Biomass use in the steel industry: back to the future?

Einsatz von Biomassen in der Stahlindustrie: zurück in der Zukunft?

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Use of biomass can contribute to mitigation of the CO₂ emissions in the steel industry. An approach for sustainable use of biomass must consider diverse technological, economic, environmental and social aspects. This paper will focus primarily on biomass sources, resources, availability, processing steps and products as well as trading and costs. Afterwards three major options for the use of biomass in the steel industry are presented: injection, incorporation into the charging materials and reducing gas generation. Two technologies — an injection into the blast furnace and an introduction of self-reducing pellets and composites with embedded charcoal — are discussed in more detail.

From among many options to mitigate the CO₂ emissions in the steel industry, only few can be introduced in short or middle terms both from economic and technical points of view. Use of biomass as renewable energy source is one of such options.

An approach to sustainable industrial use of biomass must consider diverse technological, economic, environmental and social aspects. The role of these aspects varies significantly in different world regions and countries. Therefore it is hardly possible to find out a uniform global solution for biomass use.

For estimating the total environmental effect of biomass use along with the photosynthesis effect further factors like feedstock type and production, harvesting, processing and transport have to be considered. Furthermore, economic and technological factors have to be analysed carefully. For example, unique biomass properties such as very low sulphur content, high ratio of carbon to ash and high specific surface may improve metal quality and furnace productivity. On the other hand, the presence of harmful elements in some types of biomass must be controlled; they may affect the metal quality and smooth furnace operation. Low density and high affinity to absorb moisture from the atmosphere are also problematical by the biomass use in the steel industry.

In this contribution, after a brief overview of the past and presence of charcoal ironmaking, biomass sources, resources, availability, processing steps and products as well as trading and costs are discussed controversially.
Technological success of biomass application in the steel industry is determined by their certain chemical, physico-chemical, physical and mechanical properties. Quality requirements depend also on the use mode. Prepared biomass in form of charcoals or torrefied materials are characterized by improved quality for metallurgical applications.

Afterwards three major options for the use of biomass in the steel industry are presented:
- injection into shaft furnaces or EAF
- incorporation into the burden materials, coal blends or fuel for sintering
- reducing gas generation.

Two technologies, primarily based on recently completed and running research projects, are discussed in detail: biomass injection into the blast furnace via tuyères and charge of biomass-containing burden into the blast furnace. Injection behaviour of two types of biomass products — charcoals and torrefied materials produced from different feedstock at various conditions — is compared with fossil coals typically used as PCI. An introduction of self-reducing pellets and iron-carbon composites with cold embedded charcoal is discussed as a measure for decreasing the carbon consumption in the blast furnace by lowering the thermal reserve zone temperature. The blast furnace technology with charging these new burden materials can only be realized at certain conditions that consider e.g. strength of such materials.

Charcoal ironmaking: historical overview and present status

Charcoal was the universal energy source in the bloomery hearth mill, bloomery furnace and then in the blast furnace until the beginning of the 18th century. In 1709, Abraham Darby replaced firstly charcoal with coke at the blast furnace in Coalbrookdale, England [1]. The more economical coke soon replaced charcoal in British furnaces, but in a number of countries charcoal blast furnaces (CBF) still operated in the 20th century. For example, the last CBF in the USA operated until 1945 [2]. Nowadays the use of charcoal in metallurgy is intimately linked to small blast furnaces in Brazil, Figure 1 [3].

The use of charcoal in blast furnaces is limited due to its low mechanical strength. The largest CBFs produce about 1 200 t HM/24h; they have hearth diameters in the range of 1.5 to 6 m and typically produce low sulphur and high phosphorous hot metal. Figure 2 shows schematically an example of a CBF plant.

Charcoal hot metal capacity in Brazil makes up 15.8 million t in 154 CBFs [4]. Charcoal-based hot metal production decreased from about 1/3 of total hot metal production in Brazil in 2007 (10.2 million t) [5] to about ¼ in 2011 (7.8 million t) [4]. In 2012 the number of operating CBFs was 62 [6]. Charcoal injection is practised in small blast furnaces in Brazil as well with injection rates of up to 100 – 190 kg/t HM [7], although its average value is about 80 kg/t HM [4]. Furthermore charcoal injections in two large blast furnaces (1 155 and 3 163 m³) with injection rates of 50 – 60 kg/t HM was reported [8].

