CHEMICAL ENGINEERING TRANSACTIONS

VOL. 50, 2016

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Katharina Kohse-Höinghaus, Eliseo Ranzi

ISBN 978-88-95608-41-9; **ISSN** 2283-9216

Value chain analysis of biocarbon utilisation in residential pellet stoves

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Biocarbon production is a thermochemical conversion process, which transfers biomass into solid fuels characterized with superior handling, grinding and combustion properties. Biocarbon can be potentially utilized as a high quality fuel in small-scale heating applications, as charcoal, powder, briquettes or pellets. However, there are only few studies on the use of biocarbon in residential stoves. Charcoal based modern residential stoves can achieve high thermal efficiency and low emissions. In this study, the main objectives were to assess the energy efficiency of the whole value chain for utilization of carbonized wood for small-scale biocarbon pellet based stoves and to evaluate the overall heat production cost of the whole value chain by a techno-economic approach, under Norwegian conditions.The carbonization temperature did not affect the stove thermal efficiency significantly. However, at higher carbonization temperatures higher biocarbon pellet production cost and higher overall heat production cost were obtained when standalone pellet production was considered. In the case of pellet and district heat coproduction, the pellet production cost was always lower than the corresponding one without district heat production.

1. Introduction

Biocarbon production is a thermochemical conversion process, which transfers biomass into solid fuels characterized with superior handling, grinding and combustion properties (Neves et al., 2011, Antal and Grønli, 2003). The process includes steps such as devolatilization, depolymerization and carbonization, and generates a solid product as the main output together with tarry vapours and gases (Brewer and Brown, 2012). The C content of the solid product can reach more than 90% on an dry ash-free (daf) basis, with O content below 6% and H content near 1% (Antal and Grønli, 2003, Demirbaş, 2001, Neves et al., 2011). The peak temperature reached during the carbonization process has a decisive effect on reaction pathways and biocarbon properties (Antal and Grønli, 2003, Demirbaş, 2001). Increasing the peak temperature typically results in higher fix-C content, surface area and porosity, while it reduces the biocarbon yield and volatile matter content (Demirbaş, 2001, Strezov et al., 2007).Moderate heating rate and long residence time are applied to maximize fix-C yields in conventional biocarbon production processes (Lehmann, 2007). Physical and chemical properties of the biomass input also considerably influence the distribution of solid and volatile products, biocarbon properties and the process efficiency (Abdullah et al., 2010, Abdullah and Wu, 2009, Ioannidou and Zabaniotou, 2007).Biocarbon can be potentially utilized as a high quality fuel in small-scale heating applications (pellet boilers and stoves) (Khalil et al., 2013), as a fuel in peak load boilers, cofiring in bioenergy plants, soil amendment, as a reductant in metallurgic industry, adsorbents, and nanomaterials in semiconductor industries. However, in this study, we focus on the potential use of biocarbon in small-scale heating applications, i.e. pellet stoves, for the Norwegian residential sector. In Norway, space heating is the major energy consumer in the residential sector (SSB, 2014). Approximately 12% of Norwegian households have common central heating while less than 1% have access to district heating (Obernberger and Thek, 2010). About 75% of the households are using electricity based heating systems, and the majority of these households also have wood stoves as combined systems, and some have pellet stoves. Thus, there is a potential to retrofit wood based heating systems with improved feedstocks. Use of biocarbon in stoves could give the most stable combustion conditions and as well lowest emissions fluctuations (Antal et al., 1996, Thrower, 1996). However, there are only a few studies on the use of biocarbon in residential stoves, one study from Norway carried out emission performance studies for automatically fed charcoal stoves of typical size of 5 kW heat output, where emissions from two different types of stoves were compared for both wood and charcoal (Ramdahl et al., 1982). Another study developed and tested a charcoal powder based residential stove for Japanese conditions, studying charcoal derived from wood and various biomass residues, and they measured highest thermal efficiency was 86% (Horio et al., 2008). Recently, torrefied pellets usage in a pellet stove was studied to improve the emission performance under Norwegian conditions, and it was found that emissions of CO, unburned hydrocarbons and the organics in particles smaller than 1 µm were reduced in comparison to wood pellets (Khalil et al., 2013). In this study, our main objective is to assess the energy efficiency of the whole value chain for utilization of carbonized wood for small-scale biocarbon pellet based stoves, and to evaluate the overall heat production cost of the whole value chain by a techno-economic approach.

