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LCA Analysis of Biocarbon Pellet Production to Substitute Coke

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Abstract

Biocarbon is a promising alternative to fossil reductants for decreasing greenhouse gas emissions and increasing sustainability of the metallurgical industry. In comparison to conventional reductants (i.e., coke and coal), biocarbon has low density, poor mechanical strength and high reactivity. Densification is an efficient way to upgrade biocarbon and improve its undesirable properties. In this study, woody biocarbon is compressed into pellets using pyrolysis oils as a binder. In fact both pyrolysis oils and charcoal can be produced through the slow pyrolysis process and represent respectively the liquid product and the solid product. Pyrolysis gases can be used to sustain the process. Mass and energy balance of the biocarbon pelletization process are calculated and used to implement a LCA analysis. Final use of the produced biocarbon will be in the silicon industry in Norway.

Keywords: LCA, biocarbon, biomass, GHG, reductant, pyrolysis

1. Introduction

Nowadays we see that many politicians are taking commitments to "coal phase out". While it is possible to substitute or reduce coal use in power generation it has to be taken into account that coal and coal derivatives like coke have also an important role in the industrial sector as fuels and reagents. Coke is produced through thermal treatment of a blend of selected Bituminous coals (called Coking coal or Metallurgical coal). The process happens in high temperature ovens in the absence of oxygen. The coke industry is lead by China, India and Japan. We have to remember in fact that China has the world's largest steel output. As a result, China is both world's largest producer and consumer. Reuters estimates that Metallurgical coke consumption will continue to increase at an annual rate of 1.71% in the following 6 years [1].

The main use of coke produced from coal is in the steel industry. The main production of crude steel in 2018 is reported in Table 1, as provided by the WorldSteel Association [2]. The total production is about 1,808.6 Mt. The World Coal Association reports that about 0.6 tons of coke are needed to produce 1 t of steel [3].

Another growing market for coke is that of multi-crystalline silicon (multi-Si) production [4]. According to the USA Geological Service (USGS) total world production in 2018 of silicon metal was about 6.7 Mt [5]. With 380,000 tons Norway is the 3rd largest producer. According to Xakalashe and Tangstad 2011 [6], crystalline silicon solar cells can be produced through two processes: the chemical route and the metallurgical route. In both processes the first step is carbothermic reduction where coke is used. Based on simple reduction reaction mass balance, it can be calculated that at least 1.36 tons of coke (about 0.95 tons of carbon) are needed to produce 1 ton of metal silicon (where coke is supposed to have about 30% volatiles content) [7].

Table 1: World steel production, 2018 [2]

Producer	Quantity (Mt)
China	928.3
EU	168.1
North America	120.5
India	106.5
Japan	104.3
CIS	101.3
South Korea	72.5
South America	44.3
Middle East	38.5
Turkey	37.3

This coke can be substituted with other carbon sources, like charcoal or biocarbon [8]. What would be the environmental benefit in terms of reduced GHG emissions? Some LCA analysis have been made comparing the Siemens process with the metallurgical route [9]. Other analyses have been performed on the LCA of coke [10,11]. The basic system boundaries are shown in Figure 1.

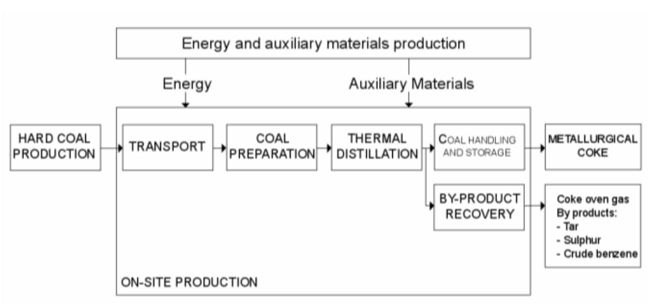

Figure 1 System boundaries of coke LCA

The GHG emissions linked with coke production are influenced by the geographic area of production and by the adopted processes [10,11]. We can say they range from 1.7 kg CO_2eq/kg of coke [10] to 0.3 kg CO_2eq/kg coke [11]. Dealing with charcoal, Bartocci et al. 2016 [12] have performed an LCA on biocarbon pellet, in which it was calculated that the GHG emissions released during charcoal pellet production are about 0.27 kg CO_2eq/kg of biocarbon. So basically we can say that the input of biocarbon and coke production can be quite similar, the big difference is in the use phase. In the use phase if we consider that the biocarbon produced at the laboratories of the University of Perugia contains about 88 wt% of fixed carbon about 1.21 ton of biocarbon is needed to produce 1 ton of metal silicon. Given that the 1 ton of carbon emits about 3.66 tons of CO_2, by substituting coke with biocarbon a reduction of 3.48 kgCO_2 per kg of metal silicon produced can be achieved.