About 4 million ha of eucalyptus and pines plantations are cultivated in Brazil. Big steel producers have their own forest and charcoal production sectors; e.g. V & M do Brazil, has 120 000 ha of eucalyptus plantation which produces charcoal to feed the blast fur-
naces and plans to triple its production by 2016 [9]. Production of 1 million t/a of charcoal-based hot metal requires 120,000 ha of planted area (considering 2.15 million t/a of dry wood to produce 650,000 t/a of charcoal). Technological improvement in all the production chain steps indicates that 87,000 ha planted will be sufficient in the near future [10].

**Reason for the biomass renaissance**

Mitigation of the CO₂ emissions affecting global warming is the main reason why 300 years after the introduction of coke instead of charcoal, the steel industry looks for production of “short-life carbon” using the biomass. There are many possibilities to reduce or even to avoid the CO₂ emissions in iron and steelmaking but only few of them can be realized in short and medium terms both from technical and economical points of view. Biomass use is one of these possibilities.

The background for favourable CO₂ balance while using renewable biomass is the photosynthesis effect; the planted forests convert radiated sun energy into chemical energy and regenerate O₂ to the atmosphere:

\[
6 \text{CO}_2 + 6 \text{H}_2\text{O} = \text{C}_6\text{H}_{12}\text{O}_6 + 6 \text{O}_2, \Delta H = 2826 \text{kJ};
\]

all the carbon in biomass is generated from CO₂ of the atmosphere and only part of it is released again as CO₂, e.g. in the ironmaking process. It has to be stressed that the use of renewable biomass-derived fuels and reductants can be considered as nearly CO₂ neutral, if the raw materials have been replaced, e.g. via new growth in plantations [12].

It can be noted that it wasn’t for technological reason that charcoal use ceased 300 years ago and experiences its renaissance now. There were economic factors at Darby’s time (the problem with insufficient crushing strength of charcoal appears much later) and rising pressure of environmental issues today.

**Sources and resources — availability and sustainability**

Biomass is a general term for organic materials derived from plants. Biomass resources are in great abundance and variety and can be categorized as follows [13]:

- Agricultural residues
- Forest biomass
- Energy crops
- Bio-waste streams
- Municipal solid waste
- Packaging and household waste wood
- Sewage sludge
- Food processing wastes etc.
- Aquatic biomass.

Presently woody and rarely herbaceous biomasses are being taken into account while discussing the biomass use in the steel industry.

The worldwide biomass use can be very roughly estimated, because reliable statistics like for the fossil energy sources is missing. Renewables provide about 13 % of the global energy supply and biomass pro-
vides more than 3/4 of all renewable energy, mainly from wooden biomass, figure 3 [14]. In OECD countries, the bioenergy share is 3% on average, mainly used for electricity and heat generation. Global charcoal production corresponds to approx. 10% of the coal and coke use for ironmaking [15].

Biomass production and availability of its free resources differs significantly by world regions. In Europe, and particularly in Germany, the wooden biomass production and use is balanced [14]. It has to be mentioned that the share of energetic use of biomass (mostly for heat and power generation) is steadily increasing and makes up more than 40% [16].

The share of biomass and renewable wastes in primary energy used in Germany was about 7% in 2010 but without net imports this share is less than 3% from biomass grown in Germany [17]. The European ambitious objective for 2020 requires that 20% of the EU’s total energy supply should come from renewables but many questions still have to be answered.

