Effects and Modeling of Sawdust Torrefaction for Beech Pellets

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This study was done to determine the effects of beech sawdust torrefaction on pellets obtained in the laboratory. Torrefied beech (*Fagus sylvatica* L.) sawdust was used to make pellets. This species was chosen based on the existence of a market for such micro-briquettes. Rigorous comparisons between torrefied and non-torrefied pellets were conducted. It was found that treating the sawdust had both beneficial and non-beneficial effects, but the total effect is positive. Economical elements were also considered, emphasizing the use of wood biomass as fuel. Theoretical and experimental aspects are taken into consideration, the experimental results being used to validate the theoretical model. The experiments performed demonstrate that heat treatment can add value if it meets certain parameters, such as a maximum temperature of 260 °C for 5 min. Heat treatment of beech sawdust in the form of pellets or briquettes was shown to be a simple, viable, effective treatment because the heating process improves the calorific value and other relevant properties of the torrefied sawdust.

Keywords: Torrefaction; Beech pellet; Sawdust; Calorific value; Modeling

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INTRODUCTION

Woody biomass resources can be found in all countries and many fields, (Lakó *et al*. 2008), such as forestry, agricultural, and marine (Plištil *et al*. 2005), and it can be used for fuel in developing or developed countries (Lundborg 1998; Prasertsan and Sajakulnukit 2006; Jehlickova and Morris 2007; Gavrilescu 2008; Kazagic and Smajevic 2009; Okello *et al*. 2013; Vilcek 2013), separately or when mixed with coal (Kostanaki and Vamvuka 2005). The European Union (EU) uses about 41.3% of the area, (4 million km^2) of its total land (10 million km^2) for agriculture and 3 million km^2 for forestry. The EU annually cuts about 426 million m^3 of roundwood (Verna *et al*. 2009). Given that wastes from logging are about 10%, the volume of the round logs, 42 million m^3 of woody debris is generated annually by the EU. Beech (*Fagus sylvatica* L.) is a woody species whose operational and processing residues (biomass) are often used to produce heat in the form of firewood, briquettes, pellets, sawdust, chips, and others. This wood species is dominant in Europe because after 30 to 40 years, the trees grow at rates of about 80 cm/year and the productivity of a beech forest is about 12 to 13 m^3/year/ha.

Energy prices are variable in different countries. They are affected by price controls, the necessity of some prices that reflect true costs, the international increase in fuel prices, the increase in network investment, and the elimination of subsidies. At the end of 2006, the average price of electricity supplied to households, which were consuming 1200 kWh/year (the average residential consumption), was 0.163 €/kWh in the European Union (Eurostat 2011); it was 0.284 €/kWh in 2014. The price of energy delivered to industrial consumers varies according to the size of the operation but is in all cases below the EU average. Thus, a consumer requiring 1,250 MWh and a maximum power of 500 kWh pays, on average, between 0.085 and 0.093 €/kWh.

Biomass is a renewable energy source (Omer 2012) just like solar, wind, geothermal, and other sources of energy, and it is present in large quantities throughout most of the world. Some estimates state that EU biomass could be used sustainably to satisfy up to 18% of the energy needs (Robert *et al*. 2005; EREC 2015), compared to other renewable energy sources, as shown in Fig. 1.