2. Methodology

Spruce woodchips are considered as the feedstock for wood pellet and biocarbon pellet production. Ultimate analyses of raw spruce (Khalil et al., 2013), spruce carbonized at a lower temperature (Tapasvi et al., 2012), and spruce carbonized at higher temperatures (Demirbaş, 2001) were used as input data to Fuelsim-Average (Skreiberg, 1997) to evaluate the thermal and energy efficiencies [7], when these solid fuels are combusted in residential stoves (Khalil et al., 2013, Koyuncu and Pinar, 2007).

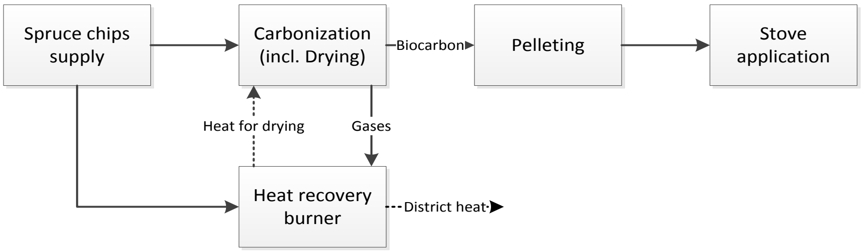

Figure 1 : Value chain for biocarbon pellet production and stove application.

Table 1 Details of the cost functions of the process equipment in the biocarbon production

Process equipment	Basis of the cost function	Equipment purchase cost function (M$)	Reference year	Installation factor	Reference
Fuel storage	$\dot{M}_F$ (mass flow, wet tonne/h)	$(\dot{M}_F/33.5)^{0.65}$	2001	1.86	(Hamelinck and Faaij, 2002)
Biomass conveyor	$\dot{M}_F$ (mass flow, wet tonne/h)	$0.35(\dot{M}_F/33.5)^{0.8}$	2001	1.86	(Hamelinck and Faaij, 2002)
Fuel dryer	A_d (area, m^2)	$15000 + 10500{A_d}^m$	1998	1.86	(Towler and Sinnott, 2013)
Carbonization	m (weight of the vessel, kg)	$f_m 70 (m)^{-0.34}$	2000	1.80	(Peters et al., 2003)
Air compressor	$\dot{W}_{air}$ (compressor power, MW_e)	$6.03(\dot{W}_{air}/10)^{0.67}$	2009	1.46	(Larson et al., 2009)
Heat recovery burner	Vg (volumetric flowrate of inlet gas, m^3/h)	$0.48Vg^{0.82}$	2004	1.86	(Mussatti, 2001)

Techno-economic analysis was performed for the whole value chain consisting of spruce woodchips supply, conversion into biocarbon, pelleting and pellet stove application (Figure 1). Mass and energy balances were solved in a Microsoft Excel spreadsheet for the whole value chain, except for the stove application, for which

Fuelsim-Average was used. The drying efficiency, the thermal efficiency of the heat recovery burner and the energy loss during pelleting were assumed to be 75%, 90%, 5%, respectively.

The cost of biomass supply was estimated according to Norwegian conditions (Kempegowda et al., 2015). A biocarbon production capacity of 40 dry tonnes/day was assumed in four parallel units with a capacity of 10 dry tonnes/day each. The methodology of economic analysis is reported in details elsewhere (Kempegowda et al., 2015), therefore only the differences are described here. In this study a depreciation period of 15 years, a construction and commissioning duration of 1 year and an income tax rate of 28% were assumed, and the reference year was 2015. The cost functions of biocarbon production is given in Table 1, while in the case of pellet production and stove application direct vendor quotes were obtained. The district heat tariff was 78 US$/MWh.

