ENERGY EFFICIENCY, ENVIRONMENTAL ASPECTS AND COST-EFFICIENCY OF SMALL-SCALE BIOCARBON CONVERSION APPLICATIONS – VALUE CHAIN ANALYSIS

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ABSTRACT: 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, objective is to assess the energy efficiency of the whole value chain of spruce wood residue conversion to carbonized biocarbon and co-district heat potential, as well, conversion of biocarbon to pellets and applying converted biocarbon pellets in stoves of nominal capacity of 8 kW. Study evaluated the overall specific pellet and heat production cost for the value chain using techno-economic method specific to Norwegian conditions. Study concluded that carbonization temperature generally resulted in increased total energy efficiency of pellet production both with and without district heat production. However, carbonization temperature did not affected 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 without district factor. In the case of pellet and district heat coproduction, the pellet production cost was always lower than the corresponding one without district heat production.

Keywords: Wood pellet, biocarbon pellet, pellet stove, thermal efficiency, environmental performance, techno-economics

1 INTRODUCTION

Traditional small-scale residential heating applications using woody biomass in different shapes (logs, briquettes, pellets) are a source of significant emission levels of unburnt (particles, CO, hydrocarbons, etc.). A main reason for this is the inherent drawback of all raw woody biomass fuels, i.e. they have a large content of volatiles in addition to the biocarbon content, resulting in a batch combustion behavior giving varying heat output and unstable combustion conditions. Even though more dominant for wood logs and briquettes, this behavior can also be seen for each single wood pellet fed into a pellet stove, especially at low load operation. Hence, thermal upgrading of woody biomass to fuel qualities depleted in volatiles and enriched in biocarbon is one way forward towards more environmentally sustainable residential biomass utilization. Biocarbon production is a thermochemical process , this raw biomass into solid fuels. The main characteristics are *superior handling, grinding and combustion properties* [1, 2]. The process includes multiple process steps, first being devolatalization, depolymerization and carbonization, and generates a solid product as the main product output together with hydrocarbon gases both condensable and non-condensable [3]. The process of carbonization can reach product quality consisting carbon (C) content more than 90% on an dry ash-free (daf) basis, with O content below 6% and H content near 1% [1, 2, 4]. Operating conditions such as peak *temperature* achieved by carbonization process has influential effect on *reaction paths*, *biocarbon properties* [2, 4].Depending on the properties, fixed carbon, reactivity , porosity and surface area, biocabron can be utilized in cooking, residential heating, peak load boilers, adsorbent, sail conditioning, metallurgical production. Physical and chemical properties depends on the carbonization process type and process conditions (Temperature, Pressure, heating rates). 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. Major energy consuming sector is residential heating sector in Norway [5]. Charcoal based modern residential stoves can achieve high thermal efficiency and low emissions. There are few studies on high efficiency charcoal fed stove utilization in Norway and Japan, automatically fed charcoal stoves [6], charcoal powder based residential stove for Japanese conditions, measured highest thermal efficiency was 86% [7]

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.

2 METHODOLOGY

In this work, Spruce forest wood residues are considered as the feedstock for production of biocarbon pellet though pressurized and atmospheric carbonizaiton process. Ultimate analyses of raw spruce gathered from the Khalil et.al [8], spruce carbonized at a lower temperature [9], and spruce carbonized at higher temperatures [4], spruce pressurized at high pressure gathered from wang et.al (reference), were used as input data to Fuelsim-Average developed by Skreiberg [10] to evaluate the thermal and energy efficiencies [7], these when these solid fuels are combusted in residential stoves. Reported flue gas emissions [8, 11] were also used as input to Fuelsim-Average.