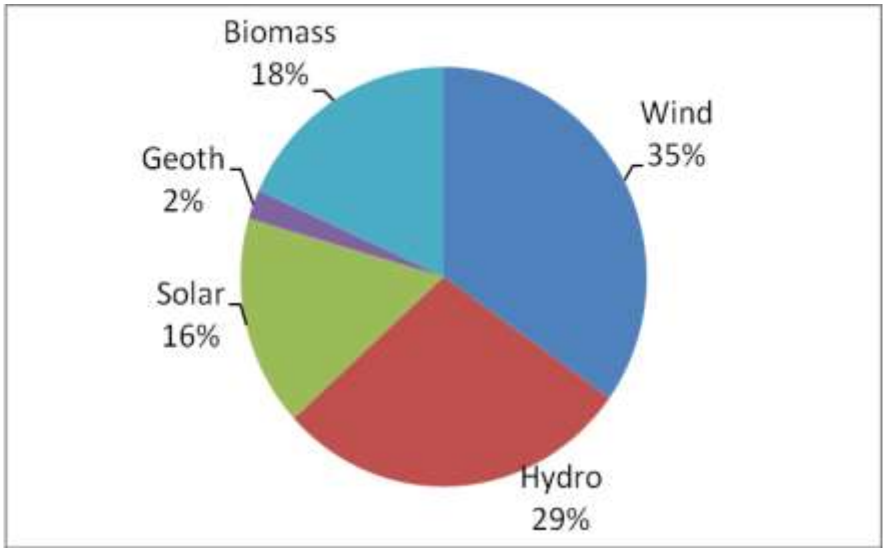


Fig. 1. Relative share potential of renewable energy sources in the EU, in 2020 (EREC 2015)

Torrefaction is the heat-treatment of coarsely chopped material in an oxygen/nitrogen atmosphere at 200 to 300 °C (Chen *et al.* 2014) to improve the properties of the treated material. Torrefied biomass is typically 70% of its original weight and contains 90% of its original energy (Teuch *et al*. 2004). Moisture absorption by torrefied biomass is limited, ranging from 1 to 6% (Bridgwater 2012). The moisture content of torrefied material used in furnaces (7 to 8%) can be lower than that of standard pellets and briquettes (8 to 10%). During thermal treatment, the biomass loses more hemicellulose than cellulose and lignin (Batidzirai *et al.* 2013). Subsequently, the calorific value of the torrefied pellets increases. Torrefied biomass is also more porous, with a bulk density of 180 to 300 kg/m^3 depending on the original biomass density and the thermal conditions of the treatment (Nielsen *et al*. 2009). It is more fragile because it loses mechanical strength during torrefaction, which makes it easier to press and compact (Uslu *et al.* 2008). The production of pellets through sawdust torrefaction does have deficiencies; however, so it is useful to balance the advantages and disadvantages of this process using, *e.g*. a SWOT (Strength-Weakness-Opportunities-Threats) analysis, as shown in Table 1.

Table 1. SWOT Analysis of Sawdust Torrefaction

	Helpful	Harmful
Internal Origin	Strengths - Increasing calorific power, a smaller amount of material burned, and fewer pollutants introduced into the atmosphere; -Decreased hygroscopicity of pellets, better stability in time, the posibility of use without being packed, less biodegradable -Better efficiency of combustion because low moisture content is maintained	Weaknesses -An additional operation (torrefaction), new investments, new costs, etc. -Hardening of the outer surface of the sawdust particles and a decrease in adhesion -Mass losses, including moisture content
External Origin	Opportunities - The market is weak in this area - The market is looking for new solutions - Global energy/climate crisis	Threats - Customers and sellers are sceptical of new trends - Higher price scares retailers and customers

Production of pellets requires a raw material (fine sawdust) with optimal moisture content below 10 to 12%. However, the pelleting press can support up to 20% moisture content. If the original material is too wet or too dry, the necessary pressure for densification increases significantly (Greenhalf *et al.* 2013). Subsequently, the raw material is heated by friction at 120 to 150 °C to activate the lignin and produce highly stable pellets (Demirbas 2001; Demirbas and Demirbas 2004; Chen *et al*. 2011; Chen *et al*. 2012).

Based on the estimates of Sikkema *et al.* (2011), pelletizing facilities built by 2030 will improve the pellet quality by 2 to 3 times. Torrefied pellet production facilities will increase from producing 0.5 Mtons at the end of 2015 to 20 to producing 28 Mtons by 2030. This is conservative, meaning that non-torrefied sawdust was assumed suitable only for energy production on a large scale (because of different strategy of countries) and that only 25% of the pellets will be torrefied. However, it is expected that most of the pellets will be converted in the integrated/CHP plant for burning, as this process has been successfully commercialized. Batidzirai *et al*. (2013) estimated that the cost of pellet production would range from 2.8 to 4.2 € /GJ. In the UE, pellet production is estimated to cost 2.72 €/kg. With a calorific value of 19 MJ/kg, pellets produced from woody species such as beech, spruce, pine, oak, and other species have a price of approximately 0.14 €/MJ. Tumuluru *et al.* (2011) showed that factories producing pellets will have production rates of 2.5 to 5 t/h, taking into account the facilities of pellets/briquettes producers. The price for one ton of dry biomass delivered from an average distance of 50 km is between 38 and 46 €.