3. Results and discussion

3.1 Efficiency analysis

Energy efficiency of biocarbon pellet production without or with district heat coproduction

Energy efficiency was assessed for the production of biocarbon pellets without and with district heat coproduction Figure 2 (a). The mass yields and the lower heating values (LHVs) of the carbonization gases were estimated based on the literature (Neves et al., 2011), while biocarbon yields (Demirbaş, 2001) and pellet LHVs given in Table 2 were calculated by correlations (Skreiberg, 1997). In the case of pellet production without district heat production the lowest and highest energy efficiencies are obtained at 477°C and 277°C, respectively. In the case of pellet production with district heat production increasing carbonization temperature results in increasing district heat production, hence the total energy efficiency increases. Coproduction of biocarbon pellets and district heat gives higher total energy efficiency at a particular temperature compared to that of standalone pellet production. A significant portion of the input biomass is used for drying as shown in the energy flow (Sankey) diagram in Figure 2 (b).

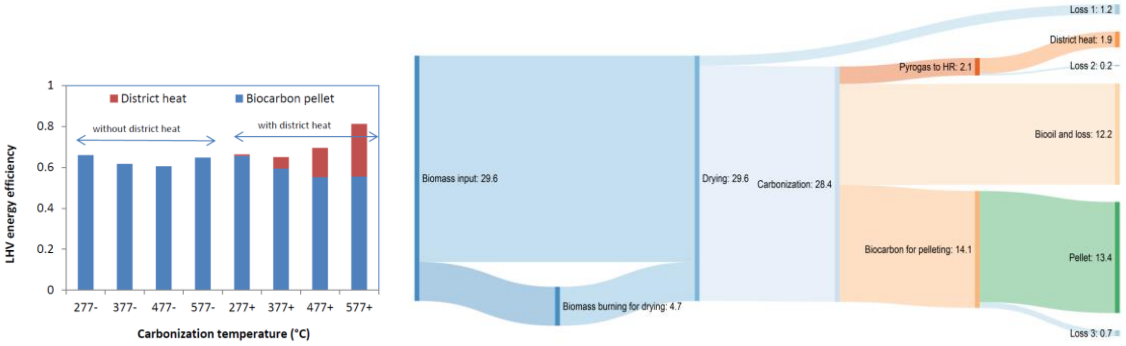

Figure 2:(a) Break down of LHV (lower heating value) energy efficiency in the case of biocarbon pellet production at various temperatures without (-) or with (+) coproduction of district heat (b) Sankey diagram for biocarbon pellet production at 477°C with district heat production, (Energy flow in MW).

Thermal efficiency of stove application

The moisture content of the raw spruce has a significant impact on the thermal efficiency of the stove as shown in Figure 3(a). The higher the moisture content in the biomass, the higher the heat losses are in the chimney. Increasing the carbonization temperature yields higher C content, and the LHV of the biocarbon pellets increases (Table 2). However, for the same excess air ratio and chimney inlet temperature the flue gas composition does not change significantly with increasing carbonization degree, which results in approximately the same thermal efficiencies in the case of the biocarbon obtained at various carbonization temperatures. The chimney inlet temperature is an important parameter to control in order to reduce the chimney losses. The higher the chimney inlet temperature, the lower the thermal efficiency is: as shown in Figure 3(b). Using raw woodchips or biocarbon obtained at different carbonization temperatures, there is not a significant difference between the thermal efficiencies at a given chimney inlet temperature and excess air ratio.

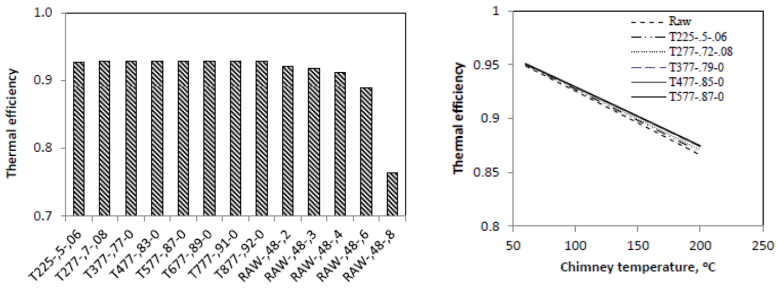

Figure 3: Thermal efficiencies of stove (a) for various carbonization temperatures (T in °C), C contents (dry ash free basis (daf)) and moisture content fractions (1st, 2nd, 3rd numbers, respectively) at an excess air ratio of 1.5 and a chimney inlet temperature of 120°C. (b) Thermal efficiency of stove as a function of chimney inlet temperature for various carbonization temperatures (T, °C), C contents (daf) and moisture content fractions (1st, 2nd, 3rd numbers, respectively) at an excess air ratio of 1.5.

