt} \times \frac{dt}{dT} \quad (9)$$

Putting, $\beta = \frac{dT}{dt}$ in equation (9)

$$\frac{d\alpha}{dT} = \frac{d\alpha}{dt} \times \frac{1}{\beta} \quad (10)$$

Now, equation (10) can be written as:

$$\frac{d\alpha}{dT} = Ae^{-\frac{E}{RT}}(1-\alpha)^n \times \frac{1}{\beta} \quad (11)$$

Equation (11) exhibits the differential form of the non-isothermal rate law. Non-isothermal experimental data is used to find out the parameters for kinetics which is based on methods of model-free technique.

2.2.1.1 Model-free methods

2.2.1.1.1 Kissinger Method

Kissinger described a method which is based on model-free non-isothermal that provides the activation energy E single valued for whole conversion process. The method used to find the activation energy E value using the slope $(-E/R)$ and curve between $\ln(\beta/T_m^2)$ and $1,000/T_m$ performed for different series at various rates of heating (β), where T_m is the peak of temperature in the DTG curve (Kissinger, 1956). The equation is as follows:

$$\ln\left(\frac{\beta}{T_m^2}\right) = \ln\left(\frac{AR}{E}\right) - \frac{E}{RT_m} \quad (12)$$

2.2.1.1.2 The Flynn-Wall-Ozawa method

The Flynn-Wall-Ozawa (FWO) process is a model-free isoconversional process (Ozawa, 1965; Flynn and Wall, 1966) that includes the use of Doyle's approximation (Doyle, 1965) that is express as: $\log(P(x)) \approx 2.315 + 0.457x$. The temperatures related to α (conversion fraction) which is a fixed value obtained from performing experiments by varying the heating rates, β , and evaluating and fitting $\log \beta$ vs. $1,000/T$.

$$\log \beta = \log\left[\frac{AE}{g(\alpha)R}\right] - 2.315 - 0.457\frac{E}{RT} \quad (13)$$

The slope of such a plot gives the value of $-0.457E/R$.

2.2.1.1.3 Kissenger-Akahira-Sunose

The kinetic parameters from non-isothermal TGA data were obtained by using the Kissenger-Akahira-Sunose (KAS) process (Kissinger, 1956; Akahira and Sunose, 1971). Below equation is used to summarise the isoconversional process.

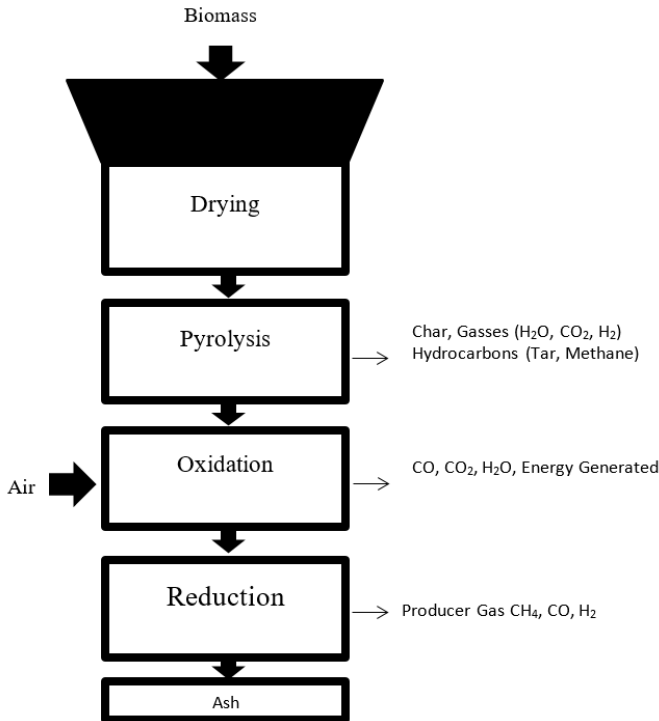
$$\ln\left(\frac{\beta}{T^2}\right) = \left[\frac{AE_a}{Rg(\alpha)}\right] - \frac{E_a}{RT} \tag{14}$$

Graph between $\ln\left(\frac{\beta}{T^2}\right)$ vs. $1,000/T$ use to find out $-E/R$, using slope.

2.3 Downdraft wood gasifier

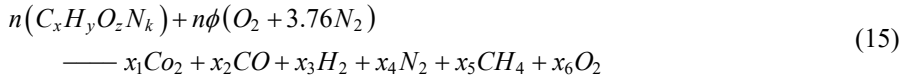
Downdraft gasifier is a fixed bed gasifier, in which biomass, air and gas flows downward direction by gravity (Asadullah, 2014). For the smaller scale application, downdraft gasifiers are considered to be well suited for power generation via IC engines (Gai and Dong, 2012; Sheth and Babu, 2009). Four zones of downdraft gasifier are shown in Figure 2. In the gasifier, exothermic and methane formation reactions occurs in the oxidation zone and reduction zone respectively. Chopped biomass in the downdraft gasifier reactor was lighted by holding a fire as wick close to air nozzle. After 20 min of operation, the producer gas was checked by igniting the gas in the burner. The composition of producer gas was estimated by utilising a gas chromatograph unit.