Because some authors observed a slight mechanical durability of torrefied pellets, this drawbck can be improved with natural aditives (Lunguleasa 2011; Stelte *et al*. 2011). Table 2 shows some biomass fuel costs as compared to those of fossil fuels (Tabarés *et al.* 2000; Tumuluru *et al.* 2011) in EU.

Table 2. Costs of Biomass and Fossil Fuels When Used for Heat Production

Fuel	MC (%)	Unit price (€)	Calorific power (MJ/kg)	Price of heat (€/MJ × 10^3)
Sawdust and chips, kg	10%	0.4	17.7	22.59
Firewood, m^3	20%	0.6	17.1	35.08
Softwood briquettes, kg	10%	1.70	17.0	100.0
Hardwood briquettes, kg	10%	1.80	17.1	105.26
Hardwood pellets, kg	8%	2.62	17.8	147.19
Softwood pellets, kg	8%	2.58	17.2	150.00
Charcoal, kg	10%	1.03	20.5	50.24
Natural gas, m^3	-	0.6	35.1	17.09
Pit coal, kg	10%	2.2	20.8	105.76

The goals of the present study were the following: 1.) modeling of the calorific increase achieved by sawdust torrefaction based on hemicellulose and holocellulose losses; 2.) increase the calorific value of torrefied sawdust for pellet/briquette production; 3.) conduct an economical evaluation of the use of torrefied pellets *versus* non-torrefied ones.

EXPERIMENTAL

Materials and Equipment

Three types of experiments were conducted: sawdust torrefaction, creation of torrefied pellets, and determination of the calorific value. Finally, based on the experiments conducted and on other existing data, a micro-economic evaluation of torrefied pellets as compared to non-torrefied pellets was completed.

Beech sawdust was used for torrefaction. This material was obtained by slicing and splitting beech timber (*Fagus sylvatica* L.) into pieces 25, 38, and 40 mm thick. The sawdust was screened with 1.0- and 0.4-mm sieves, yielding a fraction with an average size of 0.7±0.1 mm. This fraction was dried in a laboratory oven until oven-dry moisture content was obtained. It was further heat-treated to 200-300 ^{o}C in air atmosphere (nitrogen 78.2%, oxygen 20.5% and others) with a thermostated oven. Pellets 10-mm in diameter, 12-20 mm length, and 1.15 g/cm^3 density were made using a hand pressing device (an auxiliary pelletizing device of the calorimeter). The device for producing pellets consists of a cylindrical channel in which the sawdust is inserted and a piston will press and compact sawdust with a hand wheel. The pellets were conditioned to 8% moisture content and kept wrapped in foil. The calorific value (CV) of the pellets were determined using a OXY-1C calorimeter (Shanghai Changji Geological Instrument Co., China) that uses explosive burning (excess of oxygen at a pressure of 30 atm). The calorific values of other non-torrefied pellets with the same moisture content (8%) were determined.

Methods

After the beech sawdust fraction was obtained, the sawdust was dried to 0% moisture content (MC) and treated for different times (3, 5, or 10 min) and at different temperatures (200, 220, 240, 260, 280, or 300 °C). Heat treatment was performed in a lab calciner with a thermostat and time adjustment capabilities (Griu 2014). Sawdust samples were weighed before and after the treatment to within an accuracy of 0.001 g, and based on the data obtained, the mass loss (Table 3) was calculated using the following equation,

$$M_l = \frac{m_i - m_f}{m_i} \cdot 100 \qquad [\%] \tag{1}$$

where m_i is the initial mass in g, m_f is the final mass in g, and M_l is the mass loss in %.