The biocarbon pellet has been produced with an innovative process which [13]:

1. produces pellet using pyrolysis oils as binders;
2. performs re-heating of the pellet cylinder to a temperature of 600°C to increase its strength and decrease its porosity.

To check the carbon footprint of biocarbon produced with this new procedure and compare it to the one of coke, a detailed LCA analysis is performed.

2. Materials and methods

2.1 Goal and scope of the LCA analysis

The goal and scope of the analysis is to perform an LCA on 1 kg biocarbon produced through an Integrated Pyrolysis Regenerated Plant (IPRP) plant developed at the University of Perugia, Italy, and to use this data to calculate how much it would influence the GHG emissions in the production of solar silicon at an Elkem plant, situated in Kristiansand Norway and having the production capacity of 7500 t/year [9].

2.2 Feedstock

The feedstock that we assumed will be used to produce biocarbon is represented by pine wood. The process to simulate the wood chips impact is "*Wood chips, from | post consumer | wood, measured as dry mass {GLO} | market for | Alloc REC, U*" taken from the database Ecoinvent 3.3. The impact on Climate Change is about 0.0244 kgCO_2eq/kg wood chips. This impact is due in part to the transport operations and in part to the sawmill operations.

2.3 Biocarbon pellet production plant

To calculate the annual biocarbon demand it has to be taken into account that, as reported in [9] to produce 1 kg of solar grade silicon about 1.13 kg of metal grade silicon are used. So given a production of 7500 t/year of Elkem Solar Silicon (ESS^{TM})about 8475 t/year of metal grade silicon are required. This means that the annual demand of biocarbon would be about 10,255 t/year. This means that the hourly plant capacity would be about 1.34 t/h of charcoal and about 4.6 t/h biomass.

The modeling of pyrolysis plant mass and energy balances is based on previous experiences performed in Italy and China with the IPRP plant developed at the University of Perugia and the polygeneration plant developed in HUST University, Wuhan, China [12,14,15].

3. Results

3.1 Biocarbon pellet mass and energy balances

In Figure 2 it is reported a pyrolysis reactor coupled with a pelletization plant and a reheater reactor to produce biocarbon pellet.

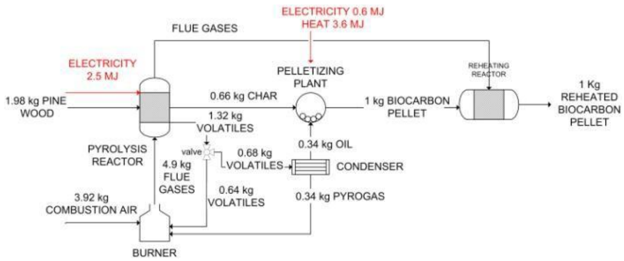

Figure 2 Industrial system for the production of biocarbon fuel

To design the mass and energy balances of the reactor the following assumptions have been made:
- the yields of pyrolysis products are distributed in the following way: 1/3 char, 1/3 biooil, 1/3 pyrogas;
- in the volatiles burner an air to fuel ratio of about 4 is considered, as reported also in [16];
- the electricity and heat consumption of the pelletizing plant is based on what is reported in [17].

To simulate the impact of the plant the following two processes were considered:
- *"Heat, central or small-scale, nautural gas {GLO} |market group for | Alloc Rec, U"*; taken from Ecoinvent 3.3 database;
- *"Electricity, medium voltage {NO} | market for | Alloc Rec, U"*; taken from the Ecoinvent 3.3 database.

The choice of the electricity process was done to grant that the data were specific of the Norwegian situation.

