Low \( \text{CO}_2 \) ironmaking in the blast furnace

Roheisenerzeugung im Hochofen mit niedrigen \( \text{CO}_2 \)-Emissionen

The steel industry contributes to the global emissions of fossil \( \text{CO}_2 \) by around 7%, mainly related to coal and coke used in the BF. At the same time the BF is, and will be in a foreseeable future, the most energy efficient method for ore based hot metal production. Several R&D teams have investigated concepts to minimize \( \text{CO}_2 \) emission as e.g. the ULCOS top gas recycling BF, high injection of \( \text{H}_2 \), use of bio-mass products and HBI. In this paper these different options, and in some cases combination of these are analyzed relative the BF conditions and their possible impacts on fossil \( \text{CO}_2 \) emission are compared.

Die Stahlindustrie trägt zu den globalen Emissionen von fossilem \( \text{CO}_2 \) mit ca. 7% bei, die hauptsächlich auf den Einsatz von Kohle und Koks im Hochofen (HO) zurückzuführen sind. Gleichzeitig bleibt der Hochofen auf absehbare Zeit die energieeffizienteste Methode für erzbasierte Roheisenerzeugung. Mehrere Forschergruppen haben verschiedene Konzepte untersucht, mit denen sich die \( \text{CO}_2 \)-Emissionen minimieren lassen, wie z. B. das ULCOS-Top-Gas-Recycling BF, die Injektion von \( \text{H}_2 \)-Gas oder die Verwendung von Biomasseprodukten und HBI. In diesem Beitrag werden verschiedene Optionen und, in einigen Fällen, Kombinationen aus diesen analysiert und im Hinblick auf die Bedingungen im Hochofen sowie ihre Auswirkungen auf die fossilen \( \text{CO}_2 \)-Emissionen verglichen.

The steel industry contributes to the global emissions of fossil carbon dioxide (\( \text{CO}_2 \)) by around 7%, mainly caused by the usage of coal and coke as reductants in the blast furnace (BF). At the same time the BF is, and will be in a foreseeable future, the most energy efficient method to produce ore based liquid hot metal. A number of concepts to minimize the emission of \( \text{CO}_2 \) have been proposed by different R&D teams, as the ULCOS TGRBF [1] (top gas recycling BF), or high injection of hydrogen \( \text{H}_2 \) [2] in combination with CCS (Carbon Capture and Storage). Other options investigated, not requiring extensive modification of the BF plants, are the use of HBI [3] or bio-based reductants [9], charging of activated coke [4…7] or carbon composite agglomerates [8; 9] including such involving biomass products [9]. All of these modifications of the BF process have been shown to reduce the \( \text{CO}_2 \) emission from the BF. However, the relative impact on \( \text{CO}_2 \) emission of the concepts has not been analyzed. In this study the relative impact as well as expected impacts on the operational conditions has been analyzed using a static heat and mass balance model. The calculations were supported by experimental experience in terms of published results, laboratory tests, trials in the LKAB Experimental BF (EBF) as well as in industrial BFs.

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Blast furnace No. 3 at SSAB in Luleå

Hochofen Nr. 3 bei SSAB in Luleå
Heat and mass balance model

Different operational cases are studied in a static heat and mass balance model [10] dividing the BF in an upper and lower part, that are connected by the equilibrium between the gaseous components CO/CO₂ and H₂/H₂O and solid Fe/FeO in the thermal reserve zone [10]. The principle of BF calculations in the model is shown in figure 1 as can be seen this includes a burden model in which the raw materials to achieve the required production rate, basicity of slag and reducing agents in the BF model is calculated. By iterative calculations the reactions shown in figure 1 are closed.

The calculations are based on a model calibrated with reference operational conditions at the SSAB BFs No. 3 in Luleå and No. 4 in Oxelösund that operates on almost 100 % pellet as ferrous burden. From this starting point the different cases are analyzed using settings realistic for each plant. The calibration data for a reference case are inserted in the model and the balances closed for the material, slag and metal as well as for the gas components and energy balance. A successful calibration was verified by closure of coke rate, heat losses and gas balance with minor adjustments. The thermal reserve zone temperature was adjusted and the shaft efficiency deduced. In the following calculation the shaft efficiency, heat losses and their distribution in upper and lower zone were fixed. For most of the cases the hydrogen efficiency was also fixed. Before starting the calibration and calculations the BF model was updated for correct handling of injection materials with different characteristics in terms of volatile, heating value etc.