Figure 2 Downdraft gasifier schematic diagram



2.3.1 Operating parameters of gasifier

The different gasification parameters of pine needle biomass like calorific value of producer gas, mass of producer gas generated by per kg of biomass, producer gas density, energy released per kg of fuel, and coefficient of thermal conversion of biomass were calculated. With the assumption that carbon, hydrogen, oxygen and nitrogen are chemical properties of biomass. Therefore, the gasification reaction of pine needle biomass can be represented by the following chemical reaction equation:



The value of carbon, hydrogen, oxygen, and nitrogen in the biomass can be taken from the ultimate analysis as mentioned in Table 1 which is required for finding values of x , y , z and k .

2.3.1.1 Air fuel ratio

Calculation on the basis of 100 kg fuel represented as follow:

$$(A|F)_s = \frac{4.76 \times \phi \times MW_{air}}{100} \quad (16)$$

2.3.1.2 Producer gas analysis

The calorific value of different compound CO, H₂, and CH₄ presented in producer gases are 12.71, 12.78, 39.76 MJ/Nm³ respectively (Prasad et al., 2014). Therefore, the calorific value of producer gas represented in term of fraction of availability in producer gas is as follows:

$$Q_{CV_g} = \frac{(x * CV)_{CO} + (x * CV)_{H_2} + (x * CV)_{CH_4}}{100} \quad (17)$$

The total mass of biomass residue used to produce 100 kmol of dry producer gas is 100 n kg. Therefore, mass of dry producer gas produced per kg of biomass residue is calculated using following formula:

$$\dot{m} = \frac{\sum x_i MW_i}{100 \times n} \quad (18)$$

$$\sum x_i MW_i = (x_1 MW)_{CO_2} + (x_2 MW)_{CO} + (x_3 MW)_{H_2} + (x_4 MW)_{H_2} + (x_5 MW)_{CH_4} \quad (19)$$

2.3.1.3 Producer gas density

At NTP, The density of producer gas is calculated on the basis of density of each compound of producer gas. The density of these compounds is listed in Table 3.

Table 3 Density of compounds in producer gas

<i>Compound</i>	<i>Density (kg/Nm³)</i>
H ₂	0.090
CO	1.250
CH ₄	0.717
CO ₂	1.977
N ₂	1.257

The producer gas density can be represented as:

$$\rho_g = \frac{P_{atm}}{R_g \times T} \quad (20)$$

2.3.1.4 Energy release per kg of pine needle biomass

The energy released per kg of biomass is represented as follow:

$$E_g = \frac{\dot{m} \times Q_{CV_g}}{\rho_g} \quad (21)$$

2.3.15 The gasification efficiency or coefficient of thermal conversion

The coefficient of thermal conversion can be represented as follow, with the two assumption first 100% thermal conversion of feedstock and second ambient temperature is 303 K at 1 atm.

$$C_g = \frac{E_g \times \left(\frac{273}{303} \right)}{Q_{CV_g}} \quad (22)$$

2.4 Economic analysis

The economic analysis of 11 kW gasification system are analysed in this section, assumption and input parameters related to economic analysis are shown in Table 7 LUCE is calculated for four different economic scenario, i.e., without capital subsidies, without capital subsidies but with charcoal production and remaining two scenario with currently available capital subsidies from centre and state government with and with charcoal production.

2.4.1 Electricity delivered by biomass gasifier power project

The annual production of electricity (E_O) through biomass gasification power plant is calculated on the basis of power output of the plant (P), the capacity utilisation factor (CUF), and the energy utilised by the auxiliary units in fraction (a) (Palit et al., 2011). It can be estimated using the following expression:

$$E_O = P(8,760 \times CUF)(1 - a) \quad (23)$$

2.4.2 Capital cost of biomass gasifier power project

Capital costs for renewable or sustainable energy technologies tend to be high. The capital cost of a biomass gasification plant comprises the capital costs of gasifier system (engine generator included), civil works, and grid connection. The total capital cost can be estimated using the following expression:

$$Cap_{pp} = Cap_{gs} + Cap_{cw} + Cap_{gc} \quad (24)$$

The annualised capital cost of biomass gasification power plant related to gasification systems, civil work and grid connection can be estimated by the respective capital recovery factor. The capital recovery factor (R) evaluated through plants useful lives (T) and discount rate (d) (Nouni et al., 2007), which can be expressed as follow:

$$R = \frac{d(1+d)^T}{(1+d)^T - 1} \quad (25)$$

$$ACap_c = Cap_{gs} \times R_{gs} + Cap_{cw} \times R_{cw} + Cap_{gc} \times R_{gc} \quad (26)$$

2.4.3 Annualised operational and maintenance cost

The annual cost of maintenance represent by the sum of annual maintenance cost of gasifier system (gasifier and engine-generator) grid connection and civil work, and the operational cost represented by the annual wages paid to the employees

$$AC_{O\&M} = Cap_{gs} \times f_{gs} + Cap_{cw} \times f_{cw} + Cap_{gc} \times f_{gc} + mwr + nm \quad (27)$$