Only forests in equilibrium (no more wood harvested than re-grown) are near to GHG neutral [17]. This requirement can only be fulfilled in restricted geographic regions and for certain plant types. For example eucalyptus is grown in Brazil six years and can be cut down in the seventh year without the necessity of replanting. Therefore, there is a permanent stock of standing wood. Once the felling is carried out, the roots, smaller branches and leaves are left in place and constitute an additional carbon stock. It means that the seven year’s gap between consecutive eucalyptus harvesting periods in Brazil assures environmental stability [18]. Seasonality or a harvest window is also favoured in South America, Australia or in Africa rather than in Europe. Above mentioned factors enable the possibility of more profitable and sustainable use of biomass in these regions. In Europe, Scandinavian countries have a potential for upgrading the biomass-based renewable energy. Of course, for further aspects like CO₂ emission trading, if this exists, eco-balance has to be taken into account by the total estimation of the efficiency of biomass use.

### Biomass trading, processing and costs

Global biomass trade is still insignificant: traded bioenergy makes up less than 1% of global energy demand despite of its contribution of approx. 11% [19]. By biomass trading, transport of treated biomass is economically beneficial because the yield of charcoal makes up about 1/3 (at temperatures around 500 °C) and torrefied materials about 2/3, figure 4. Therefore the processing on the export site is to be preferred. The chain of the biomass production and processing consists of many steps, figure 5. Available processing technologies in exporting and importing countries also have to be considered both from economic and environmental points of view. The global warming potential of the emissions during production might be greater than the global warming potential of the emissions during combustion. Therefore advanced industrial technologies for charcoal production which enable the recovery of chemicals and heat energy from the smoke are strongly recommended. Emissions of further GHG such as CO, CH₄, NMHC as well as TSP (Total Suspended Particulates) have to be taken into account. Further advantages of the industrial biomass processing technologies compared to the traditional methods are [22]:

- The yield of charcoal is higher
- Carbonization is more rapid
- Charcoal can be made from raw materials that cannot be processed by traditional methods.

The energy efficiency of the pyrolysis process and charcoal yield depend on the type of carbonizing system or reactor type, moisture content of the feedstock, wood species, wood arrangement, and the skill of the producer. Continuous retorts and screw-type

<table>
<thead>
<tr>
<th>Anthracite</th>
<th>Bituminous</th>
<th>Subbit.</th>
<th>Lignite</th>
<th>Grass</th>
<th>Straw</th>
<th>Wood</th>
<th>Waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>90.22</td>
<td>78.35</td>
<td>56.11</td>
<td>42.59</td>
<td>45.34</td>
<td>48.31</td>
<td>51.59</td>
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<tr>
<td>H</td>
<td>2.85</td>
<td>5.75</td>
<td>6.62</td>
<td>7.40</td>
<td>5.82</td>
<td>5.85</td>
<td>6.14</td>
</tr>
<tr>
<td>N</td>
<td>0.93</td>
<td>1.56</td>
<td>1.10</td>
<td>0.73</td>
<td>2.04</td>
<td>0.78</td>
<td>0.61</td>
</tr>
<tr>
<td>O</td>
<td>5.03</td>
<td>11.89</td>
<td>35.31</td>
<td>48.02</td>
<td>45.95</td>
<td>44.18</td>
<td>41.57</td>
</tr>
<tr>
<td>S</td>
<td>0.96</td>
<td>2.43</td>
<td>0.84</td>
<td>1.15</td>
<td>0.24</td>
<td>0.18</td>
<td>0.07</td>
</tr>
<tr>
<td>Cl</td>
<td>0.03</td>
<td>0.08</td>
<td>0.01</td>
<td>0.01</td>
<td>0.62</td>
<td>0.70</td>
<td>0.02</td>
</tr>
</tbody>
</table>

6 Fossil vs. renewable carbonaceous materials (average ultimate analysis results of many thousands coal and biomass samples), after [29]
Fossil vs. erneuerbare kohlenstoffhaltige Materialien (durchschnittliche Ergebnisse der Elementaranalyse vieler tausend Kohlen- und Biomassenproben), nach [29]
reactors typically enable a charcoal yield of 25 – 35 % [23]; with novel processes, such as flash carbonization, 40 – 50 % yields can be achieved [24; 25].