Analyzed cases

Injection of alternative reducing agents. Alternative reducing agents for injection at both BF sites included injection of solid biomass and gases as pure H₂, biogas and coke oven gas (COG). Figure 2 shows the characteristics of the solid biomass products and the gases used in the calculations and in figure 3 the analyzed cases are shown.

For the injected amounts of gases with characteristics according to figure 2 were in principle analysed in the similar way for both sites, see in figure 3, and the amounts of COG were based on the available amounts for injection. In the case of hydrogen and COG injection the lowering of CO₂ emission is highly dependent on the hydrogen efficiency in each BF.

The input of H₂ during the reference cases is lower in Oxelösund compared to in Luleå and so is also the hydrogen efficiency. This is the reason to minor effects achieved for these cases in BF No. 4. Using biogas on the other hand means that renew-

<table>
<thead>
<tr>
<th>PC</th>
<th>Torrefied sawdust</th>
<th>Charcoal</th>
<th>Torrefied grot *</th>
<th>H₂ gas</th>
<th>Biogas</th>
<th>COG</th>
</tr>
</thead>
<tbody>
<tr>
<td>C, % mass content</td>
<td>81.67</td>
<td>70.40</td>
<td>87.0</td>
<td>58.0</td>
<td>CH₄, % volume content</td>
<td>-</td>
</tr>
<tr>
<td>H, % mass content</td>
<td>4.09</td>
<td>5.11</td>
<td>3.40</td>
<td>5.30</td>
<td>C₃H₄, % volume content</td>
<td>-</td>
</tr>
<tr>
<td>O, % mass content</td>
<td>3.85</td>
<td>23.50</td>
<td>8.30</td>
<td>34.00</td>
<td>H₂, % volume content</td>
<td>100</td>
</tr>
<tr>
<td>VM, % mass content</td>
<td>19.8</td>
<td>50.3</td>
<td>12.1</td>
<td>72.7</td>
<td>CO, % volume content</td>
<td>-</td>
</tr>
<tr>
<td>Ash, % mass content</td>
<td>4.43</td>
<td>0.30</td>
<td>0.85</td>
<td>2.20</td>
<td>CO₂, % volume content</td>
<td>-</td>
</tr>
<tr>
<td>S, % mass content</td>
<td>0.280</td>
<td>0.010</td>
<td>0.010</td>
<td>0.62</td>
<td>N₂, % volume content</td>
<td>-</td>
</tr>
<tr>
<td>P, % mass content</td>
<td>0.020</td>
<td>0.010</td>
<td>0.003</td>
<td>0.12</td>
<td>H₂O, % volume content</td>
<td>-</td>
</tr>
<tr>
<td>HHV, MJ/kg</td>
<td>32.45</td>
<td>28.11</td>
<td>32.70</td>
<td>22.80</td>
<td>LHV, MJ/kg</td>
<td>120</td>
</tr>
</tbody>
</table>

* forest residue

Characteristics of injected solid biomass and gases used in modelling

Eigenschaften der eingeblasenen festen Biomasse und der für die Modellierung verwendeten Gase
able C is contributing to reduction and lowering of fossil CO2 emission.

Figure 4 shows the results from selected cases for solid biomass, when replacing a certain percentage of the injected reducing agents the rate of biomass will be higher in Luleå due to higher total injection rate. As can be seen the fossil CO2 emission can theoretically be reduced with up to almost 34 % when injecting 100 % torrefied sawdust at high rate.

The estimated effect on the CO2 emission per kg of biomass product used is similar in both BFs as shown in figure 5. By adding 1 kg of torrefied grot, torrefied sawdust or charcoal the CO2 emission can be reduced by approximately 1.4, 2.2 and 3.0 kg, respectively. The use of 100 % torrefied sawdust or grot results in flame temperatures below 2 000 °C, the effect is largest for grot that also results in high top gas temperature. However, in principle this can be coped with by increased O2 enrichment to the blast. Increased specific gas volumes will result in higher top gas temperatures but on the other hand the gas can also be used as energy source in heating furnace, power plant etc. All biomass products assumed has low sulphur content but the phosphorus content is high in torrefied grot. Phosphorus input limits the recycling of BOF slag at the BF and at highest levels assumed the hot metal will reach too high contents of phosphorus.