2.4.4 Annualised fuel cost

For the gasification system running on 100% producer gas the fuel cost depends upon the cost of biomass consumed by the gasification system. Where the biomass consumption by the gasification system depends on several factors such as biomass quality like; calorific value moisture content, ash content and operating load. It was observed that cost of biomass at the plant site was 1.5 INR/kg including the collection and transportation cost. For a given hourly biomass consumption annual fuel cost can be calculated as follow:

$$AC_F = 8,760 \times CUF \times C_{bm} \times S_{sbfc} \quad (28)$$

2.4.5 Levellised unit cost of electricity

The levellised unit cost of electricity (LUCE), is the ratio of total cost expenditure like; capital cost, O&M, and fuel cost on the gasification power plant over the net electricity produced by the plant for a given period of time. Mathematically it can be presented as follow:

$$LUCE = \frac{AC_c + AC_{O\&M} + AC_F}{E_a} \quad (29)$$

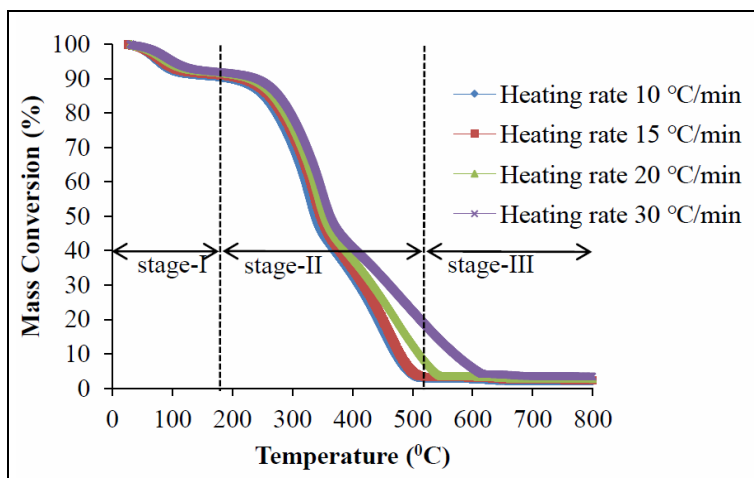
3 Results and discussion

3.1 Thermal degradation process

The behaviour of pine needle biomass with heat was studied by thermogravimetry. It was observed in 25–800°C temperature range with different heating rates (10, 15, 20, and 30°C/min) using the nitrogen ambience. Thermal decomposition of biomass is found to consist of three stages, in agreement with previous findings (Kumar et al., 2008; Ioannidou et al., 2009; Aboyade et al., 2011; Ceylan and Topçu, 2014). These stages can be sketched out as shown in Figure 3:

- 1 stage I, below 187°C dehydration of sample is shown
- 2 stage II, active pyrolysis process at temperatures between 187°C and 520°C
- 3 stage III, passive pyrolysis extended up to 800°C.

Figure 3 Comparison of TGA curves for pine needle at different heating rate (see online version for colours)



As found in Figure 3, the moisture removal occurs up to 187°C which is considered as stage one. The mass loss rate depends upon temperature: as we increase the temperature the weight loss also increases because of the rate of pyrolysis which is low at lower temperature. It is observed that at 800°C the unconverted solid residue increased by 66% when heating rate is increased from 10 to 30°C/min. That means the efficiency of heat transfer decreases at elevated heating rates (Damartzis et al., 2011; Idris et al., 2012; Chutia et al., 2013). Higher heat transfer efficiency was observed at lower heating rates due to the gradual heat transfer to the internal parts of the biomass.

The second stage happens in the temperature range of 187–520°C for low heating rates, and extends up to 620°C for high heating rates. Like other lignocellulose biomass, pine needle comprises of hemicelluloses, cellulose, and lignin (Biagini et al., 2006). More than 87% of weight loss has been noticed in this stage, which is caused by the breakdown of hemicellulose, cellulose, lignin and volatile matter removal. Hemicellulose is more reactive, so a lower temperature is required for decomposition as compared to

cellulose, while lignin requires higher temperatures for decomposition (Shafizadeh, 1982). Furthermore, in this temperature range different products like tar, gases evolved. Coke formation also takes place. All the products are formed due to sophisticated chemical reactions.

Stage III is the passive pyrolysis zone where the decomposition rates are slower. This is because the char formed is further gasified here.