The cost structure of charcoal production is different for different feedstock types. For example, the costs of charcoal production from forest chips include stumpage price, production cost of chips (cutting, chipping etc.), transportation costs (to the charcoal plant) and charcoal production costs itself [25]. Charcoal production stage costs are determined by the applied carbonization technology, cost of utilities such as electricity, fuels, water and heat, labour costs and maintenance costs [26]. These costs change widely depending on the country and on the capacity of the plant [25]. In industrial countries, charcoal production stage costs, converted into euros, are in the range of 80 to 290 €/t charcoal [25; 27]. The total charcoal production costs are in the range of 268 to 478 €/t charcoal from logging residues [24]. Transport costs of charcoal to the steel works have to be considered additionally.

Quality characteristics and requirements
Bioenergy, originating from photosynthesis of green plants, is stored in biomass as chemical energy. Energy density of biomass is in the range of 17 – 21 MJ/kg on a dry ash-free basis [28].

The following biomass properties should be considered by their metallurgical applications:

- **Chemical**:
  - proximate analysis
  - ultimate analysis
  - ash composition.
- **Physico-chemical**:
  - reactivity
  - ash melting behaviour
  - calorific value
  - ignition behaviour (depends on the amount of volatile matters).
- **Physical and mechanical**:
  - grindability. Long fiber stalk originating biomass (e.g. hay or straw) often show poor grindability
  - porosity
  - specific surface (the surface areas of biomass are quite different. It differs for some biomass of the factor 10 at the same process conditions)
  - apparent density.

Figure 6 shows the typical composition of several classes of fuels. Biomass differs from fossil carbonaceous materials (coals) by:

- Higher oxygen content
- Lower carbon content
- Lower sulphur content
- Higher chlorine and alkali (particularly potassium) content in herbaceous biomass (grasses, straws)
- Broad range of ash content (0.1 – 25 %)

- **Lower heating values**
- Much lower bulk density
- More fibrous and less friable structure.

**O:C Molar Ratio**

Comparison of biomass and coal on a molar H/C vs. O/C ratio (average data for the samples based on many hundreds to several thousand individually measured results [29])

*Vergleich der molaren H/C- über O/C-Verhältnisse von Biomasse und Kohle (durchschnittliche Werte der Proben, basierend auf einigen hundert bis mehreren tausend einzelnen Messergebnissen [29])*

**Charcoal piece from European oak**

Holzkohle von europäischer Eiche

**Figure 7**

Comparison of biomass and coal on a molar H/C vs. O/C ratio (average data for the samples based on many hundreds to several thousand individually measured results [29])

*Vergleich der molaren H/C- über O/C-Verhältnisse von Biomasse und Kohle (durchschnittliche Werte der Proben, basierend auf einigen hundert bis mehreren tausend einzelnen Messergebnissen [29])*
better grindability (important for injection)

- better crushability (important for embedding).

Pyrolysis can be defined as thermal decomposition in an oxygen-free or oxygen-poor atmosphere and at temperatures above 300 °C [31]. Typically charcoal is produced at temperatures between 400 and 500 °C, sometimes 600 °C. The torrefaction process is a mild pyrolysis with maximum temperatures of 300 – 350 °C.

Chemistry of charcoal from wooden biomass depends on carbonization conditions but not on the wood type. The higher the carbonisation temperature is, the lower VM content and the higher carbon content in charcoal are, figure 9 [3]. Charcoals produced from different wood types (eucalyptus, oak and olive have been examined) at the same conditions (carbonization time and temperature) have similar chemical compositions. Ash content depends remarkably on the presence and thickness of bark in the wood, figure 8.

Chemistry of torrefied biomass depends on both the torrefaction process conditions and raw biomass. At low and medium temperatures (a range of 200 – 350 °C was examined) the effect of pyrolysis parameters is small or negligible but at high temperatures increasing carbon content, decreasing oxygen content and rising calorific value become remarkable (TB-l, TB-m and TB-h in figure 10 correspond to “low”, “medium” and “high” torrefaction temperatures respectively) [33]. Characteristics of raw biomasses (e.g. ash and volatile matter content) affect the quality of torrefied products as well. For example, change in LCV (Lower Calorific Value) depending on the torrefaction temperature might be different for softwood like pine (TB1 in figure 10) and hardwood like beech (TB2 in figure 10) [34].