These calculations are based on constant H2 efficiency and therefore its effect is limited and following the effect from use of COG, NG (natural gas) and hydrogen, see figure 6. From the practice, reports and publications increased efficiency of H2 is found when introducing into the BF. The gas injection results in higher specific gas volumes and higher temperature in the thermal reserve zone (TRZ), which will improve the conditions for reduction with H2. The use of biogas results in significant CO2 emission as seen in figure 6, biogas contains hydrogen and renewable carbon. Due to cracking COG, NG and biogas will reduce the flame temperatures significantly, this is not the case for pure H2.

Top charging of biomass. Biomass from the top can be added in different ways as e.g. via agglomerates, as part of the coke or as charcoal but the effects will be of similar type. For simplification, top charging of charcoal, figure 2, was analyzed, in this investigation according to the cases presented in figure 3. Lowering of TRZ temperature shifts the reduction reaction (1) to the right and the indirect reduction is increased, this is taken into account in the heat and mass balance model

$$CO + FeO \rightarrow Fe_{net} + CO_2$$  \hspace{1cm} (1)

The type of reducing agents added and the effect on fossil CO2 emission estimated in the calculations shown in figure 7. As can be seen the CO2 emission can be lowered with up to 5 – 28 % depending on the amount added and the assumption on change in thermal reserve zone temperature. Improved C efficiency results in lower content of CO in the top gas and following slightly lower heat value.

Top charging of pre-reduced burden. Top charging of HBI/DRI was analyzed using published results from

---

### Table: Injected Bio/PC

<table>
<thead>
<tr>
<th>Injected Bio/PC</th>
<th>% mass content / % mass content</th>
<th>Ref</th>
<th>Solid biomass</th>
<th>Gas*</th>
<th>Top charged bio</th>
<th>Combined cases</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid inj. Lu.</td>
<td>kg/tHM</td>
<td>143</td>
<td>0/100</td>
<td></td>
<td>0/100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solid inj. Ox.</td>
<td>kg/tHM</td>
<td>115</td>
<td>20/80</td>
<td>50/50</td>
<td>1000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas inj. Lu.</td>
<td>m3(STP)/tHM</td>
<td>----</td>
<td>0/100</td>
<td>50/100</td>
<td>150/150</td>
<td>50/150</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas inj. Ox.</td>
<td>m3(STP)/tHM</td>
<td>----</td>
<td>0/100</td>
<td>50/100</td>
<td>150/150</td>
<td>50/150</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coke Lu./Ox.</td>
<td>kg/tHM</td>
<td>309/355</td>
<td>Calc./ref./calc.</td>
<td></td>
<td></td>
<td>Calculated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top Bio Lu.</td>
<td>kg/tHM</td>
<td>----</td>
<td>20/50</td>
<td>100/100</td>
<td>20/20</td>
<td>20/20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top Bio Ox.</td>
<td>kg/tHM</td>
<td>----</td>
<td>20/50</td>
<td>100/100</td>
<td>20/20</td>
<td>20/20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HBI Lu.</td>
<td>% mass content **</td>
<td>----</td>
<td>0/50</td>
<td>20/20</td>
<td>20/20</td>
<td>20/20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HBI Ox.</td>
<td>% mass content **</td>
<td>----</td>
<td>0/50</td>
<td>20/20</td>
<td>20/20</td>
<td>20/20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRZT Lu.</td>
<td>°C</td>
<td>850</td>
<td>As ref./ref-20</td>
<td>ref-50</td>
<td>As ref./ref-45</td>
<td>As ref./ref-45</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRZT Ox.</td>
<td>°C</td>
<td>845</td>
<td>As ref./ref-45</td>
<td>As ref./ref-45</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

H2, biogas, COG or NG. COG is analyzed for 50 and 60 m3(STP)/tHM, ** % mass content of pellets, ***COG, TRZT= Thermal reserve zone temperature.
the ULCOS trials in the LKAB experimental BF [3] for the estimation on the likely change in gas efficiency when replacing 20 or 50 weight % of the hematite pellets with HBI containing almost 90 % metallic Fe and 9.2 % of FeO. It was assumed that the HBI was produced from the same type of pellets as used in the ferrous burden. The calculations were done for two assumed injection rates of PCI; 143 and 180 kg/tHM for BF No. 3 in Luleå and 115 and 150 kg/tHM for BF No. 4 in Oxelösund. Due to higher amount of scrap charged during the reference period at BF No. 4 the amount of HBI used in the calculation will be lower and also the reduction in fossil CO₂ emission as can be seen in figure 8.