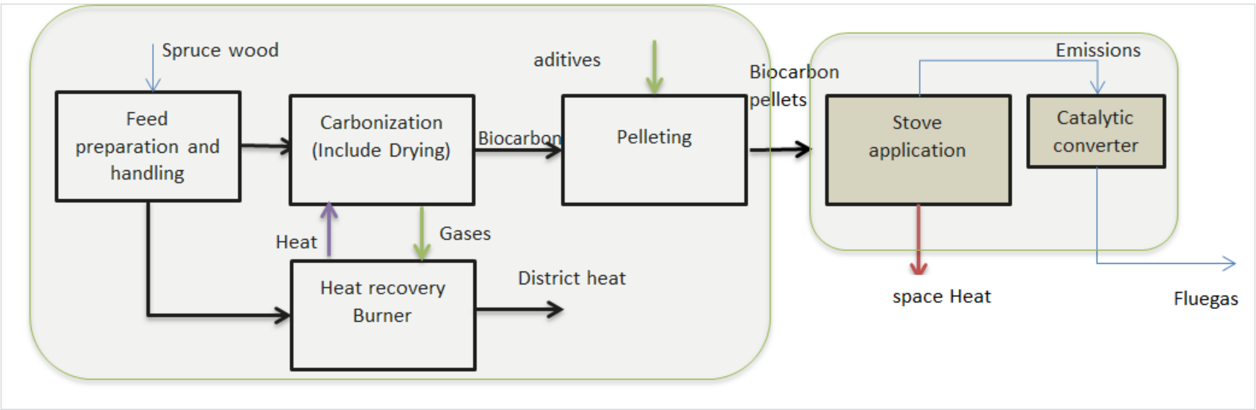

Figure 1: Value chain for biocarbon pellet production and stove application.

Value chain analysis was performed for the whole value chain consisting of spruce woodchips supply, carbonizaiton process, pellet production line and utilization of pellet in stove application (Figure 1). Excess heat producced by buring fuel pyrogases are used for district heat and auxiliary drying process. The heat from burning the carbonization gases is either used for raw spruce drying or district heat production. Mass and energy balances were solved in a Microsoft Excel spreadsheet (Figure 2) for the biocarb produciton value chain, except for the stove application, for which Fuelsim-Average was used to evaluate stove performance based on the indirect method. 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 Kempegowda [12]. 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 [12], 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 district heat tariff was 78 US$/MWh.

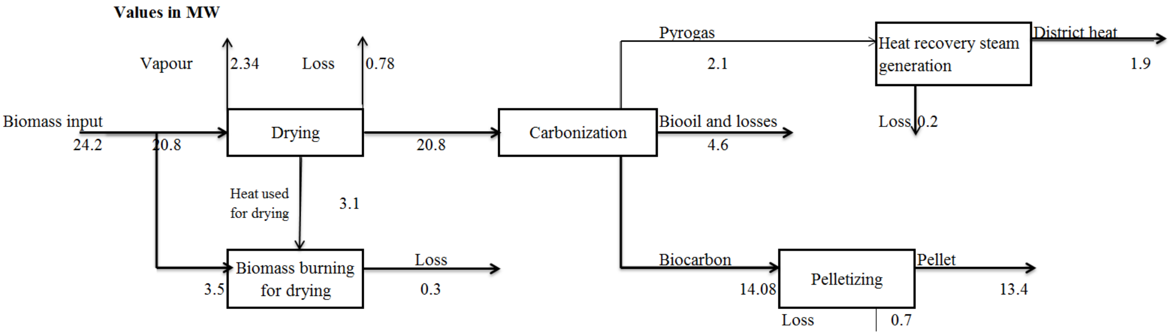

Figure 2: Mass and energy balance of Carbonization plant at 477 ^{o}C

3 RESULTS AND DISCUSSION

3.1 Energy conversion efficiency for biomass to biocarbon for carbonization process

Enegry conversion efficiency of converting biomass to biocarbon depends on process conditions such as heating rate slow or rapid, carbonizaiton temperature, pressure.