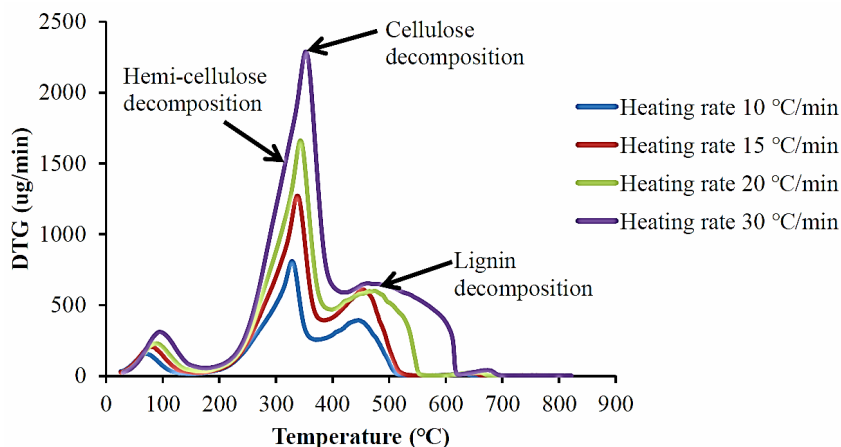
3.2 Effect of heating rate

Figure 4 shows the differential thermogravimetric analysis curves (DTGA), indicate two different mass loss peak. The second peak is smaller than the first peak. It is shown that with increment of heating rate there is shifting of temperature peak (from 10 to 30°C/min).

The pyrolysis of pine needle starts at 187°C, and with a further increase in temperature the rate of loss in mass rose sharply and achieve maximum values at 327, 337, 343 and 351°C with rates of heating as 10, 15, 20 and 30°C/min, respectively.

The decomposition of pine needle in the second stage is linear up to the maximum value of the first DTG peaks, because of the degradation of hemicellulose and cellulose in the temperature range of 220–400°C (Prasad et al., 2014). Hemicelluloses typically degrade in a temperature range of 160–360°C. In contrast the temperature domain for cellulose decomposition is 240–390°C (Varhegyi et al., 1989). According to Yang et al. (2007) and Sanchez-Silva et al. (2012), the degeneration temperature of hemicellulose is in the range of 220–315°C and that for cellulose is in between 315–400°C.

Figure 4 Correlation of DTG curves for pine needle at different heating rate (see online version for colours)



The second DTG peaks are because of lignin decomposition. Yang et al. (2004) suggested that at temperatures above 350°C a second peak in the DTG curve appears due to lignin decomposition. Gottipati and Mishra (2011) reported a similar trend of mass loss where lignin decomposes between 350°C and 580°C for all the samples of lignocellulose biomass. The second DTG peaks at 446°C (393 $\mu\text{g}/\text{min}$) are smaller as compared to the first DTG peaks, and increase upto 652 $\mu\text{g}/\text{min}$ at 465°C for higher heating rates.

As shown in Table 4, at low heating rates the amount of solid residue generate is less, but increases with an increasing the rate of heating, the main reason for this is the thermal gradient, which is large within the particles of sample, and hence required more resident time for pyrolysis. There is a shift in TGA and DTG curve maximum points in the direction of higher temperatures without changing the thermal decomposition profile. This was explained by Quan et al. (2009) on the basis of limitation of heat transfer. While doing analysis at lower heating rates, a large thermal energy feed to the system spontaneously and to attain the equilibrium between temperatures of furnace and purge gas longer time is required. For the similar time period and temperature range, a shorter reaction time is obtained for higher heating rate, hence sample will decompose at higher temperature, which causes the maximum rate curve shifts to the right.

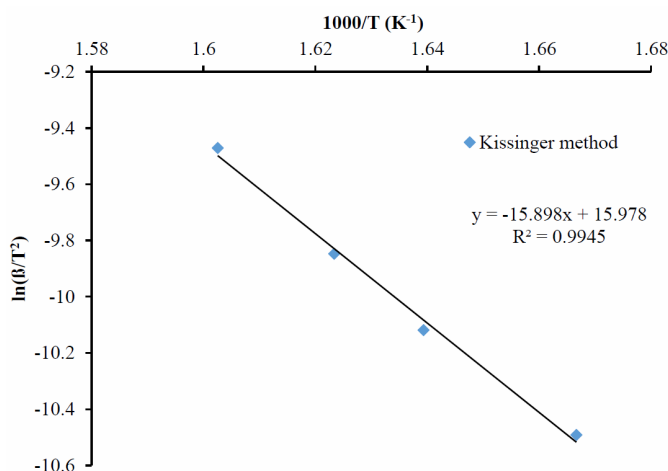
Table 4 Effect of heating rate on mass conversion

Heat rate (°C/min)	T_{1p} (°C)	Mass loss ($\mu\text{g}/^\circ\text{C}$)	T_{2p} (°C)	Mass loss ($\mu\text{g}/^\circ\text{C}$)	Burnout temperature (°C)	Ash (%)
10	327	68.4	449	37.2	500	2.09
15	337	66.5	460	38.6	509	2.37
20	343	65.7	475	29.0	544	2.74
30	351	61.0	613	10.3	614	3.47

3.3 Kinetic analysis

There are two parameters which are important for pyrolysis of pine needle. The names of two parameters are activation energy and pre-exponential factor. They can be find out by using two models namely as KAS and OFW models. There is a relation between conversion and activation energy that can be analysed by using iso-conversional method.