Figure 8 shows that fossil CO₂ emission at the BF can be reduced with approximately 10 % when replacing 20 % of the hematite pellets and 25 % when replacing 50 % of them. The lower amounts of reducing agents will result in lower amounts of limestone as the amount of ash that needs to be neutralized is lowered.

Top gas recycling. Top gas recycling in line with ULCOS top gas recycling BF [1] were also assumed and the impact on fossil CO₂ emission calculated. The injection temperatures of hot gas were set to 850 °C in order to allow the use of metallic heat exchanger for heating of the recycled gas and the recycling ratio to 95 % except for the last case for Oxelösund in which 99 % recycling was assumed. The calculation results show lowering of fossil CO₂ emission approximately 20 % for version 1 with cold gas injected at the tuyère
Cases and results from heat and mass balance calculation on the injection of gases for BF No. 3 in Luleå (left) and BF No. 4 in Oxelösund (right). Upper diagrams show the input of reducing agents and the lower the potential impact on fossil CO$_2$ emission.

Ergebnisse der Wärme- und Stoffbilanzberechnung für die Injektion von Gasen für Hochofen 3 in Luleå (links) und Hochofen 4 in Oxelösund (rechts). Die oberen Grafiken zeigen den Einsatz der Reduktionsmittel, die unteren die potenziellen Auswirkungen auf die fossile CO$_2$-Emission.

Cases and results from heat and mass balance calculation on top charging of biomass for BF No. 3 in Luleå (left) and BF No. 4 in Oxelösund (right). Upper diagrams show the input of reducing agents and the lower the potential impact on fossil CO$_2$ emission.

Ergebnisse der Wärme- und Stoffbilanzberechnung für die Beschickung mit Biomasse für Hochofen 3 in Luleå (links) und Hochofen 4 in Oxelösund (rechts). Die oberen Grafiken zeigen den Einsatz der Reduktionsmittel, die unteren die potenziellen Auswirkungen auf die fossile CO$_2$-Emission.
level and gas of 850 °C in the shaft. Using hot gas at both levels resulted in approximately 25% fossil CO₂ savings. These results are well in line with the reported trial results and can be seen from figure 9.

**Combined cases.** Implementation of, for example, top charging or injection of a low amount of biomass products as well as charging of some HBI are likely to have little impact on the BF operation. By combining these concepts it could be possible to reduce the fossil CO₂ emission substantially but are at the same time keeping the BF process almost as usual. Therefore some combined cases were analyzed, a summary of selected ones is stated in figure 3 and the results are shown in figure 10.

As shown in figure 10, CO₂ savings of approximately 10 – 12% can be reached by combining 20% torrefied saw dust in the coal blend with top charging of 20 kg/tHM of charcoal. If also HBI is added the savings reach close to 30% for Luleå and almost

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**Cases and results from heat and mass balance calculation on top gas recycling for BF No. 3 in Luleå (left) and BF No. 4 in Oxelösund (right).**

<table>
<thead>
<tr>
<th>143 kg/tHM</th>
<th>143 kg/tHM</th>
<th>180 kg/tHM</th>
<th>143 kg/tHM</th>
<th>180 kg/tHM</th>
<th>115 kg/tHM</th>
<th>115 kg/tHM</th>
<th>150 kg/tHM</th>
<th>150 kg/tHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref</td>
<td>20% HBI</td>
<td>20% HBI</td>
<td>50% HBI</td>
<td>Ref K</td>
<td>20% HBI</td>
<td>50% HBI</td>
<td>20% HBI</td>
<td>50% HBI</td>
</tr>
<tr>
<td>CO₂ per source</td>
<td>11,7</td>
<td>-11,4</td>
<td>-26,5</td>
<td>-25,8</td>
<td>-10,4</td>
<td>-10,0</td>
<td>-23,1</td>
<td>-22,5</td>
</tr>
<tr>
<td>CO₂ fossil</td>
<td>143 kg/tHM</td>
<td>143 kg/tHM</td>
<td>180 kg/tHM</td>
<td>143 kg/tHM</td>
<td>180 kg/tHM</td>
<td>115 kg/tHM</td>
<td>115 kg/tHM</td>
<td>150 kg/tHM</td>
</tr>
</tbody>
</table>

---

**Cases and results from heat and mass balance calculation on charging of HBI for BF No. 3 in Luleå (left) and BF No. 4 in Oxelösund (right).**

Ergebnisse der Wärme- und Stoffbilanzberechnung für die Beschickung mit HBI für Hochofen 3 in Luleå (links) und Hochofen 4 in Oxelösund (rechts).