Figure 11 shows a highly porous structure of charcoal compared with the dense microstructure of PC. The specific surface of charcoals is considerably bigger than that for PC and this value for charcoal rises with the increase of the carbonization temperature [32].

The large active specific surface of charcoal brings advantages by its application. For example, in the case of injection into the blast furnace, a bigger grain size of charcoal compared to PC could be used; this could provide an increase of the dust yield and energy and cost saving for grinding [3].

The biomass torrefied at a higher temperature has also more porous microstructure than pyrolysed at lower temperatures, figure 12 [35].
Quality requirements on biomass products depend on the mode used. Different quality in terms of volatile matter, moisture and alkali content, density, grain size, grindability, crushability etc. is needed for different applications discussed in the next section.

Options for usage

Biomass can mainly be used in three ways in the steel industry [36]:

- by gasification to generate gas for reduction or heating
- by injection into the blast furnace, the Corex Melter Gasifier or the electric arc furnace
- by incorporation into coal blend for cokemaking, fuel for sintering, composites and self-reducing pellets for direct reduction processes and blast furnace.

In this contribution two technologies are selected for discussion:

- biomass injection into the blast furnace via tuyères because of the highest potential for saving in net CO₂ emissions [7]
- use of composites or self-reducing pellets with embedded biomass materials because the idea to decrease carbon consumption in the blast furnace in such a way is being examined intensively.

Biomass injection. First studies on charcoal injection were carried out in the early 1990s by RWTH Aachen University in co-operation with Mannesmann S. A. (MSA) Brazil on a laboratory rig in Aachen and at a charcoal blast furnace in Belo Horizonte (inner volume 474 m³, hearth diameter 5.5 m) [37]. Presently the injection of charcoal fines is used in small CBFs in Brazil, as reported above.

<table>
<thead>
<tr>
<th>PC (base)</th>
<th>CC 1</th>
<th>CC 2</th>
<th>PC-TB2-I</th>
<th>PC-TB2-h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blast:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blast temperature, °C</td>
<td>1200</td>
<td>1200</td>
<td>1200</td>
<td>1200</td>
</tr>
<tr>
<td>Oxygen in blast, %</td>
<td>26.78</td>
<td>26.0</td>
<td>25.4</td>
<td>30.0</td>
</tr>
<tr>
<td>PC/CC/TBM, kg/t HM</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Burden and coke, kg/tHM:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sinter</td>
<td>992</td>
<td>604</td>
<td>735</td>
<td>820</td>
</tr>
<tr>
<td>Pellets</td>
<td>435</td>
<td>785</td>
<td>660</td>
<td>590</td>
</tr>
<tr>
<td>Lump ore</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Coke rate, kg/t HM</td>
<td>283</td>
<td>272</td>
<td>294</td>
<td>360</td>
</tr>
<tr>
<td>Slag</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volume, kg/t HM</td>
<td>260</td>
<td>182</td>
<td>214</td>
<td>230</td>
</tr>
<tr>
<td>Basicity</td>
<td>1.17</td>
<td>1.17</td>
<td>1.17</td>
<td>1.17</td>
</tr>
<tr>
<td>Top gas:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volume (dry), m³/t HM</td>
<td>1406</td>
<td>1364</td>
<td>1425</td>
<td>1422</td>
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<td>24.53</td>
<td>25.74</td>
<td>24.67</td>
<td>24.27</td>
</tr>
<tr>
<td>CO, %</td>
<td>23.60</td>
<td>22.97</td>
<td>23.63</td>
<td>28.38</td>
</tr>
<tr>
<td>H₂, %</td>
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<td>3.66</td>
<td>3.44</td>
<td>5.66</td>
</tr>
<tr>
<td>Calorific value, kJ/m³</td>
<td>3489.1</td>
<td>3299.4</td>
<td>3358.9</td>
<td>4198.8</td>
</tr>
<tr>
<td>Temperature, °C</td>
<td>150.3</td>
<td>152.7</td>
<td>156.2</td>
<td>127.0</td>
</tr>
<tr>
<td>Heat balance, MJ/tHM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total heat generated</td>
<td>9780.6</td>
<td>9618.30</td>
<td>9709.5</td>
<td>9661.6</td>
</tr>
<tr>
<td>Heat of top gas</td>
<td>314.1</td>
<td>307.6</td>
<td>327.0</td>
<td>269.8</td>
</tr>
<tr>
<td>External heat loss</td>
<td>700.7</td>
<td>672.6</td>
<td>693.7</td>
<td>676.5</td>
</tr>
<tr>
<td>Flame temperature, °C</td>
<td>2116.8</td>
<td>2118.9</td>
<td>2117.1</td>
<td>2108.5</td>
</tr>
<tr>
<td>Productivity, %</td>
<td>100.0</td>
<td>103.0</td>
<td>98.8</td>
<td>99.0</td>
</tr>
</tbody>
</table>