Figure 5 Plots $\ln(\beta/T_m^2)$ vs. $1,000/T_m$ using Kissinger method (see online version for colours)



The graph between $\ln(\beta/T^2)$ versus $1,000/T_m \text{ K}^{-1}$, shown in Figure 5, used to find out activation energy and pre-exponential factor using Kissinger method, T_m is the temperature that shows the maximum weight loss peaks in DTG curve that is shown in Figure 4.

Figure 5 also depicts the regression equations and the square of the correlation coefficient (R^2). Slope and intercept of plotted regression line used to find out activation energies (E) and pre-exponential factor (A) the values for activation energy and pre-exponential factors are 133.75 kJ/mol and $1.4 \times 10^{11} \text{ min}^{-1}$ respectively using Kissinger methods.

Figure 6 Graph between $\log(\beta)$ and $1,000/T$ using the Flynn-Wall-Ozawa (FWO) method (see online version for colours)

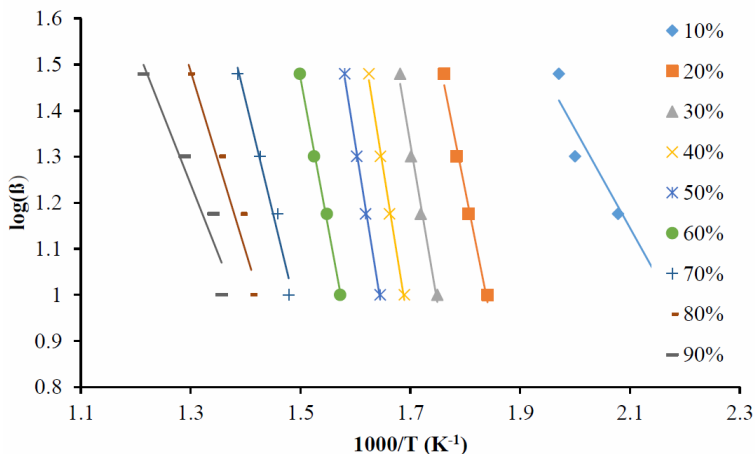
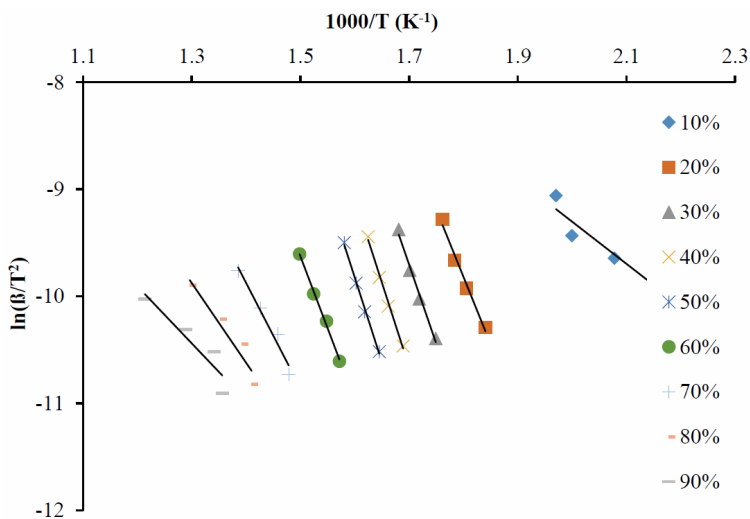
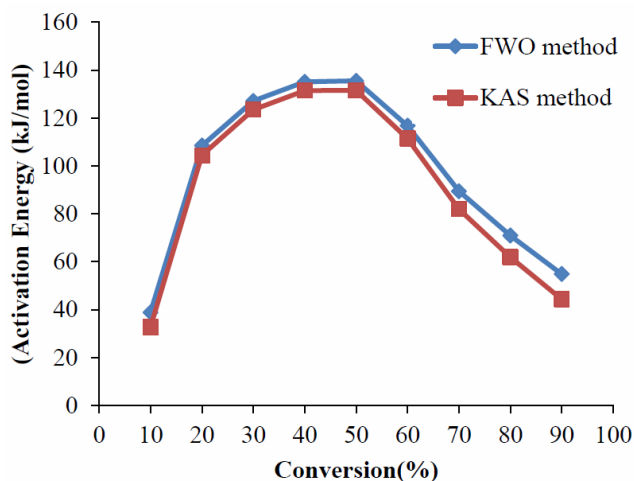


Figure 7 Plots $\ln(\beta/T^2)$ vs. $1,000/T$ using Kissinger-Akahira-Sunose (KAS) method (see online version for colours)



The temperature at different conversion from 10% to 90% with varying heating rates has been obtained. This help to calculate the kinetic parameters. FWO and KAS methods used to find out the kinetic parameters. Equations (13) and (14) provide the kinetic parameters. Plot of $\log(\beta)$ vs. $1,000/T$ using the FWO method and equation (13), is shown in Figure 6. The activation energy E , for KAS method is calculated by equation (14), and using the plot between of $\ln(\beta/T^2)$ versus $1,000/T$ as shown in Figure 7, where slopes give $(-E/R)$ at instant mass conversion.