The calorimetric method was used to determine the calorific value using explosive combustion with excess oxygen (at 30 atm) and pellet samples of 0.6 to 0.8 g and 8% moisture content with an accuracy to within 0.0002 g. The general equation used to determine the CV was,

$$CV_{MC} = \frac{C \cdot (T_f - T_i)}{m} - \sum_{i=1}^{n} Q_i \qquad [MJ/kg] \tag{2}$$

where C is the calorimetric coefficient determined by calibration with benzoic acid, expressed in MJ/°C; T_i is the initial temperature in °C; T_f is the final temperature in °C; m is the mass of pellet samples in g; and Q_i is the heat released by the copper or nickel wire in MJ/kg.

Between the two values, NCV (net calorific value) and GCV (gross calorific value), only NCV is predominantly used and is usually denoted CV. Ten tests were performed for each temperature and treatment time, and the average value of these tests was reported. Whether or not the pellet mass loss increased the CV was observed and the degree of this increase was estimated. The increasing value was determined by the following equation,

$$I_{CV} = \frac{CV_t - CV_m}{CV_m} \cdot 100 \qquad [\%] \tag{3}$$

where CV_t is the calorific value of the torrefied samples expressed in MJ/kg and CV_m is the calorific value of the control (non-torrefied) samples in MJ/kg.

MODELING THE INFLUENCE OF SAWDUST TORREFACTION ON CV

The main chemical compounds of wood are cellulose, hemicellulose, and lignin. They each have different calorific values and make up different percentages of the wood. Deciduous species contain 25% lignin, 45% cellulose, 24% hemicelluloses, and 6% other, secondary substances. During the thermal treatment of woody biomass, hemicelluloses are decomposed firstly; then cellulose, and finally lignin, as it is more resistant to high temperatures than cellulose or hemicelluloses (Shulga *et al.* 2008; Wang *et al.* 2011). Previous temperature values sometimes overlap depending on the species and treatment time. Beech contains, on average, 25% lignin, 48% cellulose, 22% hemicelluloses, and 5% secondary chemical compounds (including extractive components of the wood, fatty acids, and tryglycerides).

Chemical compounds influence the calorific value (Obernberger and Thek 2004; Chen *et al.* 2012; Moya and Tenorio 2013). Knowing that lignin from beech wood has a calorific value of 25.1 MJ/kg and that the other compounds (cellulose and hemicelluloses) have calorific values of 16.1 MJ/kg (Griu 2014), the following equation can be used to predict the total net calorific value,

$$CV = 25.1 \cdot Li/100 + 16.1 \cdot (Ce + He)/100 \quad [\text{MJ/kg}] \tag{4}$$

where Li is the lignin content in wt. %, Ce is the cellulose content in wt. %, and He is the hemicelluloses content in wt. %.

During torrefaction at temperatures from 200 to 300 °C, hemicelluloses decompose first. The mass loss does not exceed 22%, the maximum hemicelluloses content in beech sawdust. Modelling must take into account that from 1 to 22% of the hemicelluloses initially present are decomposed. After each loss, lignin and cellulose enrichment is reconsidered. The different percentages of lignin and cellulose are taken into consideration. Secondary substances (usually 5% in beech) do not significantly influence the calorific value (because they do not burn and are found in the ash) so they were neglected. Cellulose represents 66% of the calorific value and the remaining 34% is from lignin. Each percentage of hemicelluloses lost is distributed between cellulose and lignin, as seen in Table 3. Under the given conditions, the growth rate of cellulose and lignin are given by the following equations,

