Introduction

Why start GREENEAF?

What to do in GREENEAF?

What are the results of GREENEAF?

Conclusions
Why start GREENEAF?

Overview of the Steelmaking Process

<table>
<thead>
<tr>
<th>Total Crude Steel Production 2013 and EAF share</th>
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<tbody>
<tr>
<td>Germany</td>
</tr>
<tr>
<td>Europe</td>
</tr>
<tr>
<td>Canada</td>
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</tbody>
</table>

Source (image and data): worldsteel.org
Why start GREENEAF?

Energy and mass balance

<table>
<thead>
<tr>
<th>Source</th>
<th>CO₂/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>486</td>
</tr>
<tr>
<td>Europe (EU-28)</td>
<td>337</td>
</tr>
<tr>
<td>Canada</td>
<td>158</td>
</tr>
</tbody>
</table>

Electric energy: 393 kWh/t (48.5 %)

Total energy input: 810 kWh/t (100 %)

- Carburizing agents: 191 kWh/t (23.6 %)
- Natural gas burner: 50 kWh/t (6.2 %)
- Chemical reactions: 123 kWh/t (15.2 %)
- Electrode consumption: 28 kWh/t (3.4 %)
- ΔC steel: 25 kWh/t (3.1 %)
- Flue gas: 169 kWh/t (20.7 %)
- Vessel cooling: 71 kWh/t (8.8 %)
- Top cover cooling: 37 kWh/t (4.6 %)
- Slag: 31 kWh/t (3.8 %)
- Heat loss: 69 kWh/t (8.5 %)
- Balance difference: 37 kWh/t (4.6 %)

Steel:

- CaO, MgO: Scrap, HBI/DRI
- Electrode Consumption
- Offgas
- Dust
- Oxygen
- Air
- Slag
- Natural Gas

Canada (158 g CO₂/kWh)

Europe (EU-28) (337 g CO₂/kWh)

Germany (486 g CO₂/kWh)

Source: IEA
Why start GREENEAF?

Energy and mass balance

- **Electrode consumption**
  - 1-2 kg/\(t_{\text{steel}}\)
  - ≙ 4-7 kg CO\(_2\)/\(t_{\text{steel}}\)

- **Direct CO\(_2\) emissions**
  - 60-100 kg CO\(_2\)/\(t_{\text{steel}}\)

- **Other carbon sources**
  - e.g. Scrap, DRI, pig iron, CaCO\(_3\)
  - Natural gas
    - 150 MJ/\(t_{\text{steel}}\)
    - ≙ 10 kg CO\(_2\)/\(t_{\text{steel}}\)

40%-70% of direct emissions!

Coal and coke

- 12 kg/\(t_{\text{steel}}\)
- ≙ 44 kg CO\(_2\)/\(t_{\text{steel}}\)
Why start GREENEAF?

Biomass and biochar compared to fossil coal

- Biomass is currently considered as CO₂ neutral by the European Commission¹

- Different composition
  - 50 m.% C
  - 40 m.% O₂
  - 6 m.% H₂
  - Rest: mineral substances and trace elements

  ➢ Lower heating value than fossil coal
  ➢ Higher proportion of volatiles (and water)
  ➢ Higher reactivity

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What to do in GREENEAF?

Sustainable EAF steel production – GREENEAF (2009-2012)
Biochar for a sustainable EAF steel production – GREENEAF2 (2014-2016)
What to do in GREENEAF?

### Sustainable EAF steel production - GREENEAF

<table>
<thead>
<tr>
<th>Use of biochar in the EAF</th>
<th>Use of biogas in the EAF</th>
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<tbody>
<tr>
<td>Biomass selection</td>
<td></td>
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<tr>
<td>Pyrolysis process adjustment, char and biogas characterization</td>
<td></td>
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<tr>
<td>Laboratory and pilot plant tests</td>
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</tbody>
</table>
What are the results of GREENEAF?

Laboratory and pilot plant tests

- Slag foaming tests in crucibles
- Melting trials in pilot EAF plant (600 kW, 200 kg melt)
- Agglomeration of biochar fines

Slag foaming tests with coal and with char

Tapping of a trial melt in the pilot EAF

Agglomeration of biochar fines
What to do in GREENEAF?

Sustainable EAF steel production - GREENEAF

- Use of biochar in the EAF
- Use of biogas in the EAF
- Biomass selection
- Pyrolysis process adjustment, char and biogas characterization
- Laboratory and pilot plant tests
- Industrial tests
- Simulation of biogas use in the EAF
- Techno-economic evaluation
What to do in GREENEAF?