Figure 8 Activation energies calculated at different conversions for pyrolysis of pine needle by using FWO and KAS method (see online version for colours)



The activation energy from KAS and FWO methods initially increase with an increase in conversion value from 10% to 50% and decreases thereafter. The activation energy through FWO methods increases from 38.87 to 135.48 kJ/mol for conversion from 10% to 50%, then reduces to 135.48 to 54.84 kJ/mol for conversion from 50% to 90%. The same trend was observed in the KAS method: the activation energy first increases from 37.73 to 131.56 kJ/mol for conversion from 10% to 50%, then reduces to 131.56 to 52.39 kJ/mol for conversion from 50% to 90% as shown in Figure 8. The calculated activation energy shown in Table 6 was determined by using FWO and KAS method. This shows that the activation energy is depends on the degree of conversion in KAS and FWO methods. The model free iso-conversional methods calculate the activation energy as a function of mass conversion without assuming a reaction model as in the case of the model fitting method. The above used methods, OFW and KAS results, show deviation below 8%, which confirm that they are reliable enough. This deviation also is indicative of the predictive power of the KAS and FWO methods (Velazquez et al., 2013). By definition, the least possible energy required to start the reaction is called activation energy which can be utilised to obtain the reactivity of component. Gai et al. (2013) studied corn cob and rice husk kinetic mechanism and observed activation energy after calculation in a range of 98.715–148.062 kJ/mol and 50.492–88.994 kJ/mol, respectively. Velazquez et al. (2013) found the activation energy range between 120 and 250 kJ/mol for orange waste. Ceylan and Topçu (2014) obtained hazelnut husk activation energy using the KAS and the OFW methods vary in the range of 103.04–162.06 kJ/mol,

106.06–161.59 kJ/mol, respectively. Slopiecka et al. (2012) obtained activation energy to be 107.86–209.49 kJ/mol, and 104.95–209.90 kJ/mol respectively using FWO and KAS method, while studying the kinetic study of poplar wood pyrolysis. Fan et al. (2013) studied kinetic characteristics of various sources of biomass: corn straw, platane wood, camphor wood and rape straw. They obtained the varying activation energy as from 23–48 kJ/mol, 32–54 kJ/mol, 6–74 kJ/mol and 20–60 kJ/mol, respectively. The kinetic parameters obtained for TGA data suggest that the activation energy is comparable to that reported in the literature. Complete gasification of pine needle biomass requires a maximum activation energy of 135 kJ/mol.

3.4 Pine needle biomass gasification

A gas chromatograph centurion scientific 5,800, was used to measure the producer gas composition. The producer gas was collected into Tedlar polyvinyl fluoride (PVF) bag which has polypropylen (PP) material valve and a capacity of half litre. Two samples were collected and each sample was analysed twice using gas chromatograph unit. The producer gas contain H_2 , CO , CH_4 , CO_2 and N_2 as analysed by the gas choromotograph the values are 17.19, 14.95, 2.45, 14.46, and 50.95 respectively. The calorific value of the producer gas is calculated 5.07 MJ/Nm^3 , which is higher than producer gas generated through wood chips and rice husk gasification (Narvaez et al., 1996; Corella et al., 2004; Digman et al., 2009).

Table 5 Operating parameters analysis of producer gas generated through pine needle biomass gasification in down draft wood gasifier

<i>Operating parameters</i>	<i>Pine needle</i>
Mole of biomass (n)	7.22
Mole of air (ϕ)	1.90
Air Fuel ratio stoichiometric (A/F) _s	2.62
Calorific Value of gas Q_{CVg} (MJ/Nm^3)	5.07
Mass of gas generated mg (kg of gas/kg of biomass)	3.54
Molecular weight of gas MW_g	25.56
Density of gas ρ_g (kg/m^3)	1.15
Energy released per kg of biomass E_g (MJ/kg biomass)	15.66
Coefficient of thermal conversion C_{th}	0.78
Gasification efficiency η (%)	78.14

Operating parameters as listed in Table 5 it is observed that the producer gas density is 1.15 kg/m^3 , the energy released per kg of pine needle biomass is 15.66 MJ/kg which is higher than the energy released per kg of wood biomass gasification (15.01 MJ/kg wood). The coefficient of thermal conversion of biomass gasifier is 0.78 or gasification efficiency of the gasifier is calculated to be 78.14 %.

3.5 Economic analysis

The economic analysis of indicate that LUCE for 11 kW gasification system is shown in Figure 9 LUCE for without subsidy (OC1) 9.75 INR/kWh at CUF 55.9%, in OC3 with a

capital subsidy of 40% through state government and 18,000 INR/kW from MNRE the LUCE decreased to 8.3 INR/kWh. OC2 without capital subsidy and OC4 with capital subsidy represent two scenario in which gasification waste is used for charcoal making which create extra revenue for the plant, the LUCE is further reduced to 7.95 INR/kwh and 6.5 INR/kWh respectively. At higher CUF, LUCE for the OC2 and OC3 is almost same.