Energy conversion efficiency is defined by

$$\eta_{biocarbon} = y_{biocarbon}\left(\frac{HHV_{biocarbon}}{HHV_{biomass}}\right)$$

, here we used correlation suggested by Antal

$$HHV_{\text{biocarbon}} = 35.1 - 0.178\%VM - 0.4292\%Charash \quad [2]$$

for estimation of Biocarbon heating value. Energy conversion efficiency is depicted in the Figure 3 for various cases. Two wood species birch and spruce are compared, which are the wood species important for Norwegian conditions. Variables considered are heating time, pressure and peak temperature attainment. For birch species, there is no impact of prolonged heating time on both fixed carbon yield and energy conversion efficiency to biocarbon. Figure (a) suggests that increase of pressure increases the energy conversion efficiency from 44 % to 60 %. Heating time has not much impact in the energy conversion efficiency for biocarbon, however, there is impact on the energy conversion efficiency by changing different wood species, spruce showed higher efficiency as compared to birch wood species. Due to in sufficient data for the spruce and birch at high pressure flash carbonization, we have compared effect of pressure for oak species, there is no much improvement in the energy conversion efficiency of biocarbon above 1.1 MPa, this attributes is due to the not much improvement in the char yields above 2 MPa pressure, however, this fact need to be confirmed in flash carbonizer at various pressure for other wood species at different heating time and peak temperatures.

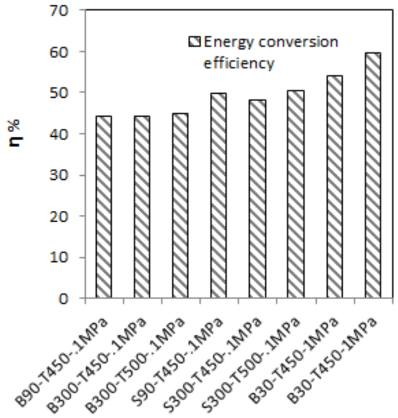

Figure 3: Energy conversion efficiency

a. Biocarbon conversion efficiency in stove

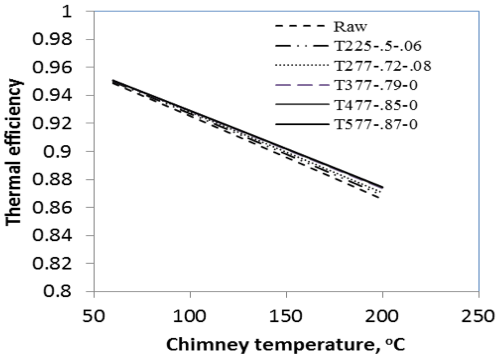

Figure 4: Thermal efficienc for various biocarbonized

3.2 Overall energy efficiency of the whole value chain

The overall energy efficiency of the whole value chain is shown in Figure 5 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. If varying the carbonization temperature at a given moisture content the same trend can be seen as in the case of the district heat coproduction scenarios in Figure 2 A.

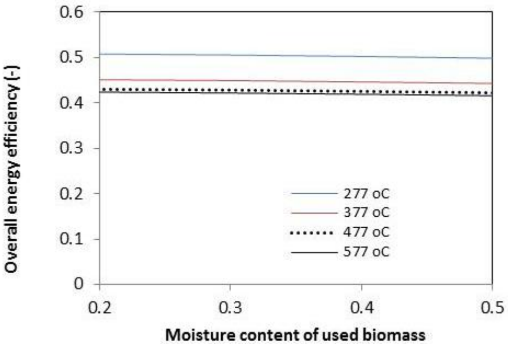

Figure 5: Overall energy efficiency of the whole value chain (conversion of raw spruce woodchips into pellets with coproduction of district heat and combustion in a residential pellet stove) as a function of moisture content of the raw spruce woodchips at an excess air ratio of 1.5 and a chimney inlet temperature of 120°C for various carbonization temperatures.