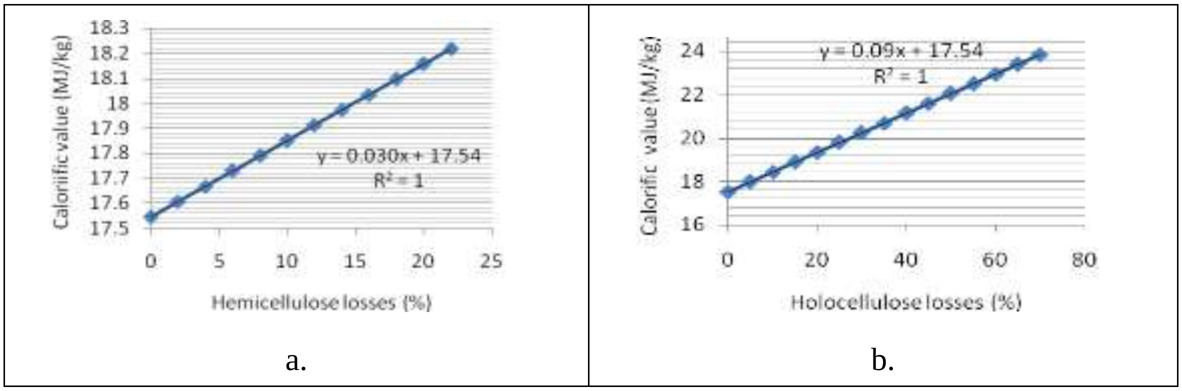
$$\begin{aligned} Ce_{ic} &= 48 + 0.66 \cdot He_{los} \\ Li_{ic} &= 25 + 0.34 \cdot He_{los} \end{aligned} \tag{5}$$

where Ce_{ic} is the increase in cellulose content in %, He_{los} is the hemicelluloses loss in %, and Li_{ic} is the increase in lignin content in %.

Table 3. Increase in the Net Calorific Value on the Base of Hemicelluloses Content during Torrefaction

Hemicelluloses, initial 22 (%)		Cellulose, initial 48%	Lignin, initial 25%	Net Calorific Power (MJ/kg)
Losses (%)	Remaining (%)			
0	22	48.00	25.00	17.54
2	20	49.32	25.68	17.60
4	18	50.64	26.36	17.66
6	16	51.96	27.04	17.72
8	14	53.28	27.72	17.78
10	12	54.60	28.40	17.85
12	10	55.92	29.08	17.91
14	8	57.24	29.76	17.97
16	6	58.56	30.44	18.03
18	4	59.88	31.12	18.09
20	2	61.20	31.80	18.15
22	0	62.52	32.48	18.21

An increase in the calorific value during torrefaction, from 17.54 to 18.21 MJ/kg (3.81%) with a 22% decrease in hemicelluloses content was observed. This linear increase is more visible in Fig. 2a (for hemicellulose).



a. b.

Fig. 2. Increasing of calorific value related to hemi- (a) and holocellulose losses (b)

Previous studies (Teuch *et al*. 2004; Chen *et al.* 2014) have shown that the increase of calorific value is higher than that obtained by this modeling, *i.e.* 5 to 8%. Therefore the problem of cellulose introduction was placed inside of the algorithm, considering that some of hemi- and cellulose are degraded during torrefaction process up to 300 °C. Considering the sum of two components (hemicellulose and cellulose) as holocellulose (70% of the total mass), the new algorithm was activated. The new model for holocellulose degradation in time of torrefaction is shown in Fig. 2b and in Fig. 3.