3.2 Emission aspects

CO is regarded as a good indicator of combustion quality. Small-scale wood stoves of Belgium conditions and their performance of CO emissions varied from 447 to 1185 mg/Nm^3 for a 10 kW wood stove (Obaidullah et al., 2014). Use of wood pellets and torrefied wood pellets in a pellet stove under Norwegian conditions (Khalil et al., 2013). CO emissions of wood pellets were 750 and 450 mg/Nm^3 at low and high loads, respectively, while CO emissions of wood pellets torrefied at 225°C were 518 and 275 mg/Nm^3 at low and high loads, respectively. I.e. significantly lower CO emission levels were achieved using torrefied wood pellets. As shown in Figure 4(a), CO concentration in the flue gas negatively affects the energy efficiency of the stove. According to measured CO emissions of wood stoves from literatures as explained above, the energy efficiency can decrease up to 4 vol% compared to a case where CO is not emitted.

3.3 Overall energy efficiency of the whole value chain

The overall energy efficiency of the whole value chain is shown in Figure 4 (b) as a function of moisture content of raw spruce woodchips. Varying the moisture content of the raw biomass does not significantly affect the overall energy efficiency at a certain carbonization temperature.

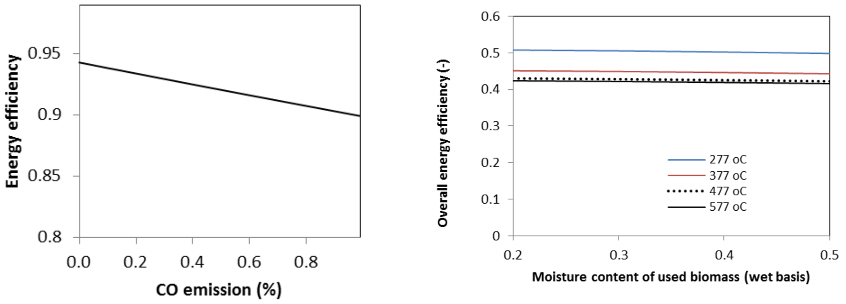

Figure 4 (a) Energy efficiency of stove as a function of CO concentration (vol%) in the flue gas at a biocarbon C content of 0.92 (daf), moisture content of 0, a chimney inlet temperature of 120°C and an excess air ratio of 1.5. (b) Overall energy efficiency of the whole value chain (conversion of raw spruce woodchips into pellets with coproduction of district heat and combustion in a residential pellet stove) as a function of moisture content of the raw spruce woodchips at an excess air ratio of 1.5 and a chimney inlet temperature of 120°C for various carbonization temperatures.

3.4 Economic analysis

The net investment cost of a pellet stove system for a nominal load of 8kW costs around 4306 US$ which includes catalyst converter (if applicable) 338 US$, chimney connection 152 US$. Pellets are made with biooil as additive. It is assumed that 5% of the LHV is lost in the pelleting process. The LHV values were calculated based on the Fuelsim model (Skreiberg, 1997). Biomass supply cost was estimated to be 16.5 US$/MWh.