3.3 Emission aspects

Emissions in the gases consisitng CO indicates quality of combustion. There recently several works on wood pellets, torrefied pellets stove perofmanace studies. Obaidullah et al. [13] studied small-scale wood stoves and their performance: CO emissions varied from 447 to 1185 mg/Nm^3 for a 10 kW wood stove. Khalil et al. [8] combusted wood pellets and torrefied wood pellets in a pellet stove. 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 6, 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. To control CO in the acceptable guidelines, According to recent emisison inventry on a mass basis, CO emissions for fuel wood and charcoal stoves are almost similar 101.2 g/kg, this needs CO emission control devices such as catalytic converter to reduce the CO emissions. In our study biocarb based stoves are retrofited with catalytic converter to reduce the emisssions. Comercial catalytic covnverter after burner ABCAT is post retrofited to control the emissions, achievable CO reduciton is upto 65 %., as well this can also control PAHs, HCs to acceptable range.

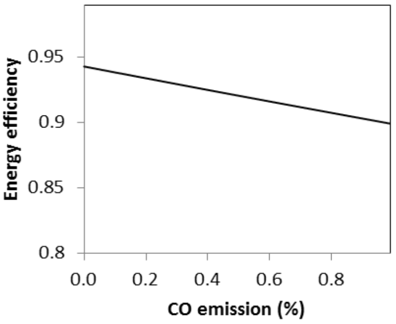

Figure 6: Energy efficiency of stove as a function of CO emission (excess air ratio of 1.5)

3.4 Economic analysis

Biocarbon production cost: Biomass supply cost estimated to be 16.5 US$/MWh. As shown in Table , the pellet production cost and overall heat production cost are based on the yields and heating values at various carbonization degree, yield decreases as the temperature increased however heating values are increased due to the improved carbon content. These datas areused for techno-economic analysis.

Table I: Biocarbon yield and heating values at various carbonization temperature

Carbonization	Biocarbon yield[1]	Biocarbon
°C	g DM/g DM spruce woodchips	MJ/kg DM
277	0.38	26.21
377	0.33	27.33
477	0.29	28.88
577	0.28	30.08

As shown in Figure 1, carbonization plant with retrofitting with district heating plant is considered as a potential market is already exist in Norway. Pellet production cost decreases compared to that when the heat from burning the carbonization gases is used for drying the raw spruce woodchips. In relation to existing wood pellet stoves, The Norwegian wood pellet price varied between 0.33 and 0.50 NOK/kWh (40 and 60 US$/MWh, respectively) between 2010 and 2013 [14]. The biocarbon pellet prices given in lie within this range.

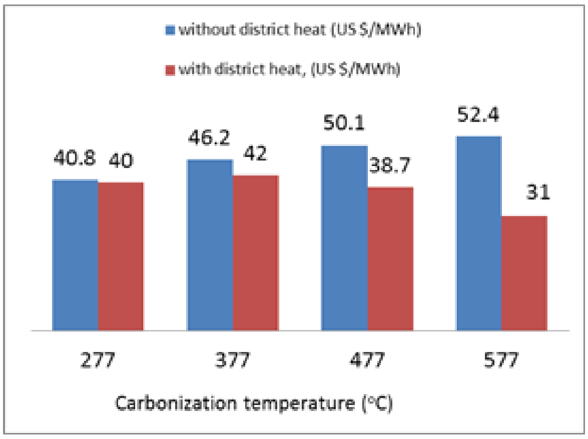

Figure 7: Pellet production cost for stove application with and without district heat

As well sensitivty analysis are performed by considering the major influential facors such char yield, plant factor, operaiton and maintenance (O&M), interest rates, spruce supply price and investment for the carbonizaiton plant. Biocabron production cost is higly sensitive to biomass price.

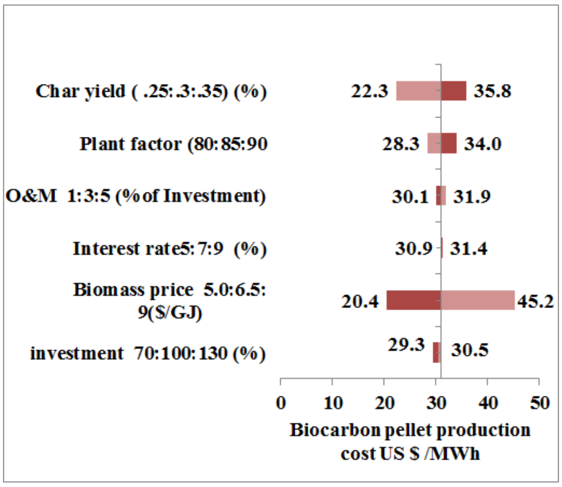

Figure 8: Biocarbon production cost sensitivity ($/MWh)