BF operation results (selected calculated parameters), after [35]
Figure 13 shows operation parameters of a modern blast furnace when injecting charcoals (CC) and torrefied biomass (TB), calculated using a mathematical model. Injection rate was kept at 200 kg/t HM. The flame temperature was controlled by oxygen enrichment of the blast. The sinter/pellets ratio was adjusted to keep slag basicity on a constant level [35]. Composition of auxiliary reducing agents is given in figure 10.

An analysis of figure 13 and figure 10 shows that the injection of charcoal with low ash and high basicity (CC 1) instead of PC decreases the slag volume and coke rate compared to the base case of operation with PCI; heat loss decreases and furnace productivity rises. Top gas volume and its calorific value decrease as well. When injecting charcoal with high ash content and relatively low basicity (CC 2), main operation parameters including coke rate and productivity can worsen (depending on the reference PC characteristics) [3]. Injection of a high amount of TB characterized by very high VM, very low carbon content and correspondingly low calorific value, would strongly affect the BF operation; therefore only 50 % of PC was replaced with TB by the calculations. Coke rate increases by 27.2 and 23.3 % by using TB torrefied at about 200 °C (TB2-I) and 300 °C (TB2-h) respectively. Additional enrichment of the blast with oxygen enables keeping the furnace productivity on the initial level and decreasing in top gas temperature. A rise of CO content in top gas and its calorific value indicates a lowering of gas utilization rate. Slag volume and heat loss decreases while injecting TB [35]. The coke replacement ratio for charcoal and torrefied biomass calculated using another simulation model showed similar results [38; 39]. A comprehensive experimental study on injection of charcoals from oak, olive and eucalyptus showed that conversion behaviour of the tested charcoals under conditions simulating the blast furnace raceway is comparable to or even better than that for PCI [3]. Particularly at a high injection rate, charcoal conversion behaviour becomes more favourable because the conversion degree depends on its concentration in the blast (O/C atomic ratio) not as strong as that for PCI, figure 14. The grey area in figure 14 corresponds to a PCI rate of about 150 – 180 kg/t HM. The reason for such a behaviour might be derived from the differences in the microstructure of charcoal and coal, see figure 11: the usual deficit of oxygen at a high injection rate in the case of charcoal injection is obviously compensated by oxygen in pores that promotes its further gasification. If a certain amount of charcoal residues nevertheless leaves the raceway, these unburned particles will be consumed successfully by reactions of secondary gasification, i.e. by solution loss reaction in the furnace shaft [5]. Furthermore coke reactivity can be decreased when charcoal ash will cover its surface; a very thin white film of charcoal ash can be seen on the SEM picture, which evidently protects coke from the solution loss reaction, figure 15 [3].