Die obigen Grafiken zeigen den Einsatz von Reduktionsmitteln und HBI, die unteren die potenziellen Auswirkungen auf die fossilen CO₂-Emissionen. Die Injektionsraten für PCI betrugen 143 und 180 kg/t Roheisen für Luleå und 115 und 150 kg/t Roheisen für Oxelösund.

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**Cases and results from heat and mass balance calculation on top gas recycling for BF No. 3 in Luleå (links) and Hochofen 4 in Oxelösund (rechts).**

Ergebnisse der Wärme- und Stoffbilanzberechnung zum Topgas-Recycling für Hochofen 3 in Luleå (links) und Hochofen 4 in Oxelösund (rechts).
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21% for Oxelösund. The reasons to higher impact in Luleå is mainly the higher injection rate, which gives higher amount of biomass introduced at tuyère level, but also due to that more HBI is added.

**Concluding remarks**

As shown by the results from the heat and mass balance calculation all analyzed methods can contribute to significant CO₂ emission savings and the method to select will be influenced by the local conditions, availability of materials, existing facilities at the integrated plant and how the produced BF gas is used within the plant.

Injection of biomass products has great potential for reducing the fossil CO₂ emission related to the BF and increase in energy output through the BF top gas may also reduce the use of oil, NG etc. in heating furnaces or power plants. There is raw biomass available in the region but there are presently not sufficient facilities for making biomass products suitable for BF use but there is interest for such developments in the forest sector. This development can be enhanced by demonstrating the feasibility in use at the BF plant in combination with PC or separately. So far operational injection trials using 20% grinded torrefied sawdust in a blend with PC has been successfully conducted at the LKAB Experimental BF. Industrial trials are required for stating the optimum way for introducing biomass product into the BF and also finding the long term effects on the operation as well as on the secondary materials to be recycled via injection or agglomeration.

When injecting gas, biogas is most positive as it contains renewable C apart from hydrogen and both contributes to indirect reduction and lower total consumption of fossil C. However, there is limited amount of biogas available for use at the BF plants, the biogas needs to be treated for CO₂ removal.

Top charging of charcoal is another alternative giving substantial CO₂ emission savings. This can be especially suitable as additive in the ferrous layers in order to enhance indirect reduction of the pellets. If sufficient charcoal is available, the limitation might be the strength of charcoal as well as its low density. Already 20 kg/tHM will increase the volumes of the ferrous layers significantly. Use of torrefied material as direct charge is not feasible due to its substantial content of volatiles that can be lost via the top gas and cause difficulties in the gas cleaning.

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**Cases and results from heat and mass balance calculation on combined cases for BF No. 3 in Luleå (left) and BF No. 4 in Oxelösund (right).**

Ergebnisse der Wärme- und Stoffbilanzberechnung für kombinierte Lösungen für Hochofen 3 in Luleå (links) und Hochofen 4 in Oxelösund (rechts). Die TRZ-Temperaturen für die Referenzfälle waren 850 und 845 °C für Luleå bzw. Oxelösund.
HBI charging has also the potential to significantly reduce the CO₂ emission at the BF but for using high amounts as e.g. 50 % the production rate should preferably be increased. Lower added amounts like 20 % of HBI or some other scrap product can be used for lowering the CO₂ emission and especially if a slight increase of the production rate is desired.

The combined cases with lower amount added in terms of biomass products for injection together with top charging of charcoal as well as HBI addition was shown to give effects up to around 20 – 30 %. This could be an advantage from BF operation point of view as the overall process is likely less influenced by such modification.

Top gas recycling has been proven in experiments to give the savings that have been estimated in the modelled cases. As the top gas will be used for BF operation others as e.g. oil, NG, COG, biogas or biomass have to be used in heating furnaces, for district heating and power plants. Moreover, it will need installation of CO₂ capture plant and enlargement of oxygen production capacity. By limiting the hot gas temperature to 850 ºC and using metallic heat exchangers the hot stoves are available for periods with conventional BF operation.

Acknowledgements. The research work presented in this paper has been carried out mainly within the project Blast Furnace with minimum CO₂ emission that is a strategic research project in the research area of “Metalliska Material” hosted by Swedish Steel Producers Association and funded by Vinnova. The paper is a contribution from Centre of Advanced Mining and Metallurgy (CAMM) at Luleå University of Technology supporting all presented research scientifically and economically.

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