Biochar for a sustainable EAF steel production - GREENEAF2

- Substitution of charge coal
- Substitution of injection carbon
- Char and briquettes acquisition and characterization
What are the results of GREENEAF?

Char and briquettes acquisition and characterization
What are the results of GREENEAF?

Biomass acquisition and characterization
What to do in GREENEAF?

Biochar for a sustainable EAF steel production - GREENEAF2

- Substitution of charge coal
- Substitution of injection carbon
- Char and briquettes acquisition and characterization
- Development of char injection methodology
- Long time industrial tests of biomass charging
- Industrial tests of char injection
**What are the results of GREENEAF?**

**Charging trials – Palm kernel shells**

<table>
<thead>
<tr>
<th></th>
<th>C&lt;sub&gt;total&lt;/sub&gt; / C&lt;sub&gt;fix&lt;/sub&gt; (%)</th>
<th>Volatiles (%)</th>
<th>Ash (%)</th>
<th>Heating Value (MJ/kg)</th>
<th>Sulphur (%)</th>
<th>Phosphor (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anthracite</td>
<td>85-90 / -</td>
<td>8</td>
<td>10</td>
<td>29</td>
<td>1</td>
<td>0.01</td>
</tr>
<tr>
<td>PKS</td>
<td>43-55 / 28</td>
<td>63-72</td>
<td>2-4</td>
<td>16-19</td>
<td>&lt; 0.005</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Six campaigns consuming a total of 2,600 t of PKS and PKS mix respectively in 1542 heats accompanied by 374 reference heats.
What are the results of GREENEAF?

Charged PKS/anthracite and electric energy input per ton of steel

What are the results of GREENEAF?

Averaged CO and H₂ concentrations in the off gas

What to do in GREENEAF?

Biochar for a sustainable EAF steel production - GREENEAF2

- Substitution of charge coal
- Substitution of injection carbon
- Char and briquettes acquisition and characterization
- Development of char injection methodology
- Long time industrial tests of biomass charging
- Industrial tests of char injection
- LCA assessment
- Evaluation of project results and definition of EAF operating practices designed for biochar/biomass utilization
Conclusions

Technical

- EAF steelmaking is a complex batch process with a very high variability from batch to batch but also a high flexibility. Each plant is unique in the steel grades it produces in combination with the equipment it has available.
- Operating practices have to be adjusted to biomass/biochar behaviour in the furnace (e.g. use of post-combustion oxygen has to be adjusted).
- Biochar fines are not suitable as a substitute for fossil charge carbon, because of their very large surface area and high reactivity.
- Agglomeration tests showed that it is possible to produce briquettes of biochar, which have similar characteristics as anthracite coal with regard to abrasion tests and combustion behavior.
- Slag foaming is in general possible, but needs further R&D.
- None of the trial campaigns with CO₂-neutral biochar and biomass used as charge carbon showed any negative impact on steel or slag quality or furnace operation.
Conclusions

Emissions

- Use of CO$_2$-neutral biomass or biochar can avoid CO$_2$ emissions relevant for the EU ETS in the range of 12 % to 60 % of the total emissions per ton steel.
- The replacement of fossil coal with biochar can avoid a large proportion (up to 70 %) of direct CO$_2$ emissions of the EAF steelmaking process.
- From a European perspective, 4 million t$_{CO2}$ could have been saved by the ten biggest European electric steel producers in 2010.

<table>
<thead>
<tr>
<th></th>
<th>EAF steel production</th>
<th>Potential CO$_2$ savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>13.2 Mt</td>
<td>22.7 % 0.8 Mt</td>
</tr>
<tr>
<td>Canada</td>
<td>5.5 Mt</td>
<td>39.5 % 0.3 Mt</td>
</tr>
</tbody>
</table>

Conclusions

Economy

- Economic feasibility of fossil coal substitution depends on steel grades produced, operating practices and furnace equipment due to possible impacts on productivity.
- Due to low prices for fossil coal and EU emission allowances (EUA) and an insufficient biochar market the substitution of fossil coal with biomass or biochar is currently not economic in Europe.
- In the future, especially the use of biogenic residues could have a positive effect on the economics of the coal → biochar substitution.
- Rising prices for fossil coal or the expected rise of prices for EUA’s will change the economy of biomass/biochar use in electric steelmaking in Europe.

Benchmark contract prices for Australian metallurgical coal

Australian Government, Department of Industry, Innovation and Science (2016)
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Thank you for your attention

Dr.-Ing. Thomas Echterhof
RWTH Aachen University
Department for Industrial Furnaces and Heat Engineering
Kopernikusstraße 10
52074 Aachen
Germany
echterhof@iob.rwth-aachen.de