Torrefied biomass has significantly higher oxygen and volatile matter content and lower carbon content compared to both fossil coal used for injection and charcoal. This results in different conversion behaviour of mentioned substances. Figure 16 illustrates the decomposition process of the torrefied biomass (TB1-I, TB1-m, and TB1-h in figure 10) and fossil coal (PC in figure 10) in air atmosphere; the tests were performed in a laboratory tube furnace [33]. Heating and volatile release stages are almost completed in
100 s under the applied test conditions. Mass loss rate at this moment compared to initial volatile matter content is much higher for TB than for fossil coal, figure 12. This phenomenon may be caused by the higher ignition temperature of coals, but indicates also different compositions of volatile matter in coals and torrefied biomass. The differences between the three torrefied biomass samples are rather small, but the devolatilization decreases with increasing torrefaction temperature [33].

Injection tests of torrefied biomass under the raceway simulating conditions using lab and pilot facilities will be reported soon [40].

Injection of pyrolysed biomass might also be used to enhance efficiency and flexibility of the blast furnace lower zone control and to adopt its performance. The way to realize this idea is based on the adjustment of properties of pyrolyzed biomass discussed in the previous section, particularly carbon and volatile matter content, by changing the parameters of the pyrolysis process.

**Biomass embedding.** The use of self-reducing pellets (SRP) and composites with embedded high reactive carbonaceous materials like biomass can decrease reducing agent consumption in the blast furnace by means of transition of wustite-iron reduction equilibrium to lower temperature affecting decrease of thermal reserve zone (TRZ) temperature or the starting temperature of solution loss reaction (CO₂ + C = CO) [41; 42]. In Japan the trials at the Oita Works BF No. 2 have been conducted with charging of cement bonded carbon-iron ore composites named “Reactive Coke Agglomerate” (no biomass but coke as carbonaceous material!). This non-fired composite material was mixed into the sinter layer with a maximum rate of 54 kg/t HM [43]. The test results confirmed that the temperature was lowered at the reduction equilibrium point and that the gas utilization rate was increased. It has to be stressed that carbon saving at lower reserve zone temperature while using highly reactive materials can only be realized at certain conditions [44] that consider e. g. strength of such materials. Therefore the use of new burden materials in a small or mini blast furnace with lower strength requirements on raw materials is preferable.

Figure 18 shows the microstructure of SRP non-isothermally reduced under conditions that simulate the temperature and gas atmosphere while the pellets move through the TRZ, figure 19. Phase analysis obtained from SEM with EDX (energy dispersive X-ray) testifies the presence of large areas of metallic iron in SRP; SRP embedded with charcoal are characterized by less FeO and highest porosity.

Figure 20 shows the characteristics of pellets isothermally reduced for 30 min. SRP with embedded fossil coal and charcoal (every 18 % mass content) and conventional iron ore pellets as reference were tested. Embedded carbon improves iron oxide reduction. The charcoal effect is stronger compared to coal due to its higher reactivity; particularly solution loss reaction is accelerated significantly, as can be derived from the change in carbon mass loss.

**Table 16**

<table>
<thead>
<tr>
<th></th>
<th>PC</th>
<th>TBM1-n</th>
<th>TBM1-m</th>
<th>TBM1-h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass loss after 100 s in air, % mass content</td>
<td>10.8</td>
<td>81.0</td>
<td>77.2</td>
<td>72.0</td>
</tr>
<tr>
<td>VM, % mass content</td>
<td>24.7</td>
<td>84.7</td>
<td>80.2</td>
<td>76.2</td>
</tr>
<tr>
<td>Ratio of mass loss in 100 s to VM content, %</td>
<td>44</td>
<td>96</td>
<td>96</td>
<td>95</td>
</tr>
</tbody>
</table>

**Figure 17**

Comparison between mass loss during gasification and initial volatile matter content, after [33]

**Figure 18**

SEM micrographs of pellets after non-isothermal reduction: white: metallic iron; grey: FeO; dark grey: mixing phase of Fe-Si-Al-O; black: pores [45]

REM-Mikrographen von Pellets nach der nicht-isothermen Reduktion: weiß: metallisches Eisen; grau: FeO; dunkelgrau: Mischphase aus Fe-Si-Al-O; schwarz: Poren [45]
Naceous material is needed for efficient carburization. Carbon crystallinity can serve as indicator of carbon quality in respect of carburization reaction. Low crystallinity carbon is advantageous for carburization reaction [46]. Crystallinity strongly depends on heat treatment temperature: the higher the heating temperature, the higher the crystallinity of the carbon structure. The use of biomass materials is beneficial as a source of low crystallinity carbon because they are produced at low temperatures below 1000 °C.