Figure 9 Comparison of LUCE for different economic operating conditions (see online version for colours)

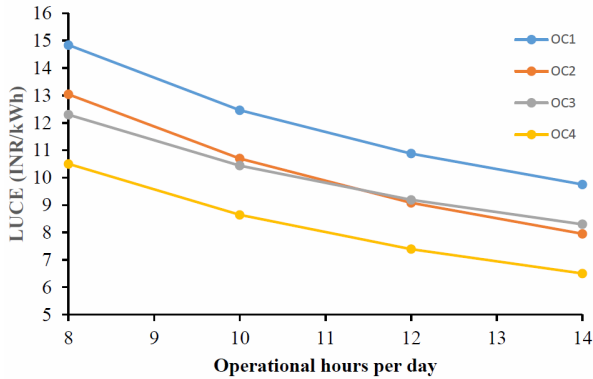


Figure 10 Relative cost contribution of different component in LUCE at different CUF (see online version for colours)

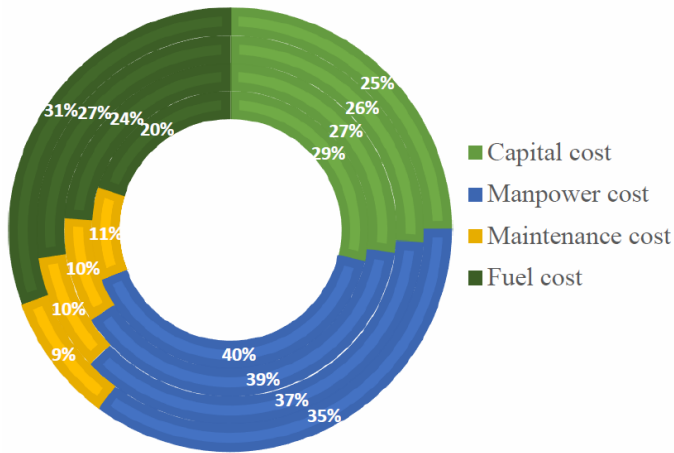


Figure 10 shows the relative contribution of different component in LUCE, if the CUF increases from 31.96% to 55.9% (increases diagonally), the contribution of biomass cost in LUCE increases from 20% to 31%. Where the cost contribution of other components, i.e., manpower, maintenance and capital decreases by upto 5%. Such a pattern occurred due to increasing electricity output at higher CUF, which further reduces the LUCE.

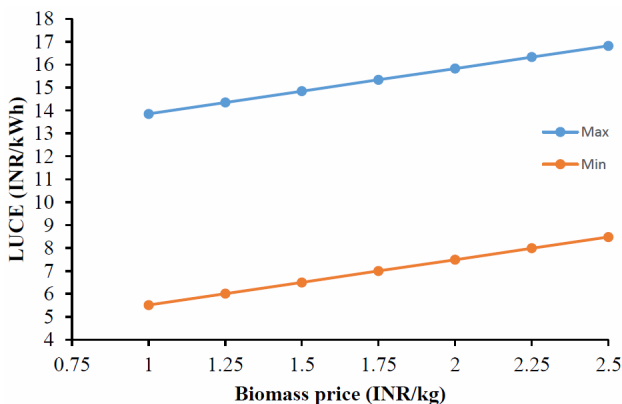
Table 6 Calculated E , A and R^2 values using FWO and KAS method for different conversions

Conversion α (%)	FWO method			KAS method				
	Fitted equation	E (kJ/mol)	A (min ⁻¹)	R^2	Fitted equation	E (kJ/mol)	A (min ⁻¹)	R^2
10	$y = -2,136.4x + 5.6313$	38.86658556	1.89E+03	0.94	$y = -4,538.19x - 1.4295$	37.7305552	9.43E+03	0.9155
20	$y = -5,963.1x + 11.96$	108.4840556	2.89E+09	0.9859	$y = -1,2559x + 12.791$	104.415526	9.02E+08	0.9851
30	$y = -6,986.5x + 13.204$	127.1023217	6.48E+10	0.9881	$y = -1,4848x + 15.542$	123.446272	2.5E+10	0.9877
40	$y = -7,424.2x + 13.528$	135.0652053	1.72E+11	0.9946	$y = -1,5807x + 16.208$	131.419398	6.92E+10	0.9947
50	$y = -7,447x + 13.241$	135.4799956	1.10E+11	0.9965	$y = -1,5824x + 15.493$	131.560736	4.23E+10	0.9966
60	$y = -6,416.1x + 11.093$	116.7252853	1.09E+09	0.9965	$y = -1,3396x + 10.468$	111.374344	2.83E+08	0.9960
70	$y = -4,914x + 8.3014$	89.3982407	2.69E+06	0.974	$y = -10,333.2x + 3.9207$	85.9103594	3.48E+05	0.9646
80	$y = -3,898.2x + 6.5524$	70.91823807	6.91E+04	0.948	$y = -8,162.17x - 0.2035$	67.860317	4.86E+03	0.9234
90	$y = -3,014.5x + 5.1586$	54.84147265	4.06E+03	0.9207	$y = -6,300x - 3.4998$	52.3784692	1.45E+02	0.8692