3.2 Biocarbon pellet carbon footprint

The final carbon footprint of the produced biocarbon pellet is presented in Figure 3. It can be seen that the total carbon footprint is about 0.672 kgCO2eq/kg of biocarbon pellet. This value is higher compared to that calculated in [12] for biocarbon pellet and it is also higher than that reported for coke in [11]. The first fact can be explained with the use of part of the volatiles to produce the biocarbon pellet, in this way the pyrolysis process cannot be sustained only by burning pyrolysis volatile products but needs also the use of electricity to promote the process. Besides in [12] the consumption of energy for the pelletization process was evaluated based on experimental data collected at laboratory level, while the industrial process has for sure higher energy consumption data. The second fact can be explained considering that the data reported in [11] are probably referring only to the coking process. Besides for coke the pelletization process is not needed, while in the case of biocarbon it is beneficial to reduce the porosity of the charcoal itself.

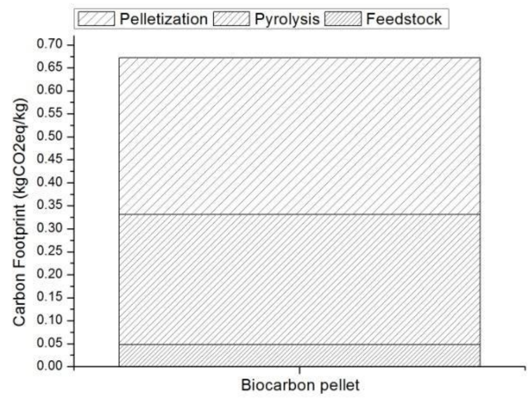

Figure 3 Biocarbon pellet carbon footprint

3.3 Solar grade silicon carbon footprint

If we consider the data shown in Figure 3 in the context of the whole multi-crystalline Silicon production chain we can substitute the biocarbon carbon footprint to the carbon footprint of the raw material in the analysis presented by Elkem [18] and we can redraw the graph on LCA GHG emissions of Elkem Solar Silicon, based on the reduced emissions due to the substitution of coke with biocarbon.

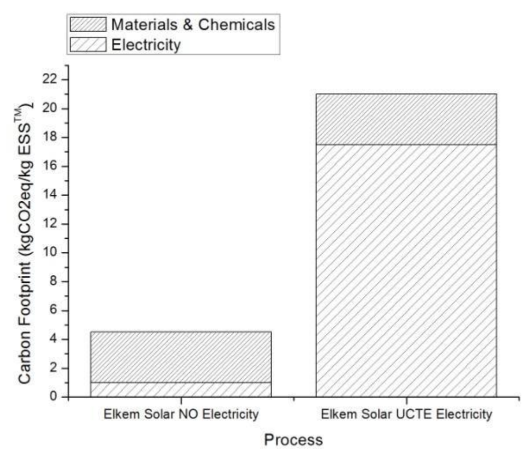

Figure 4 LCA GHG emissions of ESS™, modified from [18]

As it can be seen from Figure 4 the final carbon footprint of ESS™ can decrease with about 10 kg CO_2eq/kg ESS™, when coke is substituted by biocarbon. This means that the direct emissions shown in [18] would disappear.

The two scenarios proposed in Figure 4 show the difference if we consider in the impact the electricity produced from the Norwegian energy mix or the electricity produced from the European mix (UCTE mix).

4. Conclusions

In this paper the carbon footprint of biocarbon produced from pyrolysis at 600°C in a continuous plant coupled with a pelletization unit and a reheating reactor is presented. The pelletization step and the reheating reactor are necessary to produce a biocarbon with the required qualities to substitute coke in the production of solar grade silicon. The carbon footprint of the analysed biocarbon pellet is about 0.672 kgCO2eq/kg. If used to substitute coke this can produce a decrease in the emissions of about 10 kgCO2eq/kg ESS^{TM}. This is a preliminary analysis. The pyrolysis plant design and thermal optimization can be further improved.

Further work will be also focused on detailed uncertainty analysis and sensitivity analysis. In particular the influence of the raw material used for biocarbon production should be better assessed. Part of the issues on transport were also neglected, by using a feedstock process which contained already the transport to the gate of the plant and considering that the biocarbon plant will be installed close to the solar silicon production plant.

Acknowledgements

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