Potential for utilization of biomass materials for carburization depends on effects of carbon crystallinity and ash content in biomass on carbon dissolution in molten iron and carburization reaction in the iron-carbon composites. The study on carburization behaviour of iron ore-carbon composites with different charcoals allows for concluding that [47]:

- Charcoal heat-treated at lower temperature is advantageous for carbon dissolution in molten iron.
- No significant differences in carbon crystallinity of charcoals from different wooden biomass and bamboo were found.
- Charcoal ash may prevent the carburization reaction between iron and carbon in the composite sample.

**General remarks and conclusions**

Biomass production and availability of its free resources differs significantly by world regions. Therefore it is hardly possible to find out a unique global solution and evaluation for biomass use. In Germany and in Europe, the wooden biomass production and use is balanced; it means that virtually no additional own resources are currently available. The share of energetic use of biomass (for heat and power generation) is steadily increasing.

Strategy for long-term global sustainability of biomass should be based on its primary use as raw materials; waste and biomass residues can be used as energy sources and reducing agents.

Raw biomass properties do not enable their high efficiency use in the steel industry. It is beneficial to use pyrolysed biomass such as charcoals or torrefied materials. Quality requirements on biomass products depend on their application.

In the case of biomass import, costs and emissions of its transport have to be considered. The biomass processing on the export site is preferred; advanced industrial technologies have to be used.

Main options for biomass product use in the steel industry include their

- gasification to generate gas for reduction or heating
- injection into the blast furnace, Corex or electric arc furnace
- incorporation into coal blend for cokemaking, fuel for sintering, composites and self-reducing pellets for direct reduction processes and blast furnace.

Charcoal conversion behaviour under the blast furnace raceway simulating conditions is comparable to or even better than that for PCI, particularly at high injection rates. Coarser grinding of charcoal compared to PC might be sufficient due to its large specific surface. This could lead to an increase of the dust yield and energy and cost saving.

The use of self-reducing pellets and composites with embedded charcoal can decrease reducing agent consumption in the blast furnace; this technology can be realized under certain conditions.

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**Temperature and gas composition profile during reduction of SRP [45]**

<table>
<thead>
<tr>
<th>Temp., °C</th>
<th>Time, min</th>
<th>CO2, %</th>
<th>CO, %</th>
<th>N2, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>400–700</td>
<td>60</td>
<td>25</td>
<td>15</td>
<td>60</td>
</tr>
<tr>
<td>700–1000</td>
<td>60</td>
<td>15</td>
<td>25</td>
<td>60</td>
</tr>
<tr>
<td>1000</td>
<td>30</td>
<td>10</td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td>1000–1200</td>
<td>30</td>
<td>5</td>
<td>35</td>
<td>60</td>
</tr>
</tbody>
</table>

**Mass loss and reduction rate of pellets during isothermal reduction at 900 °C in 20%CO–20%CO2–60%N2 atmosphere, after [35]**

<table>
<thead>
<tr>
<th>Pellet type</th>
<th>Total mass loss, %</th>
<th>Carbon mass loss, %</th>
<th>Reduction degree, %</th>
<th>FeO/(FeO+Fe2O3),</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional pellet</td>
<td>7.6</td>
<td>-</td>
<td>15.7</td>
<td>36</td>
</tr>
<tr>
<td>SRP with coal</td>
<td>11.1</td>
<td>30.0</td>
<td>18.3</td>
<td>52</td>
</tr>
<tr>
<td>SRP with charcoal</td>
<td>16.0</td>
<td>49.4</td>
<td>21.9</td>
<td>63</td>
</tr>
</tbody>
</table>

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References

[26] Contract No. RFSR-CT-2005-00001 and project FKZ EN-2054, the Ziel 2 program.