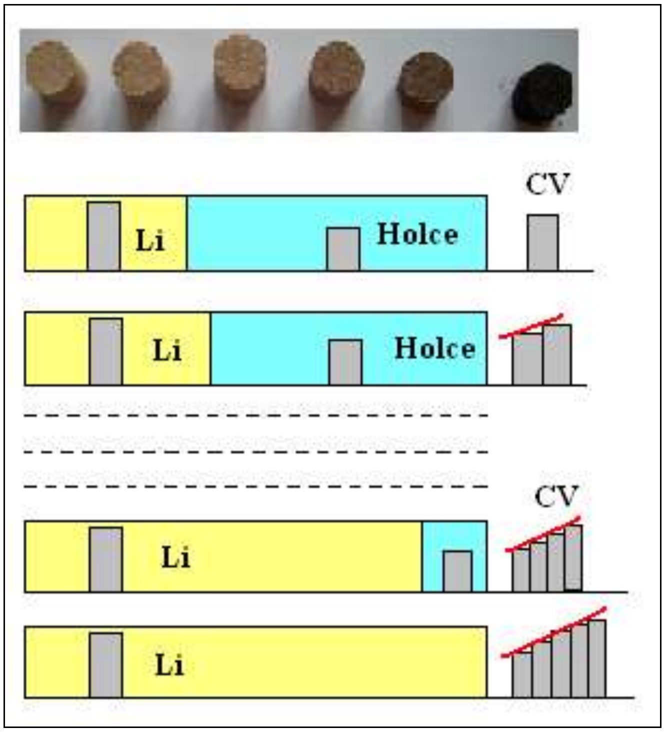


Fig. 3. Algorithm of CV increasing with holocellulose (Holce) degradation and lignin (Li) increase

There was observed a direct relationship between CV and holocellulose losses. A maximum CV of 23.84 MJ/kg (an increase of 35.9%, related to the minimal value of 17.54 MJ/kg) was achieved.

RESULTS AND DISCUSSION

Table 4 shows the mass losses and calorific value increases achieved by torrefaction.

Table 4. Mass Losses and Increase in Calorific Value after Torrefaction

Time	Temp (°C)	Mass Loss (%)	Calorific Value (MJ/kg), MC=8%	
			Torrefied Samples	Control (Non-Torrefied) Samples
3 min	200	3.88	17.886	17.509
	220	4.98	18.046	
	240	5.40	18.206	
	260	5.94	18.366	
	280	6.78	18.526	
	300	8.60	18.686	
5 min	200	5.35	18.167	
	220	6.21	18.379	
	240	7.82	18.592	
	260	9.21	18.805	
	280	11.75	19.017	
	300	13.35	19.230	
10 min	200	7.47	19.133	
	220	8.54	19.566	
	240	9.84	19.999	
	260	11.73	20.432	
	280	14.85	20.865	
	300	20.26	21.298	

Increasing treatment time and temperature were accompanied by increasing mass loss (maximum 8.6% for 3 min, 13.3% for 5 min, and 20.2% for 10 min) and pellet calorific value. Compared to a calorific value of 17.509 MJ/kg in the control pellets, treatment for 3 min increased the calorific value by 2.1% at 200 °C and 6.7% at 300 °C; treatment for 5 min increased the calorific value by 3.7% at 200 °C and 9.8% at 300 °C; and treatment for 10 min increased the calorific value by 9.2% at 200 °C and 21.6% at 300 °C.

The increase of calorific value as related to torrefaction temperature and time are shown in Fig. 4.