Table 7 Economic input parameters for 11 kW biomass gasification plant

<i>Parameters and assumptions</i>	<i>Descriptions</i>	<i>Value</i>
Assumptions	Annual maintenance cost	% of its capital cost
	Gasifier engine generator set	5%
	Grid connection network	2%
	civil work	4%
	Auxiliary units power consumption	1 kW
	Useful plant life	20 Year
Capital cost	Cost of gasifier system (includes cooling system, moisture meter)	790,000 INR
	Wood chopper machine	50,000 INR
	Installation cost	45,000 INR
	Taxes and duties	
	Material component will attract GST @5%	42,000 INR
	Installation and commissioning charges will attract GST @18%.	8,100 INR
	Grid interconnection cost	10,000 INR
	Cost of civil work	70,000 INR
Subsidies	MNRE subsidies @18,000 INR/kW	198,000 INR
	State government subsidies @40%	406,000 INR
Running cost	Price of biomass	1.5/kg
	Manpower cost 2 worker @7,000 INR/month	168,000 INR
	Maintenance cost	45,000 INR

Figure 11 Sensitivity analysis of LUCE with respect to biomass price (see online version for colours)



The sensitivity is analysed in relation to rising fuel prices, which are observed in Figure 11 that every 0.25 INR of increasing in biomass price, LUCE increases by 3.4%.

4 Conclusions

The study on pine needle biomass using thermogravimetric analysis and downdraft wood biomass is performed as an alternative source of energy through pyrolysis and gasification. Thermogravimetric analysis is used to evaluate the thermal decomposition of pine needles. Different methods are used to evaluate and correlate the kinetic parameters. The LUCE is calculated for four different economic scenario. Finally, the technical and economic evaluation results are concluded as follow:

- Pyrolysis of pine needle biomass consists of three stages, these stages can be sketched out as: stage I, dehydration or moisture removal occurs up to 187°C, stage II, active pyrolysis process occurs at 187°C to 520°C, and stage III, passive pyrolysis extended up to 800°C.
- The decomposition of pine needle in stage II is linear up to the maximum value of first DTG peaks This is due to decomposition of hemicellulose and cellulose in the temperature range of 220–400°C
- The pyrolysis of pine needle starts at 187°C, its mass loss rate in $\mu\text{g}/^\circ\text{C}$ increases sharply with increase in temperature and reaches its maximum value at 351, 343, 337, 327°C for heating rate of 30, 20, 15, 10°C/min respectively.
- At the end of pyrolysis process unconverted solid residue (Char) increased by 66% when heating rate is increased from 10 to 30°C/min.
- The activation energies are obtained in the range of from 38.57 to 135.48 kJ/mol, 37.73 to 131.56 kJ/mol by FWO and KAS methods, respectively.
- The calorific value of the producer gas produced through pine needle biomass gasification is 5.07 MJ/Nm³,
- It is observed that the producer gas density is 1.15 kg/m³, and the energy released per kg of pine needle biomass is 15.66 MJ/kg.
- The coefficient of thermal conversion of biomass gasifier is 0.78 or gasification efficiency of the gasifier is calculated to be 78.14%.
- The economic analysis indicates that for achieving financial sustainability, the biomass gasification power plant should operate on CUF more than 55%.
- With increasing CUF, the contribution of biomass cost in LUCE increases from 20% to 31%, where the cost contribution of other components, i.e., manpower, maintenance and capital decreases by up to 5%.

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Nomenclature

α	Degree of conversion.
w_i	Initial weight.
w_t	Instantaneous weight.
w_f	Final weight.
k	Temperature dependent rate constant.
A	Pre-exponential factor, min^{-1} .
E	Activation energy, kJ/mol.
R	Universal gas constant, kJ/mol K.
T	Absolute temperature, K.
β	Constant heating rate.
n	Order of reaction.
$\frac{d\alpha}{dT}$	Nonisothermal reaction rate.
$\frac{d\alpha}{dt}$	Isothermal reaction rate.

T_{1p}	Temperature of first DTG peak, °C.
T_{2p}	Temperature of second DTG peak, °C.
Δh_w	Represent manometers differential height (mm).
\dot{m}_g	Gas flow rate.
MW_{air}	Represent molecular weight of air.
$(A F)_m$	Air fuel ratio.
x	Percentage contribution in producer gas.
CV	Calorific value mass of producer gas generated per kg of biomass.
P_{atm}	Atmospheric pressure = 101,325 N/m ² .
R_g	Producer gas constant = 8,315 J/kmol – K/MWg.
T	Ambient temperature (303 K).
Cap_{gs}	Capital cost gasification system.
Cap_{cw}	Capital cost civil work.
Cap_{gc}	Capital cost grid connection.
f_{gs}	Fraction of capital cost gasification system.
f_{cw}	Fraction of capital cost civil work.
f_{gc}	Fraction of capital cost grid connection.
mwr	Annual salary.
nm	No of manpower.