Specific heat produciton cost for stove application: Simillerly, specific heat production cost for carbonized biocarbon is estimated for various carbonization temperature, based on the effieincy results, stove thermal efficiency of 92% were considered. The investment cost of a pellet stove comprising stove, chimney conection and catalytic converter for a nominal load of 8kW costs around 4306 US$ (including Catalytic after burner costs 338 US$, chimney connection 152 US$). Pellets preparation has some challenges with respect to bindability, to improve the bindability, various additives can be considred such as starch, alkaline NaOH, biooil. In our study, we are proposing biooil as an. 5% of the LHV is lost in the pelleting process due to mixing and pelleitng process. The LHV values were calculated based on the fuel sim model works of Skreiberg [10]. Overall heat production cost for various carbonized biocarbon with and without district heat factor are shown in Figure 9.Similar to the biocarbon pellet produciton cost, specific heat produciton cost decreses by considering the distirct coproduct, however with stand alone plant without district heat, produciton cost is always increases with carbonization temperature.

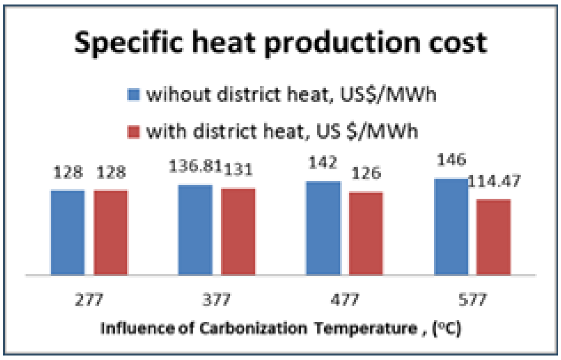

Figure 9: Specific heat production cost for stove application with and without district heat

In relation with wood pellet, overall heat production cost of 87.1 EUR/$\text{MWh}_{\text{LHV of pellet}}$ was reported [15], 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. the sensitivity towards specific biocabron production cost for selected feasible case under Norwegian conditions. Biocarbon pellet carbonized at 577 ^{o}C is considered. Sensitivity analysis also considered for biocarbon stoves, the factors selected are stove efficiency (85-95%), operating hours (1000 to 1200 hours/year), operating and maintenance costs (1-5%) of total investment (TCI), interest rate in the range of 5-9%, pellet production cost (0.25-47 $/MWh) and stove investment (70-130 %). Among these major influential factors, investment cost, pellet price, stove efficiency have major impacts on the overall heat production cost of biocarbon pellet stoves

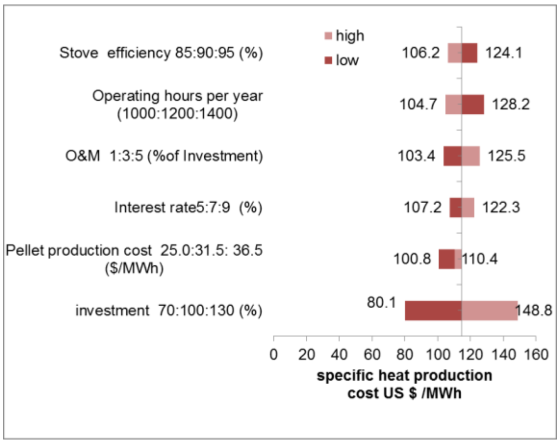

Figure 10: Specific heat production cost sensitivity ($/MWh)

4 CONCLUSIONS

The whole value chain of biocarbon production – pelleting – stove application was investigated in terms of energy efficiency, emission aspects and economic performance. 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.

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