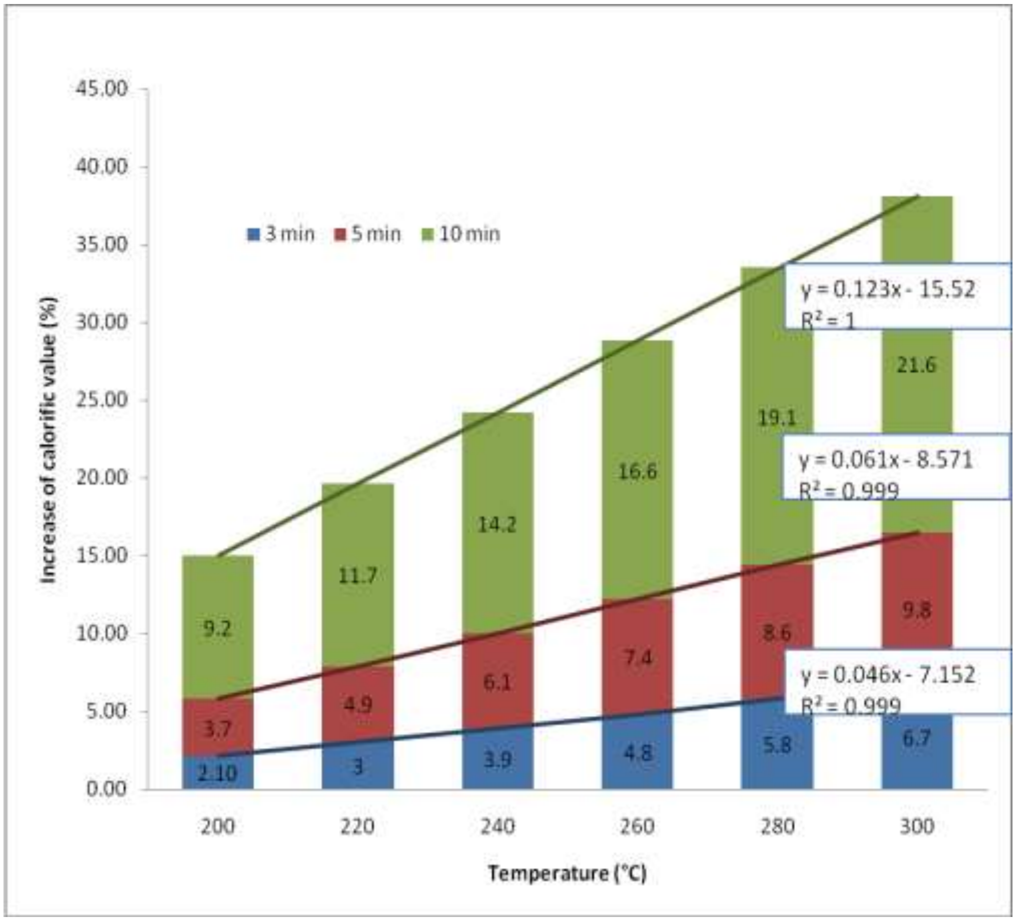


Fig. 4. Increasing calorific value with temperature and time of torrefaction

The three equations in Fig. 4 converge near the temperature range of 140 to 150 °C (when the intersection with the horizontal axis is made), meaning that this temperature range marks the beginning of hemicellulose degradation. The curve for 10-min torrefaction is very distant from the other two (about three times above), meaning that the 10-min treatment was too severe and that 5 min was the best treatment time (taking into account other properties such as color change, abrasion, and stability of pellets). A noticeable color change was also observed depending on the treatment temperature (Griu 2014; Griu and Lunguleasa 2014). From this point of view, 260 °C was the most suitable temperature. When the treatment time was 10 min and the temperature exceeded 260 °C, the color changed to black, indicating serious carbonization and degradation of the beech sawdust.

The modeling of torrefaction process predicted an increase in calorific value by 3.81% during the degradation of hemicelluloses and by 35.91% if holocelluloses are completely degraded. If these values are compared with the maximum of experimental CV increase of 21.6%, it can be concluded that not all cellulose is degraded. Only partical degradation of cellulose occurs, even if the treatment regimen is the most severe (10 min and 300 ^{o}C).

ECONOMIC EVALUATION

The economic evaluation was based on estimates of the annual investment and costs required for pellet production. The maximum capacity of one torrefaction line is estimated to be about 50 to 60 ktonnes per year, corresponding to 30 to 40 MWh of fuel (WFH 2013). Biomass used for heat production costs between 26 and 156 €/MWh, which is competitive with fossil fuels, the price of which range from 52 to 234 €/MWh. In the UK, it is estimated that wood-based energy could reduce 2.7 Mt CO_2 emissions/year if it displaces the energy from fuel oil for a furnance with a heat capacity of 30 MWh (Dhillon and von Wuelhlisch 2013).

Considering the usual price of non-torrefied pellets of about 2.6 €/kg and the main operational costs (storage, drying, pelleting, cooling, and packing) to produce pellets, a clear difference in costs between torrefied and non-torrefied pellets is observed. The prices of the two types of pellets were compared, as shown in Table 5. For determining the values of torrefied pellets, Table 5 takes into account the costs of torrefaction operation of 0.09 €/kg and additional investment costs of 0.01 €/kg.