Stove thermal efficiency of 92% were considered for economic analysis. As shown in Table 2, the pellet production cost and overall heat production cost increase by increasing the carbonization temperature in the case of standalone pellet production (Table 2). However, when district heat is coproduced, pellet production cost and overall heat production cost decreases. Selling heat results in decreased pellet production cost and overall heat production cost compared to that when the heat from burning the carbonization gases is used for drying the raw spruce woodchips. The Norwegian wood pellet price varied between 0.33 and 0.50 NOK/kWh (40 and 60 US$/MWh, respectively) between 2010 and 2013 (NOBIO). The biocarbon pellet prices given in Table 2 lie within this range. In a German case study for a small-scale wood pellet stove an overall heat production cost of 87.1 EUR/MWh (LHV basis) was reported (Obernberger and Thek, 2010), which can be converted into 109.4 US$/MWh by assuming a thermal efficiency of 90% and a conversion rate of 1.13 US$/EUR (2015). The overall heat production costs obtained in this study are slightly higher than this value.

Table 2 Biocarbon yield, pellet lower heating value (LHV), pellet production cost and overall heat production cost for the whole value chain for spruce woodchips carbonized at various temperatures. DM: dry matter

Carbonization °C	Biocarbon yield[1] g DM/g DM spruce	Pellet MJ/kg	Pellet production US$/MWh	Overall heat production US$/MWh
277	0.38	26.21	40.8 (40.0)	128.8 (128.1)
377	0.33	27.33	46.2 (42.0)	136.81 (130.63)
477	0.29	28.88	50.1 (38.7)	142.62 (125.74)
577	0.28	30.08	52.4 (31.0)	146.03 (114.47)

[1] Calculated based on the work (Demirbaş, 2001)

Sensitivity analysis for market penetration of biocarbon pellet stoves

Figure 55 shows the sensitivity towards overall heat production cost for the selected biocarbon pellet carbonized at 577 °C. The factors selected are stove efficiency (85-95%), operating hours (1000 to 1400 hours/year), operating and maintenance costs (1-5%) of total investment (TCI), interest rate in the range of 5-9%, pellet production cost (25-36.5 $/MWh) and stove investment (70-130 %) of base investment. Among these investment cost has major impact on the specific heat production cost.

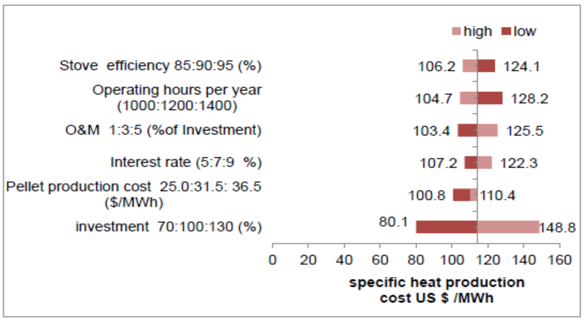

Figure 5: Sensitivity analysis for market penetration of biocarbon pellet stoves in the case of biocarbon produced at a carbonization temperature of 577°C at a base case specific heat production (114.47 $/MWh).

4. Conclusions

The value chain of biocarbon production with pelleting for stove application was investigated in terms of energy efficiency, emission aspects and economic performance. Increasing the carbonization temperature resulted in increased total energy efficiency of pellet production with district heat coproduction, however, a different trend was obtained without district heat production. The carbonization temperature did not affect the stove thermal efficiency significantly, which also means that the C content of the biocarbon did not influence the stove thermal efficiency. However, at higher carbonization temperatures, higher biocarbon pellet production cost and higher overall heat production cost were obtained for standalone pellet production. In the case of pellet and district heat co-production, the pellet production cost was always lower. Sensitivity analysis showed that investment cost, pellet price and stove efficiency have major impacts on the overall heat production cost of biocarbon pellet stoves. Further work will be needed to see the demonstrative aspects of biocarbon pellet stoves in the residential sector, including the operational and environmental emissions aspects. Previous work suggests that pellets made from torrefied biomass can significantly reduce emission levels of unburnt, and this could be significantly further improved by using biocarbon pellets and applying a catalytic afterburner.

Acknowledgements

The authors acknowledge the financial support from the Research Council of Norway, the industrial partners (Elkem AS, Department Elkem Technology; Norsk Biobrensel AS; AT Biovarme AS; Eyde-nettverket Saint Gobain Ceramic Materials AS; Eramet Norway AS; Alcoa Norway ANS) in the BioCarb+ project and the Project OTKA PD-108389 of the Hungarian National, Research, Development and Innovation Office (NKFIH).

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