Table 5. Operational Costs of Producing Torrefied and Non-Torrefied Pellets

Costs	Non-Torrefied Pellets		Torrefied Pellets	
	%	€/kg	%	€/kg
Raw Material (Moist Sawdust)	33.8	0.88	32.6	0.88
Storage Yard	2.7	0.07	2.6	0.07
Drying	30.0	0.78	28.9	0.78
Torrefaction	0	0	3.3	0.09
Pelleting	8.9	0.23	8.5	0.23
Cooling	2.7	0.07	2.6	0.07
Packing	9.8	0.26	9.6	0.26
Pellet Storage	8.1	0.21	7.8	0.21
Investment Costs	4.0	0.10	4.1	0.11
Total	100	2.60	100	2.70

The average consumption of energy for household heating is around 190 MJ/m^2/year (Robert *et al*. 2005), assuming 5 months of heating during the winter. The energy requirements for heating with torrefied pellets and the efficiency of pellet heating can be determined. Further, the costs of heating for a home with pellets with or without torrefaction can be evaluated, as shown in Table 6. The data analysis shows that the cheaper energy to heat a 200-m^2 house was obtained using torrefied pellets (7395 €/year), and the more expensive was using non-torrefied pellets (7562 €/year). Part of the costs savings are because the torrefied pellets have a higher calorific value than standard, non-torrefied pellets.

Table 6. Total Annual Costs for House Heating with Torrefied Pellets Compared to that with Non-Torrefied Pellets

No	Characteristics	Price (€)		Increase(+) or decrease(-) (%)
		Non-Torrefied Pellets, U = 0%	Torrefied Pellets 260 °C, 5 min	
1.	CV (MJ/kg)	17.50	18.80	+7.4
2.	Annual Energy Demand (MJ/year·m^2)	190	190	0
3.	Annual Demand of Pellets (kg/year ·m^2) [2:1]	10.85	10.10	-6.89
4.	Unit Price (€/kg)	2.60	2.70	+3,84
5.	Pellet Costs (€/m^2/year) [4×3]	28.21	27.27	-3,31
6.	Price of Heating Unit (€/MJ ×10^3)	148.49	143.57	-3.31
7.	Initial Investments (on 10 years) (€/year·m^2)	7.5	7.6	+1.33
8.	Maintenance and Amortization (€/year·m^2)	2.1	2.1	0
9.	Total Costs (€/year·m^2) [5+6+7]	37.81	36.97	-2.20
10.	Cost of House Heating per 200 m^2 (€/year)	7562.4	7395.6	-2.2

Table 6 shows that the annual cost of house heating is 2.2% lower than using non-torrefied pellets even though the price of torrefied pellets is 3.84% higher. The benefits of the torrefied products are that they have higher calorific value and absorb less moisture than ordinary, non-torrefied pellets. The data shown in Table 6 demonstrate the negative effects of the higher price of torrefied pellets in comparision with that of the non-torrefied pellets, as well as the positive effects of increasing the calorific value of the torrefied pellets. This positive effect of increasing the calorific value is offset by annual fuel demand, which decreases by 6.89% for a house with an area of 200 m^2. The economic analysis also considered that investment costs involved with using torrefied pellets are 1.33% higher, due to additional operation of torrefaction.

CONCLUSIONS

1. Torrefying beech sawdust showed increased the calorific value for each 3-, 5-, and 10 min treatment with increasing temperature from 200 to 300 °C.
2. Mass loss of torrefied sawdust increases with increasing of treatment time and temperature, starting from a minimum value of 3.88% for 3 min and 200 ^{o}C and peaking of 20.26% for 10 min and 300 ^{o}C.
3. The experimental aspects of this paper were used to validate the theoretical model (algorithm on calorific value growth for pellets).

4. It was found that treatment at 260 °C for 5 min was optimal to obtain qualitatively torrefied pellets. Following this treatment, the CV was 18.805 MJ/kg, an increase of 7.4% over the control pellets.
5. The economic effects of beech torrefied pellets considering the criteria of annual demand, price, and cost of house heating are numerous but positive. The increase in calorific value is the chief positive effect and the negative is the higher price. A 2.2% decrease in the cost of home heating with torrefied pellets was noted.
6. The model of the torrefaction process showed that hemicellulose loss increases the calorific value by a maximum of 3.81%, lower than the experimental result. This indicates that cellulose is also degraded during torrefaction, as the maximum CV increase with holocellulose degradation was about 35.91%. Note that not all the wood cellulose breaks down, even though the procedure used is the most severe.

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